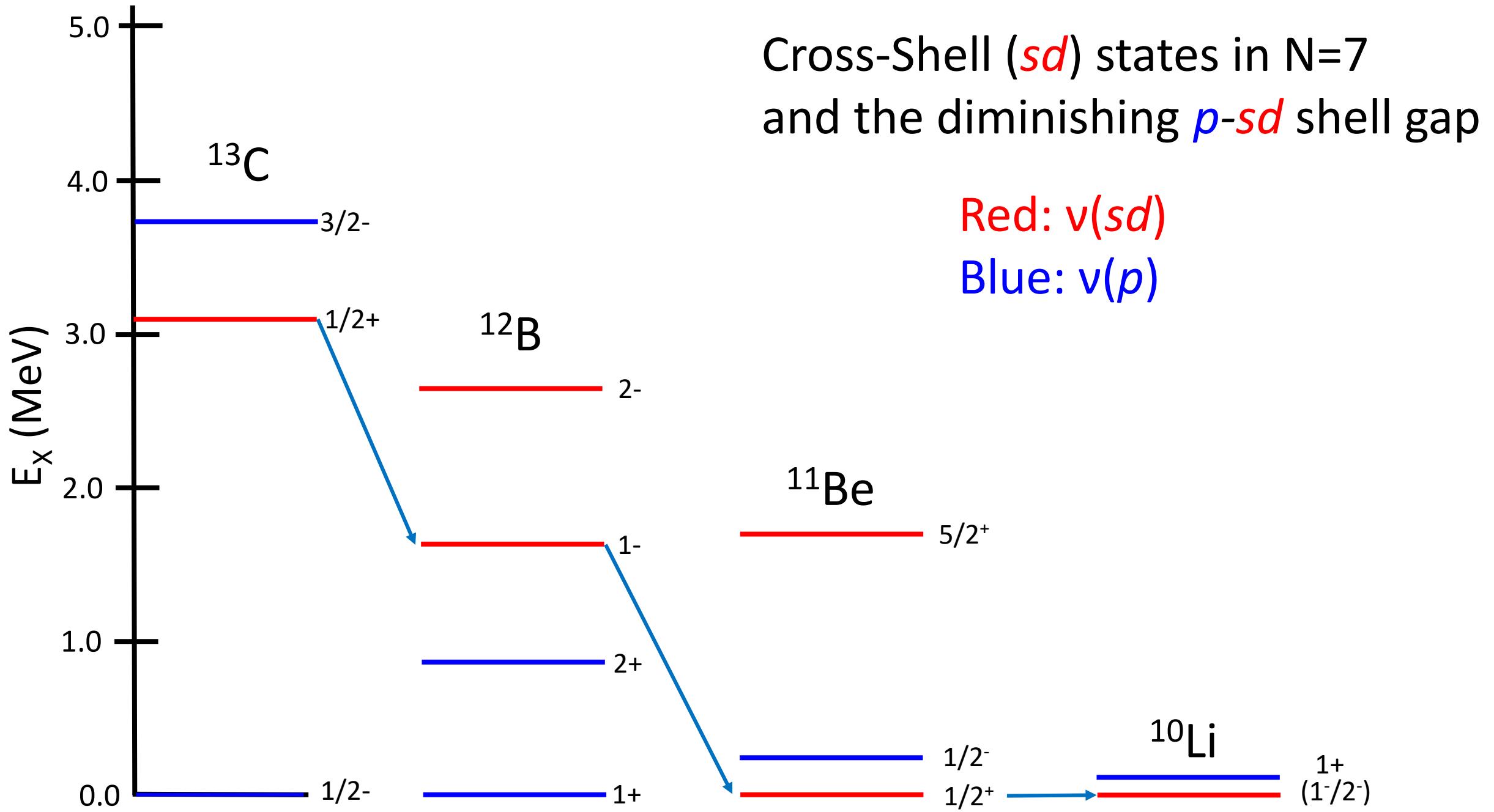
