Reaction Seminar

Study of ground-state configuration of ^{13}B via single-nucleon transfer reaction

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Content

- Background and motivation
- Experimental setup
- Data analysis and discussion
    - Elastic scattering
    - Single-neutron transfer reaction
    - Single-proton transfer reaction
- Summary

Shell evolution

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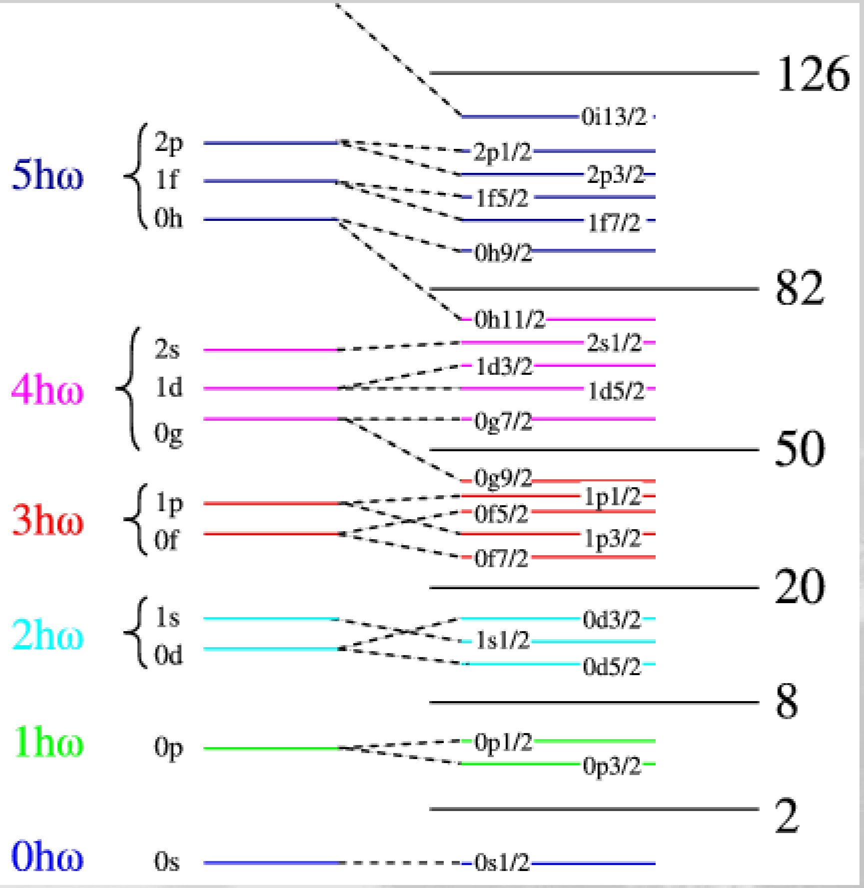

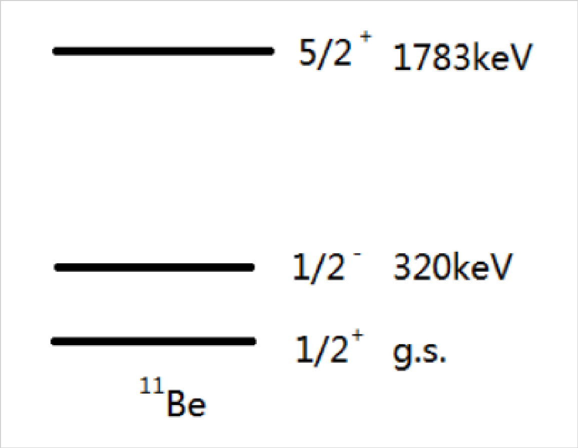

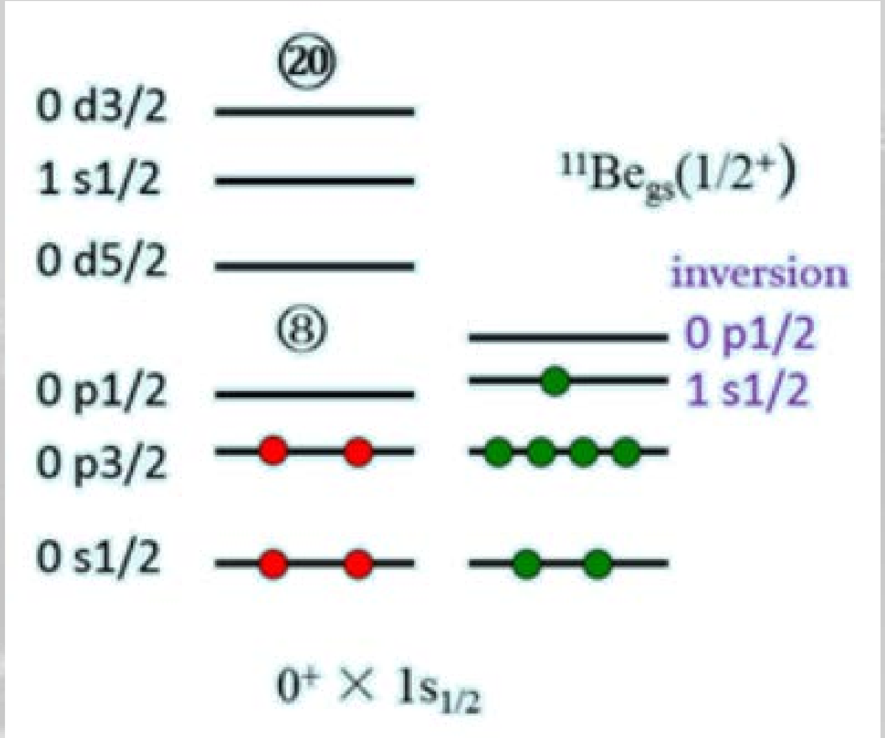

Intruder around N=8

N=7:

normal： $(1p_{1/2})_{\upsilon}^{1}$

intruder： $(1p_{1/2})_{\upsilon}^{-1}(2s_{1/2})_{\upsilon}^{1}$ --- s-wave

$(1p_{1/2})_{\upsilon}^{-1}(1d_{5/2})_{\upsilon}^{1}$ --- d-wave

N=9:

normal： $(1d_{5/2})_{\upsilon}^{1}$

intruder： $(1d_{5/2})_{\upsilon}^{-1}(2s_{1/2})_{\upsilon}^{1}$ --- s-wave

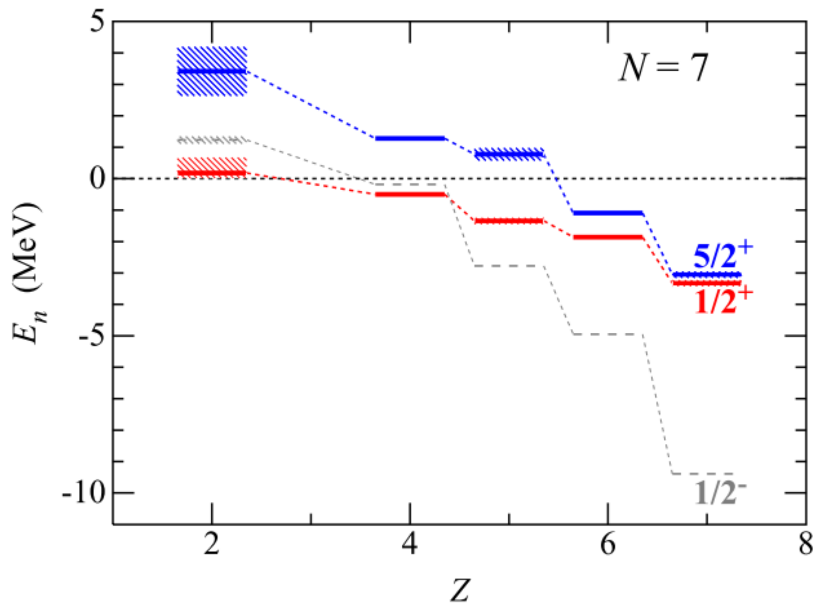

FIG. 1. (Color online) The experimental data available on the energy E_n, relative to the neutron threshold, of the $0p_{1/2}$, $1s_{1/2}$, and $0d_{5/2}$ states in $N = 7$ nuclei. The sources of the data are given in the appendix. Uncertainties are indicated by shading.

Hoffman *et. al*. 2014

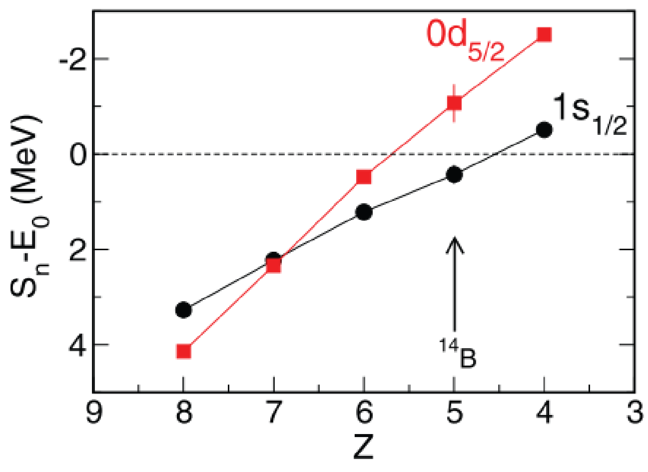

FIG. 3. (Color online) Effective single-particle binding energies of the $1s_{1/2}$ and $0d_{5/2}$ orbitals as a function of Z, for $N = 9$ isotones. The ^{14}B points are from the present measurement, and the lines are to guide the eye.

Bedoor *et. al*. 2014

N=8 isotones: ^{11}Li

Tanihata *et. al*. 2008

$0p0h$ configuration: $(1p_{1/2})^2_\upsilon$

$2p2h$ configuration: $(1p_{1/2})^{-2}_\upsilon(2s_{1/2})^2_\upsilon$ --- s-wave

$(1p_{1/2})^{-2}_\upsilon(1d_{5/2})^2_\upsilon$ --- d-wave

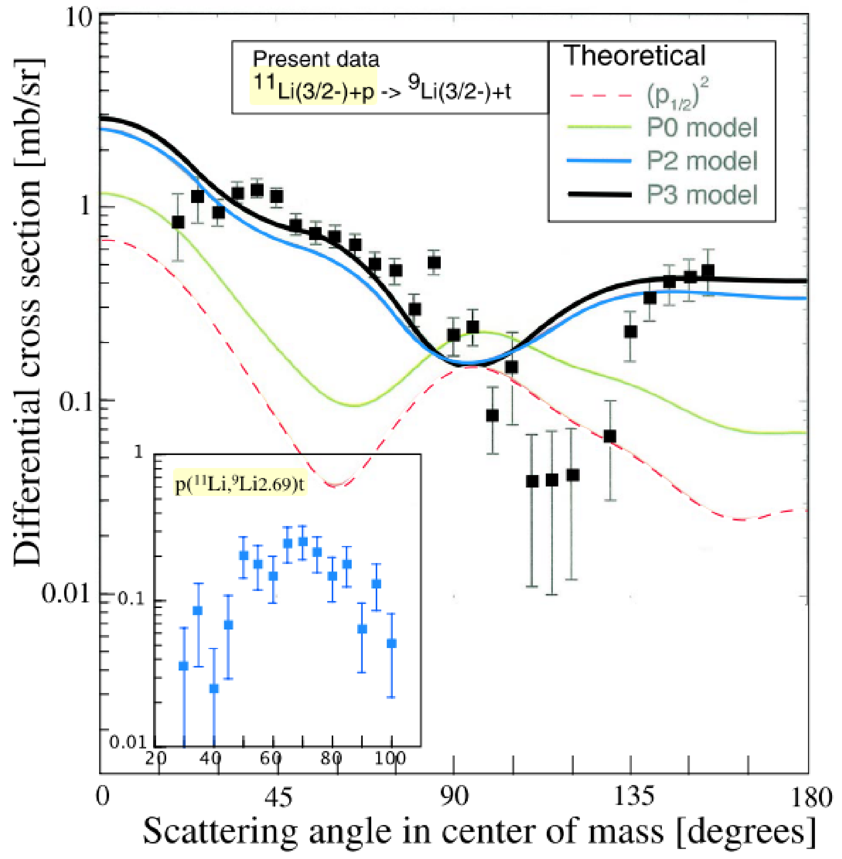

FIG. 3 (color online). Differential cross sections of the (p, t) reaction to the ground state of ^{9}Li and to the first excited state (insert). Theoretical predictions using four different wave functions were shown by curves. See the text for the difference of the wave functions.

$p(^{11}\mathrm{Li}, t)\ ^9\mathrm{Li}_{\mathrm{g.\,s.}}$

P3 model: **45% s-wave**

$p(^{11}\mathrm{Li}, p')$ by Tanaka *et. al*. 2017

$d(^{11}\mathrm{Li}, d')$ by Kanungo *et. al*. 2015

N=8 isotones: ^{12}Be

$d(^{11}\mathrm{Be},p)^{12}\mathrm{Be}$

19% *s*-wave and **57% *d*-wave** in the ground state of ^{12}Be

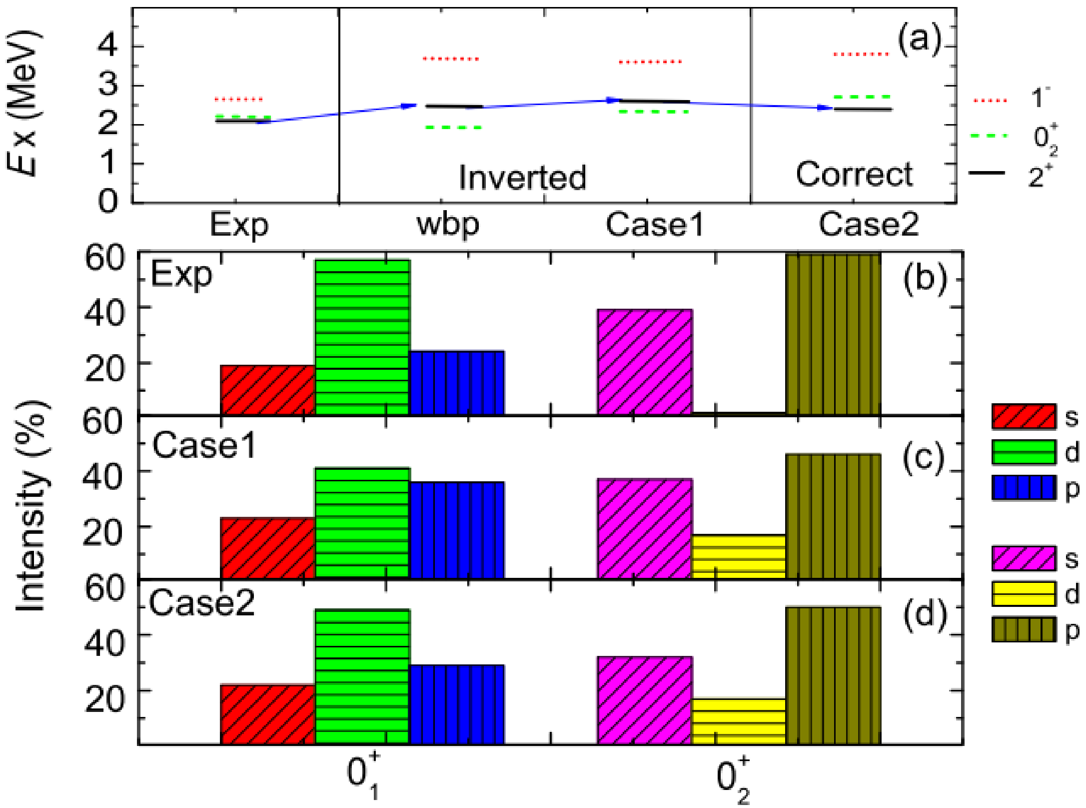

Fig. 4. (a) Comparison of the level schemes of the low-lying states in ^{12}Be between the experimental data and the shell model calculations with traditional wbp [25] or YSOX Hamiltonian. (b) The individual *s*-, *p*- and *d*-wave intensities for the 0_1^+ and 0_2^+ states deduced from experiments. (c) Shell model calculations with YSOX interaction (Case 1). (d) Same as (c) but with a decrease of 0.5 MeV for the *d*-orbit (Case 2).

Chen *et. al.* 2018

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N=8 isotones: ^{14}C

$^{14}C(p,d)^{13}C$ by Cecil *et. al.* 1975

TABLE 2

Measured spectroscopic factors and deformation parameters

Reaction	J^π	E_x (MeV)	$\mathcal{S}_{lj}$ [a])	β_L
$^{14}C(d, p)$	$\frac{1}{2}^+$	0.0	1.03 [b])	
			0.76	
	$\frac{5}{2}^+$	0.74	1.02	
			0.89	
$^{14}C(d, d')$	2^+	7.01		0.25
				0.20
	3^-	6.73		0.32
				0.25
$^{14}C(p, d)$	$\frac{1}{2}^-$	0.0	1.4	
	$\frac{1}{2}^+$	3.09	0.02	
	$\frac{3}{2}^-$	3.68	1.8	
	$\frac{5}{2}^+$	3.86	0.13	

1.3% *s*-wave and 8.4% *d*-wave

N=8 isotones: ^{13}B

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$0p0h$ configuration: $(1p_{1/2})^2_\upsilon$

$2p2h$ configuration: $(1p_{1/2})^{-2}_\upsilon(2s_{1/2})^2_\upsilon$ --- s-wave

$(1p_{1/2})^{-2}_\upsilon(1d_{5/2})^2_\upsilon$ --- d-wave

$$|\text{g.s.}\rangle = \nu[a(1p_{1/2})^2 + b(2s_{1/2})^2 + c(1d_{5/2})^2]$$

Exp.	Conclusions	Ref.
magnetic dipole moment	p-wave dominant	Williams *et. al*. 1971
1n knockout	p-wave dominant	Sauvan *et. al*. 2004
$d(^{12}\text{B},p)^{13}\text{B}$	large p-wave spectroscopic fctor	Lee *et. al*. 2010
^{14}Be β-decay	33% s-wave	Aoi *et. al*. 2002
$^{13}\text{C}(t,\ ^{3}\text{He})^{13}\text{B}$	24% $2p2h$ intruder	Guess *et. al*. 2009

No individual measurements of *s*-wave and *d*-wave strengths

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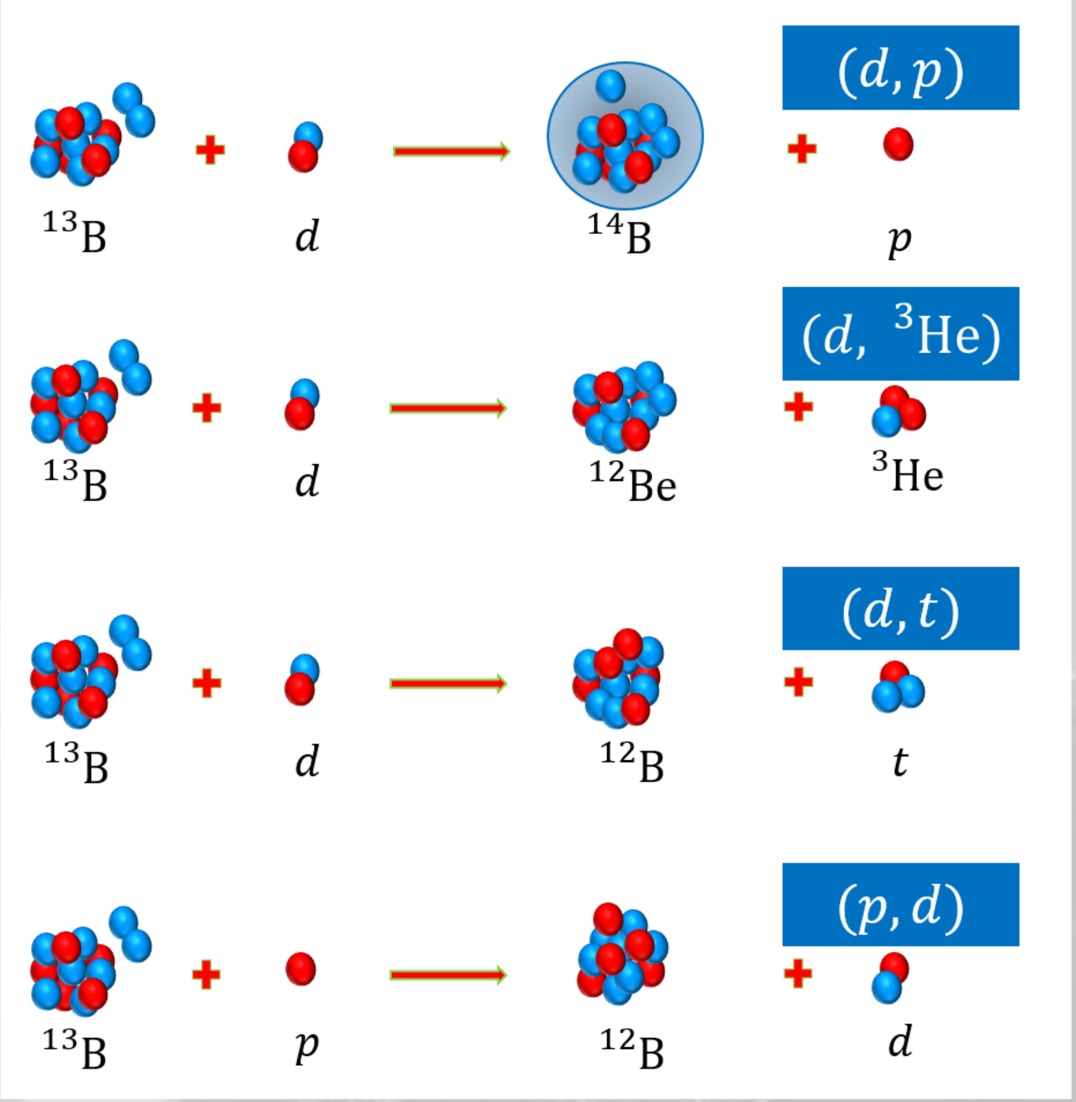
Single-nucleon transfer reaction



Missing mass method

Reaction channel

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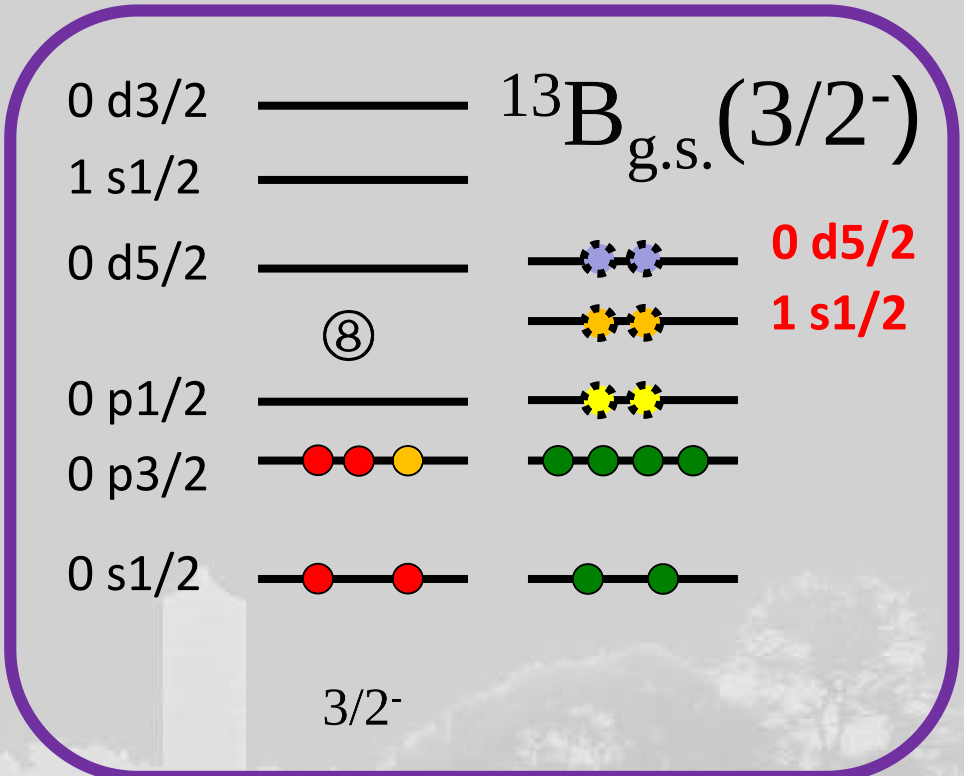
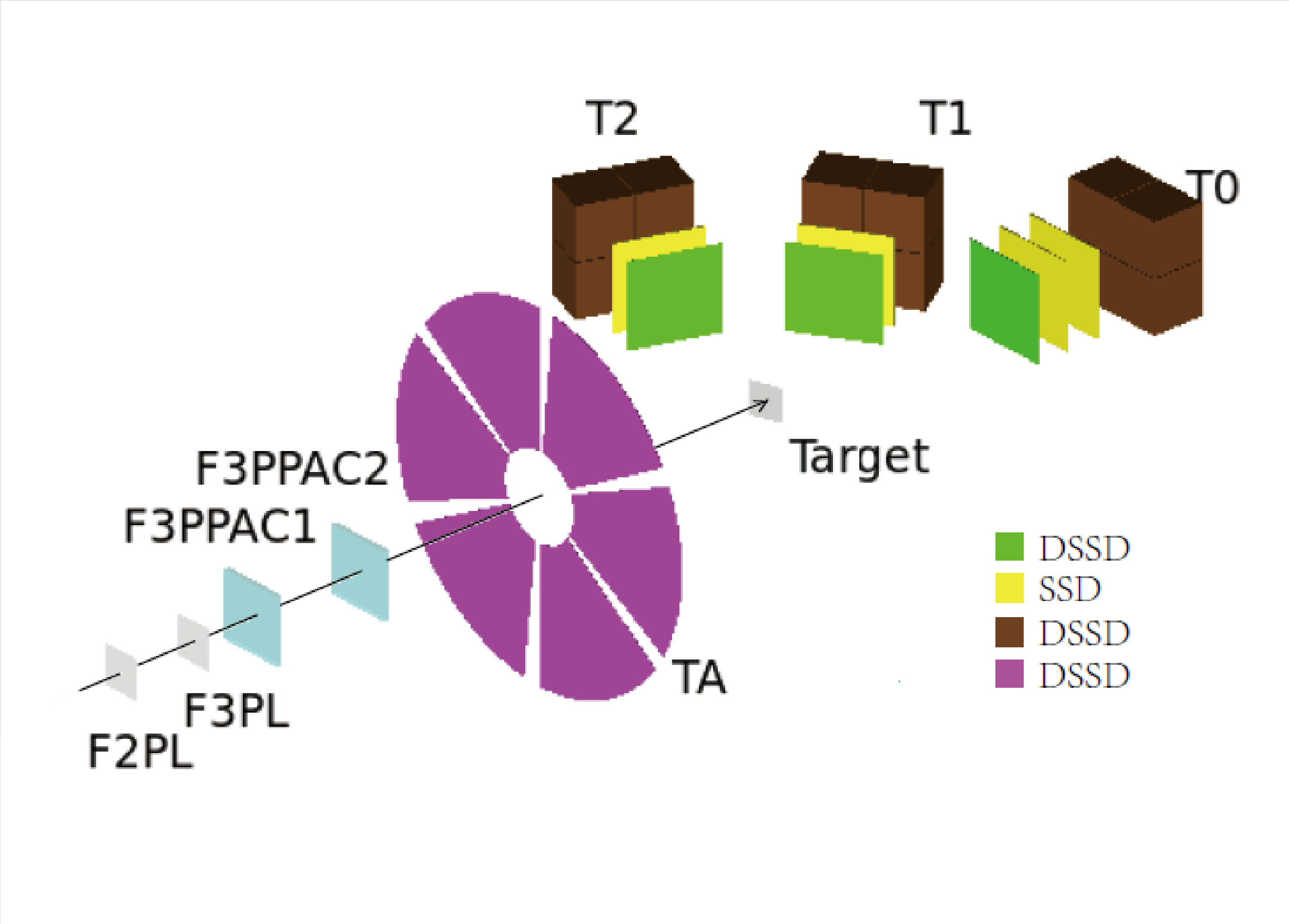


- **$d(^{13}B,\ ^{3}He)^{12}Be$ transfer reaction**
  - $p_{3/2}$ proton:
    - 0_1^+: g.s.
    - 2_1^+: 2.109 MeV
    - 0_2^+: 2.251 MeV
    - 2_2^+ or 0_3^+ ???

- **Elastic scattering**
- **Inelastic scattering**
  - 3.48 MeV $l = 0$
  - 3.68 MeV $l = 2$
  - 4.13 MeV $l = ?$
- **$p(^{13}B, d)^{12}B$ transfer reaction**
  - $p_{1/2}$ neutron:
    - 1_1^+: g.s.
    - 2_1^+: 0.953 MeV
  - $s_{1/2}$ neutron:
    - 2_1^-: 1.674 MeV
    - 1_1^-: 2.621 MeV
  - $d_{5/2}$ neutron:
    - 3_1^-: 3.389 MeV
    - 1_2^-: 4.302 MeV
    - 2_2^-: 4.460 MeV
    - 4_1^-: 4.523 MeV
  - $p_{3/2}$ neutron:
    - 0_1^+: 2.723 MeV
    - 2_2^+: 3.760 MeV
    - 1_2^+: 4.990 MeV
    - 3_1^+: 5.610 MeV

Experimental Setup
@RCNP, Osaka University



^{13}B secondary beam:
purity ~ 98%, intensity ~ 20k pps

target: CH2
2mg CD2
4mg CD2

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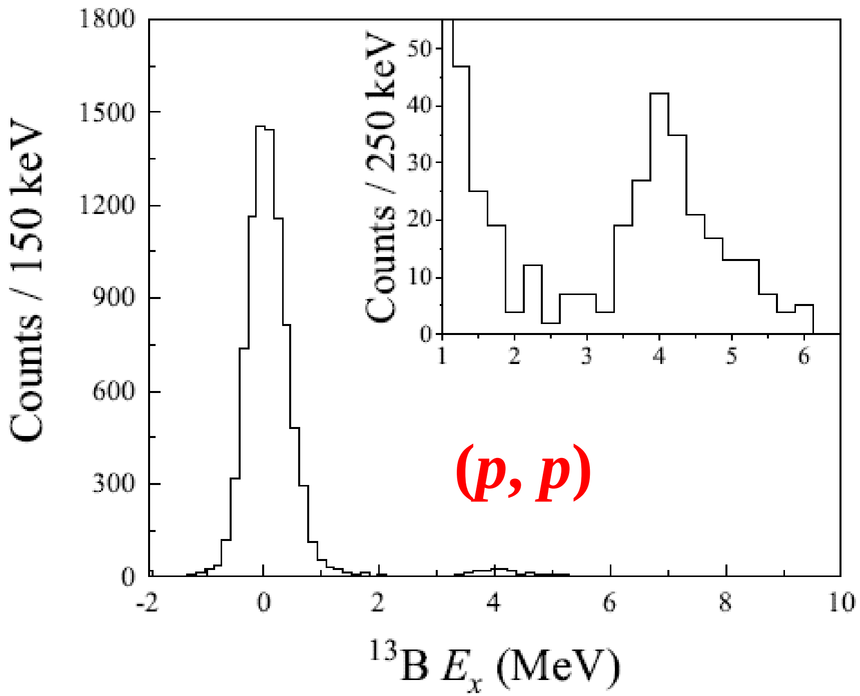
Elastic scattering



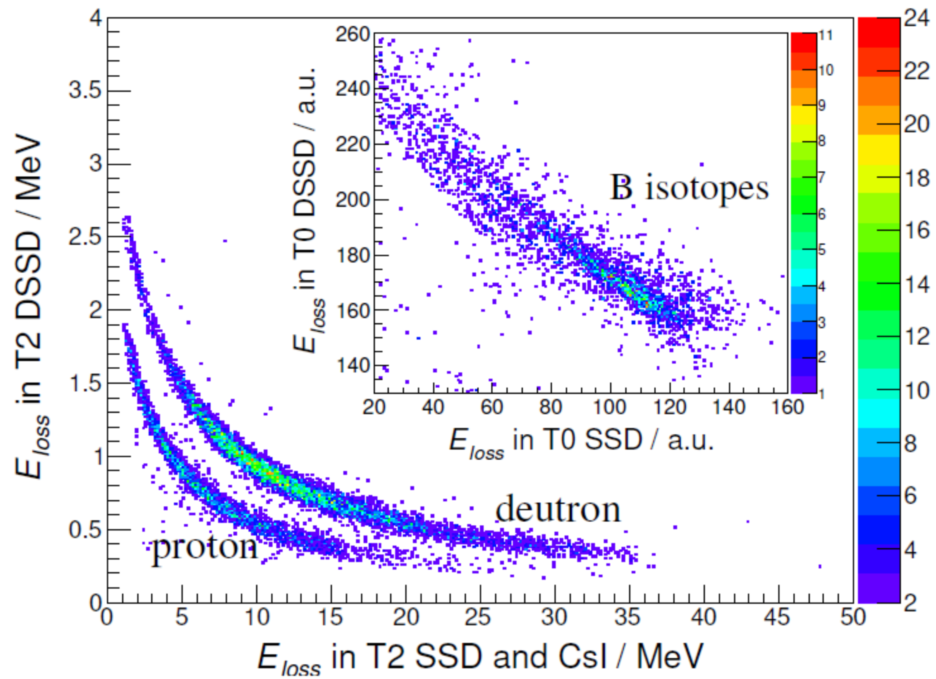
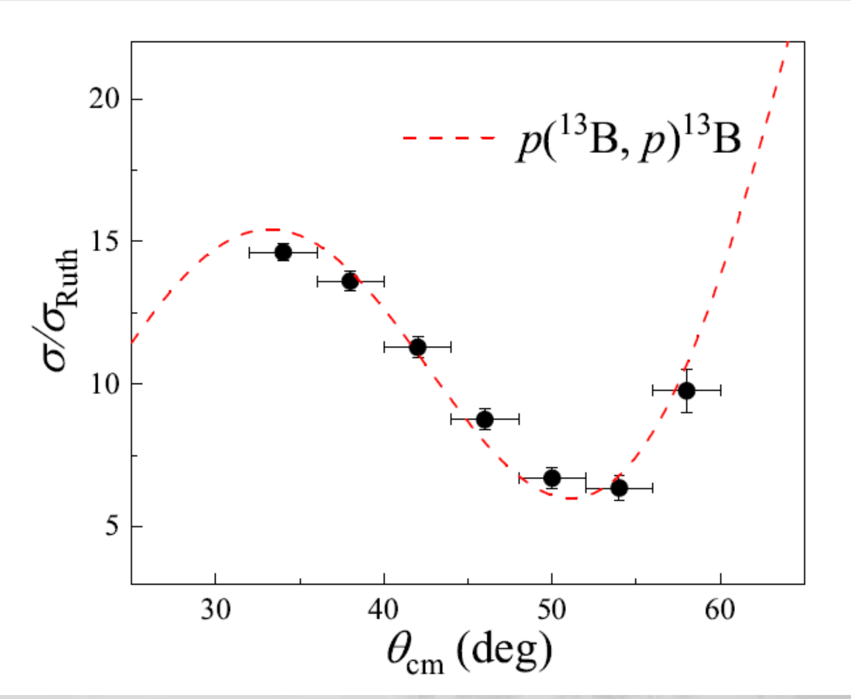


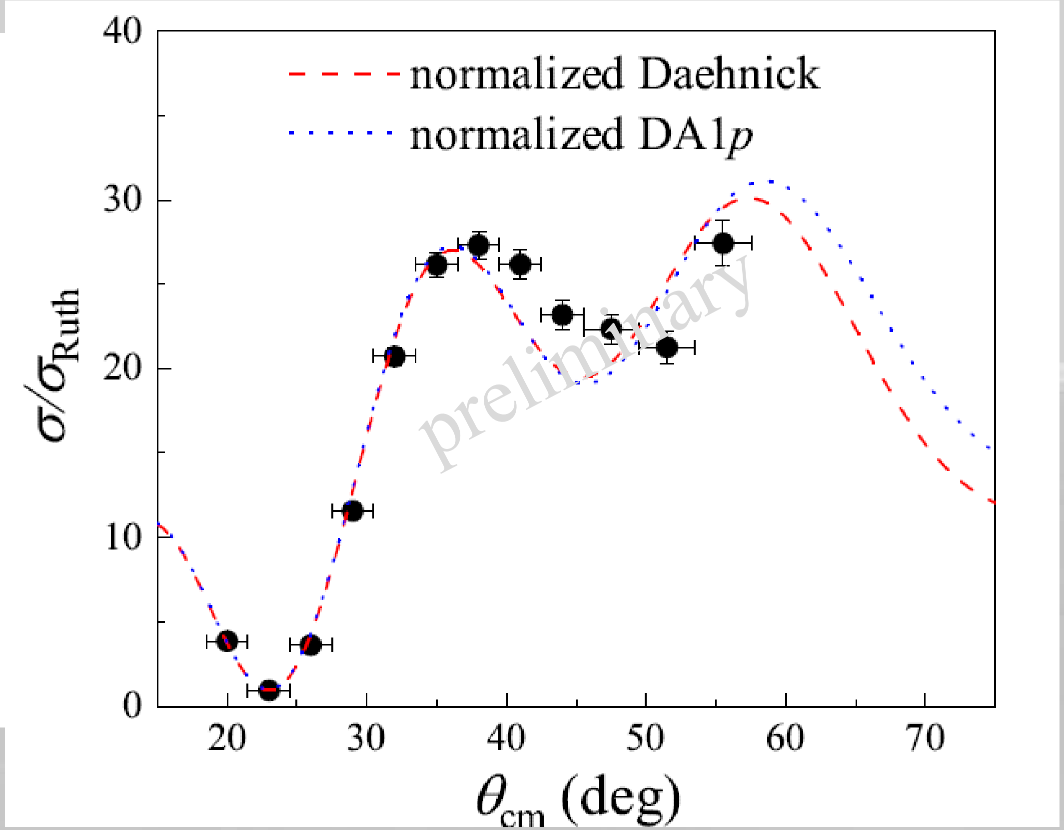
FIG. 3. Excitation energy spectrum of ^{13}B reconstruct
from the energy and momentum of scattered protons me
sured by T2. The inset figure shows the energy spectrum f
inelastic scattering.

Elastic scattering

$$U(r,E) = V_V(r,E) + i\,W_V(r,E) + i\,W_D(r,E) + V_{SO}(r,E).\mathbf{l}.\sigma + i\,W_{SO}(r,E).\mathbf{l}.\sigma + V_c(r,E),$$



WSS global optical potential



DA1*p*: Y. Zhang, D. Y. Pang, and J. L. Lou, Phys. Rev. C 94, 014619 (2016)

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$p(^{13}\mathrm{B}, d)^{12}\mathrm{B}$ transfer reaction

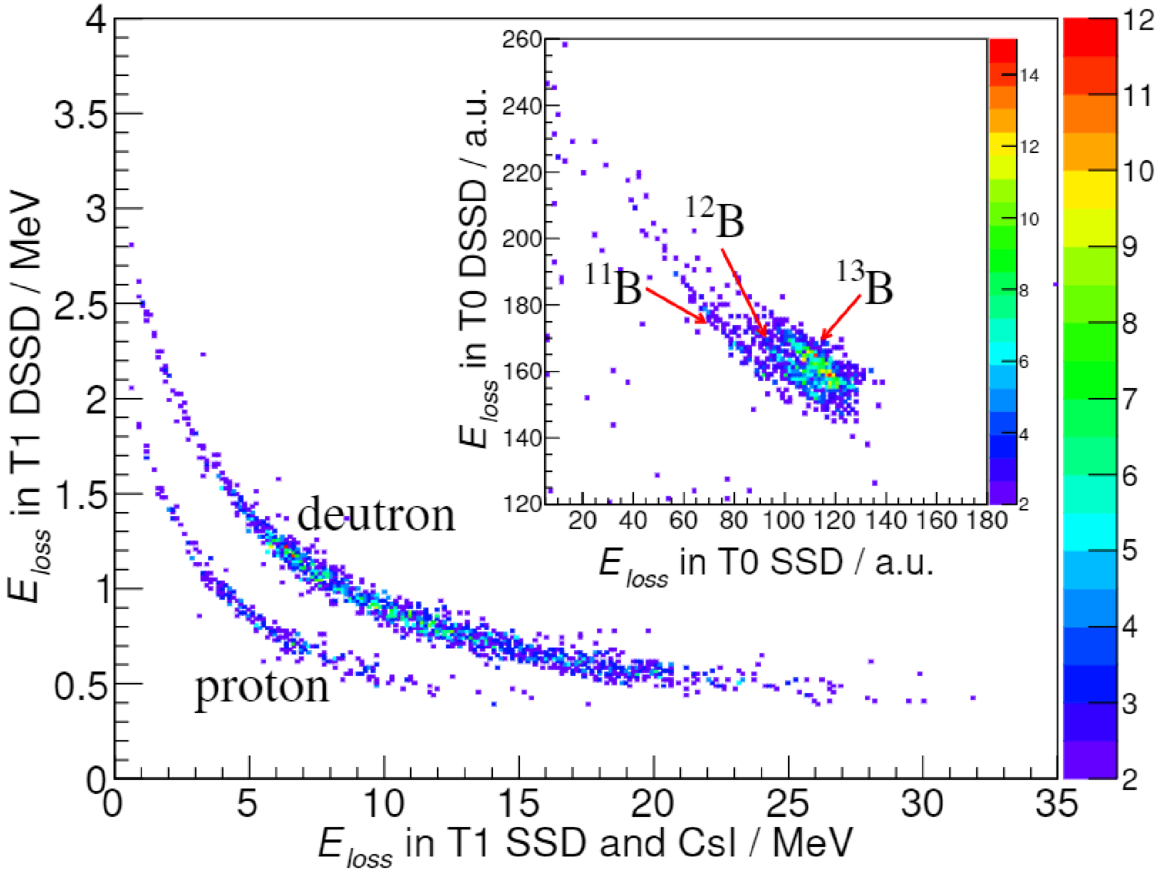

FIG. 4. Particle Identification spectrum of hydrogen isotopes detected by T1. The inset figure shows the PID measured by T0 in coincidence with T1.

Particle identification

$p(^{13}B, d)^{12}B$ transfer reaction

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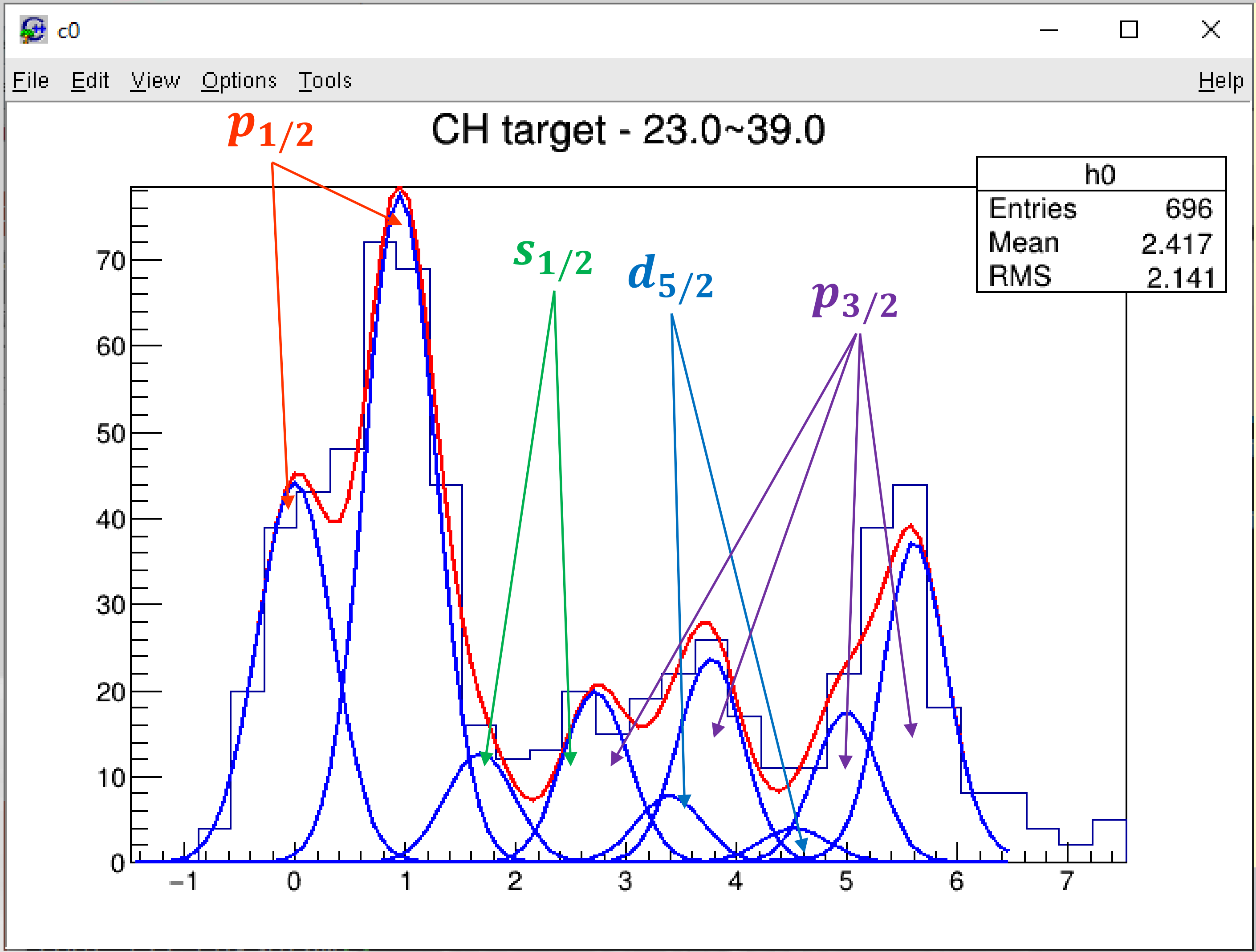

- $p_{1/2}$ neutron:
  - 1_1^+: g.s.
  - 2_1^+: 0.953 MeV
- $s_{1/2}$ neutron:
  - 2_1^-: 1.674 MeV
  - 1_1^-: 2.621 MeV
- $d_{5/2}$ neutron:
  - 3_1^-: 3.389 MeV
  - 1_2^-: 4.302 MeV
  - 2_2^-: 4.460 MeV
  - 4_1^-: 4.523 MeV
- $p_{3/2}$ neutron:
  - 0_1^+: 2.723 MeV
  - 2_2^+: 3.760 MeV
  - 1_2^+: 4.990 MeV
  - 3_1^+: 5.610 MeV

$p(^{13}B, d)^{12}B$ transfer reaction

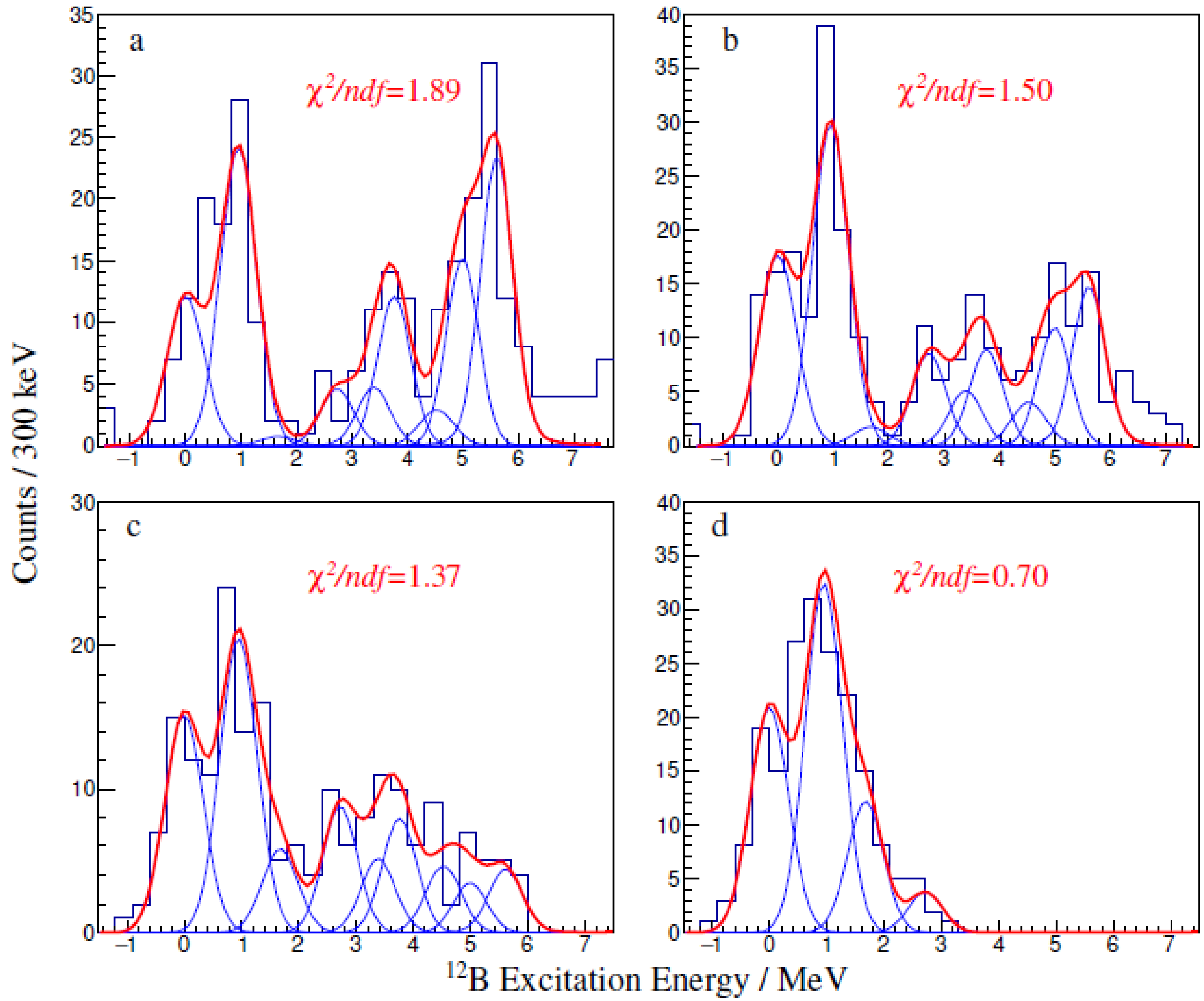

FIG. 7. Excitation energy spectra of ^{12}B reconstructed from the energy and momentum of deuterons at (a) 23° – 27°, (b) 27° – 31°, (c) 31° – 35°, (d) 35° – 39°. The blue solid lines show the fitted spectrum for each state, and the red solid curves show the total fits, i.e. sums of blue solid curves. Note that the amplitudes for states above 3 MeV are zero in (d). The number of degrees of freedom (ndf) corresponds to the number of points used in the fit minus the number of free parameters.

- $p_{1/2}$ neutron:
  - 1_1^+: g.s.
  - 2_1^+: 0.953 MeV
- $s_{1/2}$ neutron:
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$p(^{13}\mathrm{B}, d)^{12}\mathrm{B}$ transfer reaction

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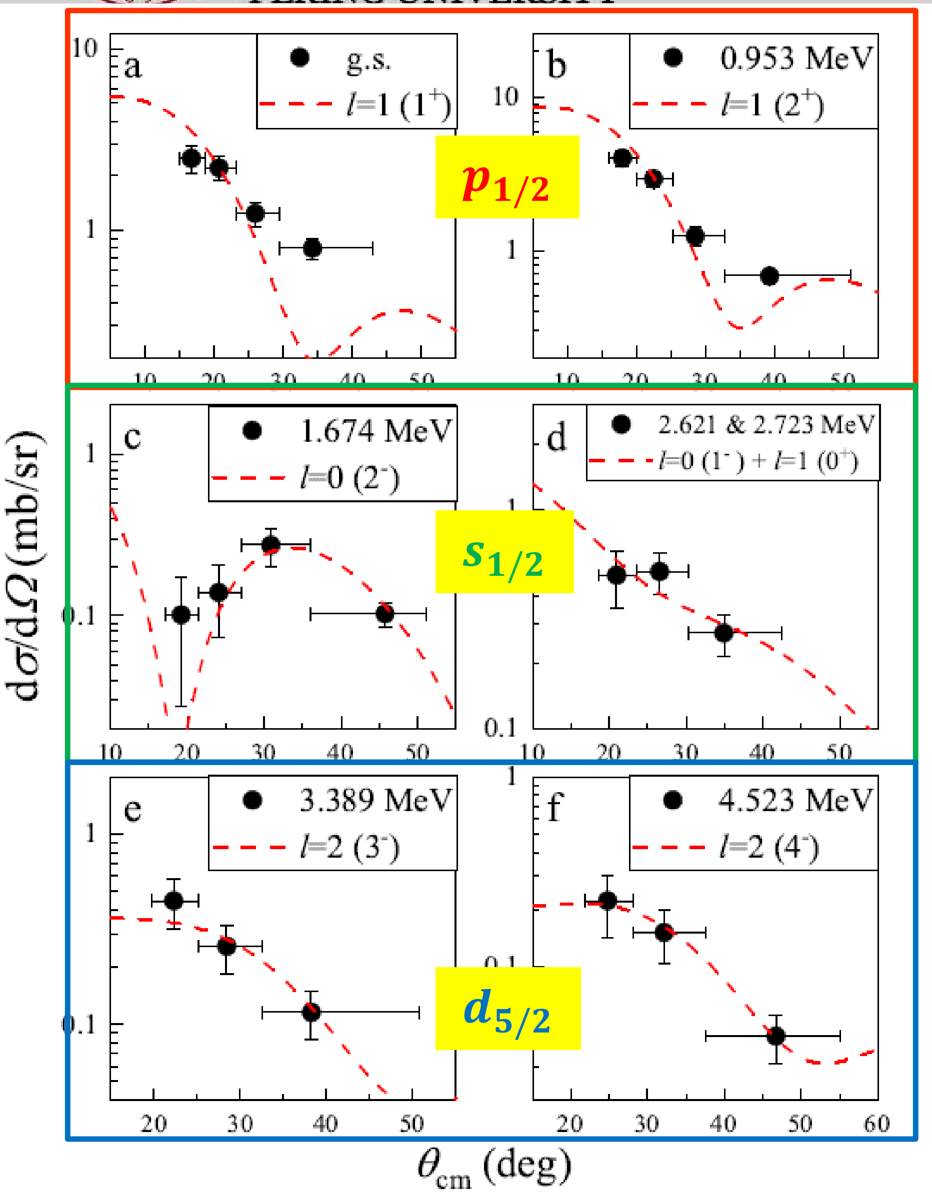

$$SF = \frac{\sigma_{\exp}}{\sigma_{\text{theo}}}$$

↑

DWBA calculation

FIG. 7. Differential cross sections of $p(^{13}\mathrm{B}, d)$ to the excited states at (a) 0.00, (b) 0.953, (c) 1.674, (d) 2.261 and 2.723, (e) 3.389, (f) 4.523 MeV. The excitation energy, the spin-parity, and the transferred orbital angular momentum l, are given in the figure. The red dashed curves are the calculated differential cross sections for each state, multiplied by the corresponding SFs. The 2.621 MeV state could not be separated from the 2.723 MeV state in this experiment, so it was fitted as one peak in Fig. 6 and decomposed by two components in (d). The right-side error bars for the center-mass (cm) angle of the last point in (c) and (f) were cutoff, due to the cone effect in nuclear reaction.

$p(^{13}\mathrm{B}, d)^{12}\mathrm{B}$ transfer reaction

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TABLE III. Excitation energies and SFs for the low-lying states in ^{12}B. The relative SFs are extracted from the present $p(^{13}\mathrm{B},d)$ reaction to the lowing-lying states in ^{12}B and the corresponding uncertainties are from the fit to the differential cross sections for each state based on the χ^2 minimization method. Comparing with the experimental results, the shell model calculation results with the WBP [41] interaction and the latest YSOX interaction [27] are also listed.

spin-parity	orbital	Exp.		YSOX		WBP	
		E_x (MeV)	$\mathrm{SF}_{\mathrm{rel}}$	E_x (MeV)	SF	E_x (MeV)	SF
1_1^+	$1p_{1/2}$	0.000	0.55(4)	0.000	0.49	0.000	0.53
2_1^+	$1p_{1/2}$	0.953	1.13(7)	1.395	0.96	1.631	1.04
2_1^-	$2s_{1/2}$	1.674	0.04(1)	1.490	0.04	2.885	0.003
1_1^-	$2s_{1/2}$	2.621	0.04(1)	2.222	0.02	3.702	0.003
3_1^-	$1d_{5/2}$	3.389	0.13(2)	2.842	0.10	4.193	0.03
1_2^-	$1d_{5/2}$	4.302		3.902	0.002	4.102	0.001
2_2^-	$1d_{5/2}$	4.460		3.359	0.03	4.362	0.006
4_1^-	$1d_{5/2}$	4.523	0.11(2) [a]	3.889	0.06	4.348	0.02

[a] Sum of the SFs of the 4.302, 4.460, and 4.523 MeV states, see text for more details.

$$|\mathrm{g.s.}\rangle = \nu[a(1p_{1/2})^2 + b(2s_{1/2})^2 + c(1d_{5/2})^2]$$

$$a^2 + b^2 + c^2 = \alpha + \beta + \gamma = 1$$

(normalization relation)

$p_{1/2}$: 84(1)%

$s_{1/2}$: 4(1)%

$d_{1/2}$: 12(1)%

$p(^{13}\text{B}, d)^{12}\text{B}$ transfer reaction

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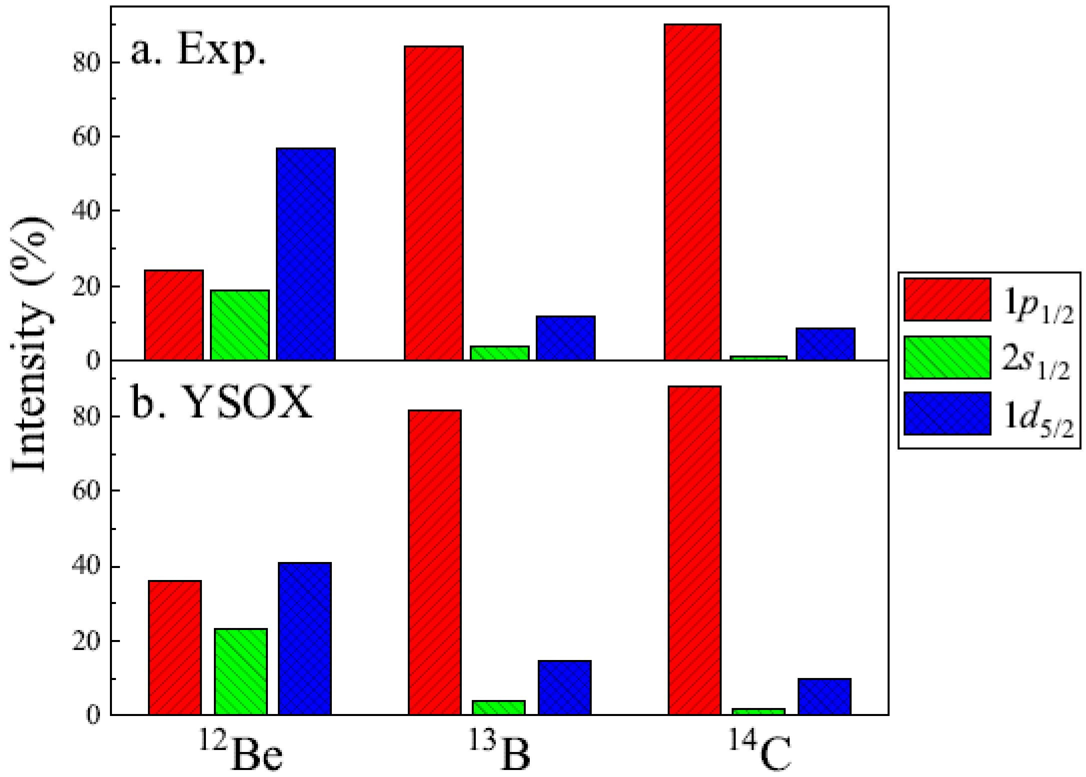

FIG. 10. (a)Individual p-, s-, and d-wave intensities in the ground state of ^{12}Be [5], ^{13}B (this work) and ^{14}C [16]. (b) Shell model calculations with YSOX interaction in full p-sd model space. The results for ^{12}Be are from Ref. [5].

arXiv:2103.01562

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Content

$d(^{13}B,\ ^{3}He)^{12}Be$

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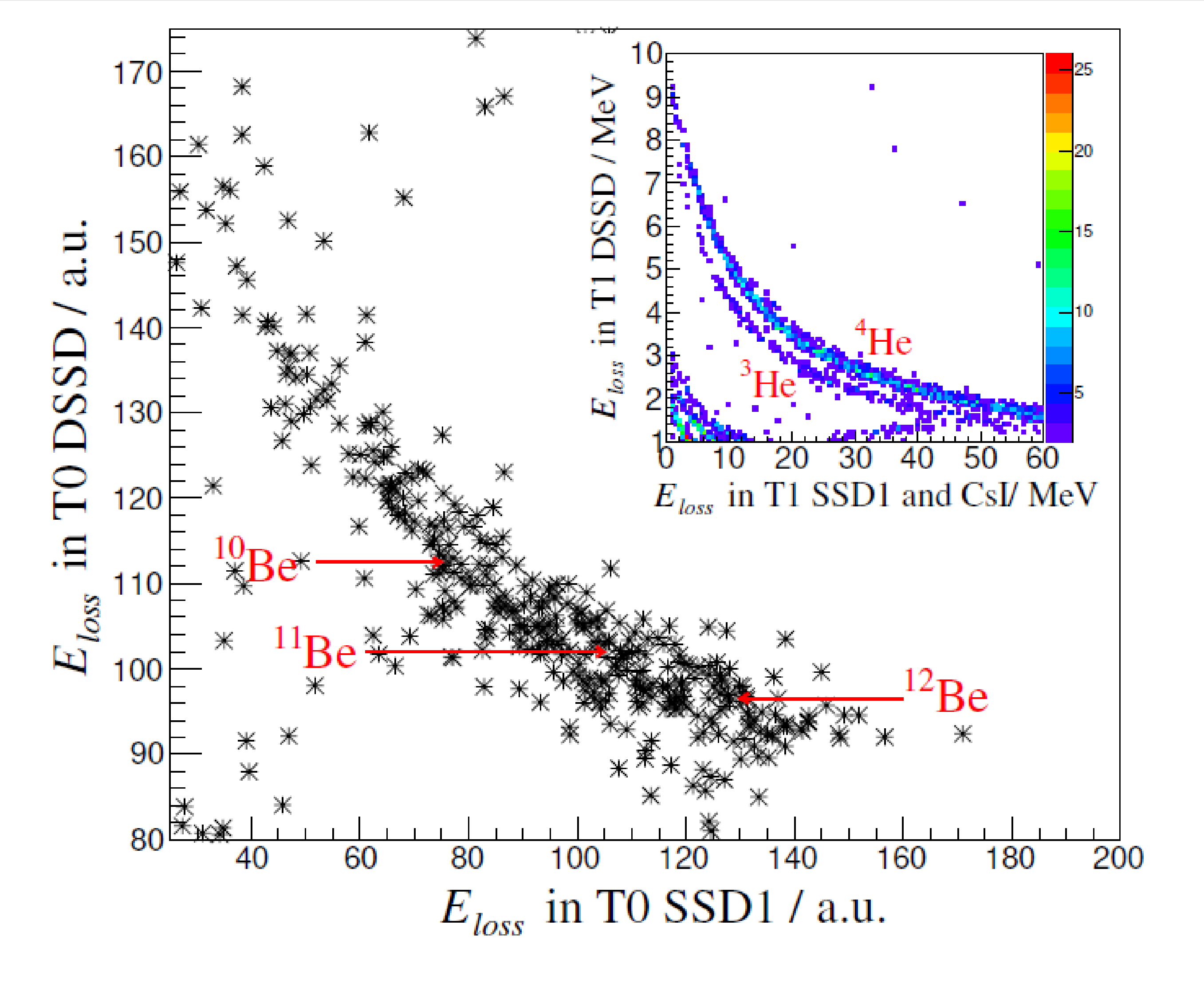

Particle identification

$d(^{13}\mathrm{B},\ ^{3}\mathrm{He})^{12}\mathrm{Be}$

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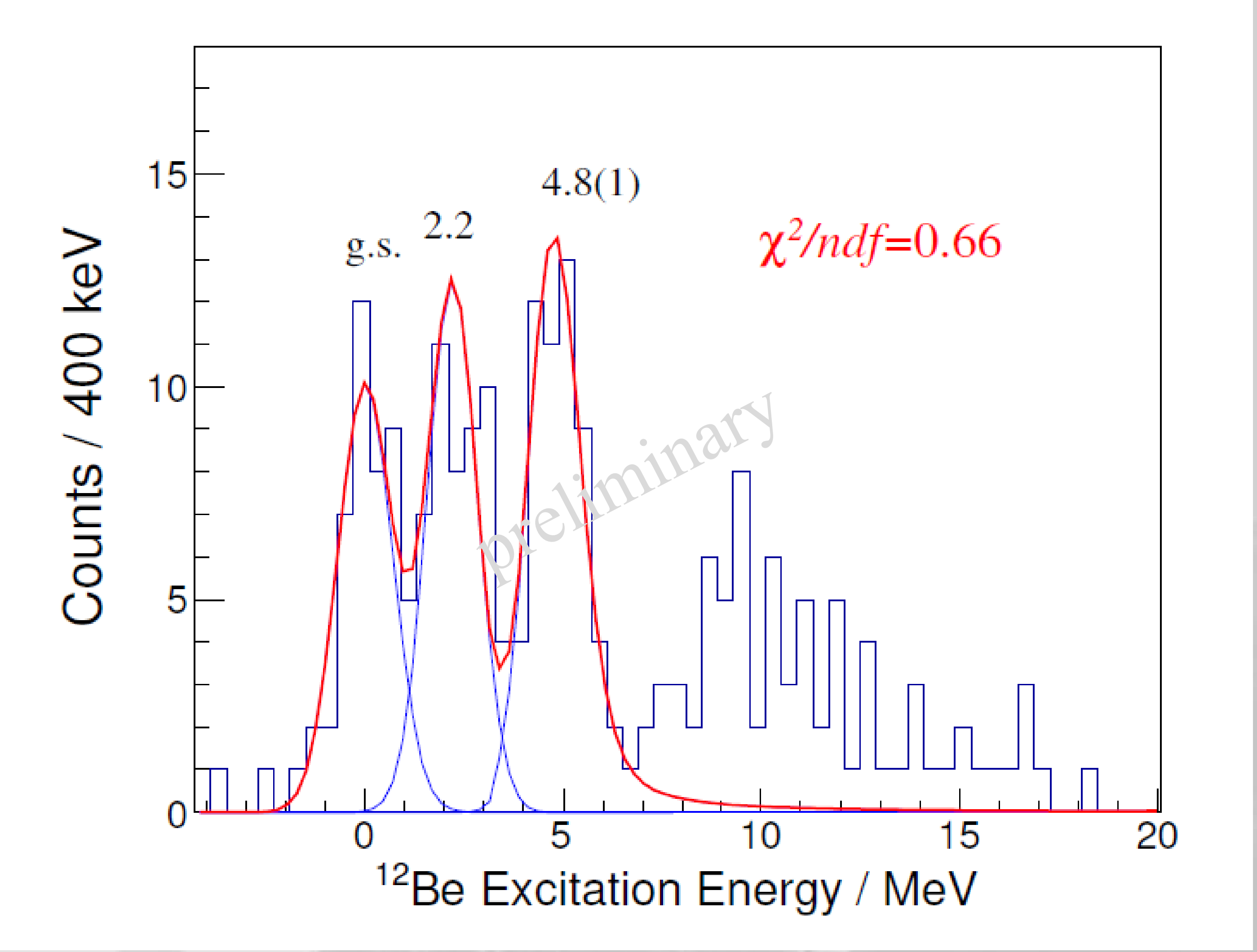

width of resonant: 0.42(28) MeV

$d(^{13}B,\ ^{3}He)^{12}Be$

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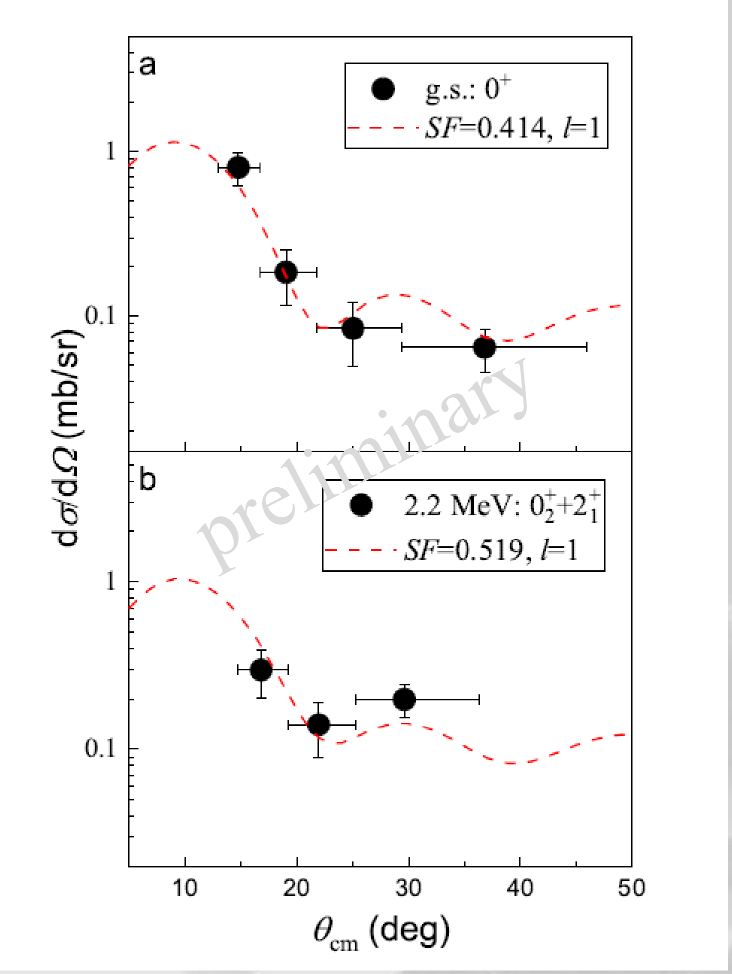
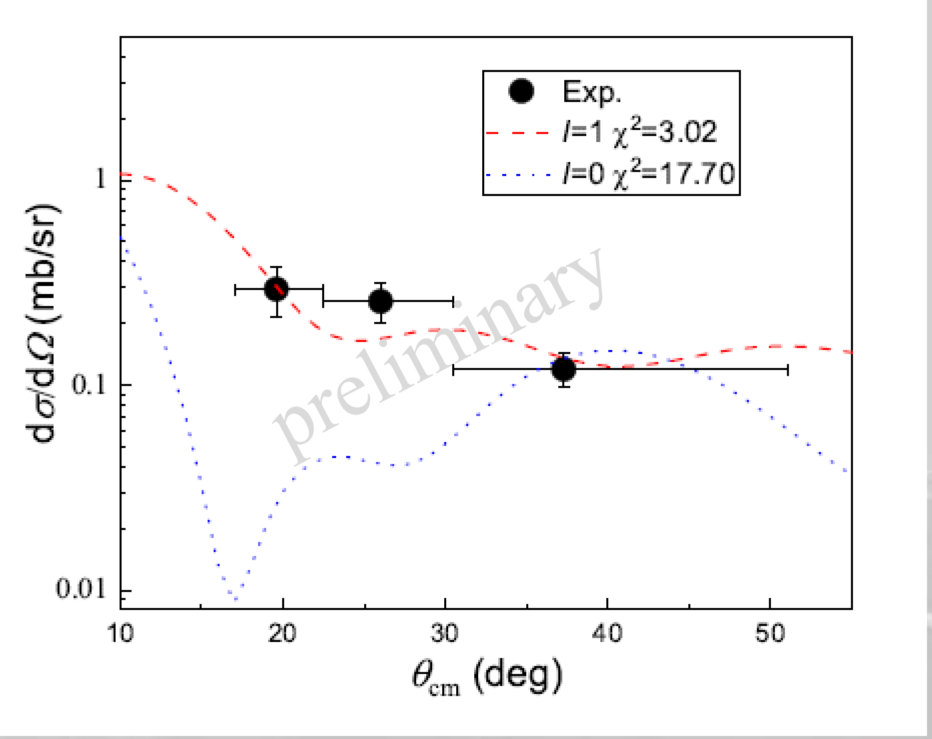
Bound states



Resonant state



$$\Gamma_n/(\Gamma_n + \Gamma_{2n}) = 84^{+16}_{-18}\ \%$$

$E_n = 1.24$ MeV state observed in the $1p$ removal reaction by Smith *et al* 2014

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Summary

- Determined *s*-, and *d*- wave neutron intensities in the ground state of ^{13}B
- Assigned the spin-parity of the 4.8 MeV resonant of ^{12}Be

Acknowledgement

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Collaborators:

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5. Institute of Physics, Vietnam Academy of Science and Technology;
6. School of Physics, Beijing Key Laboratory of Advanced Nuclear Materials and Physics, Beihang University;
7. Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-Sen University;
8. FRIB/NSCL Laboratory, Michigan State University;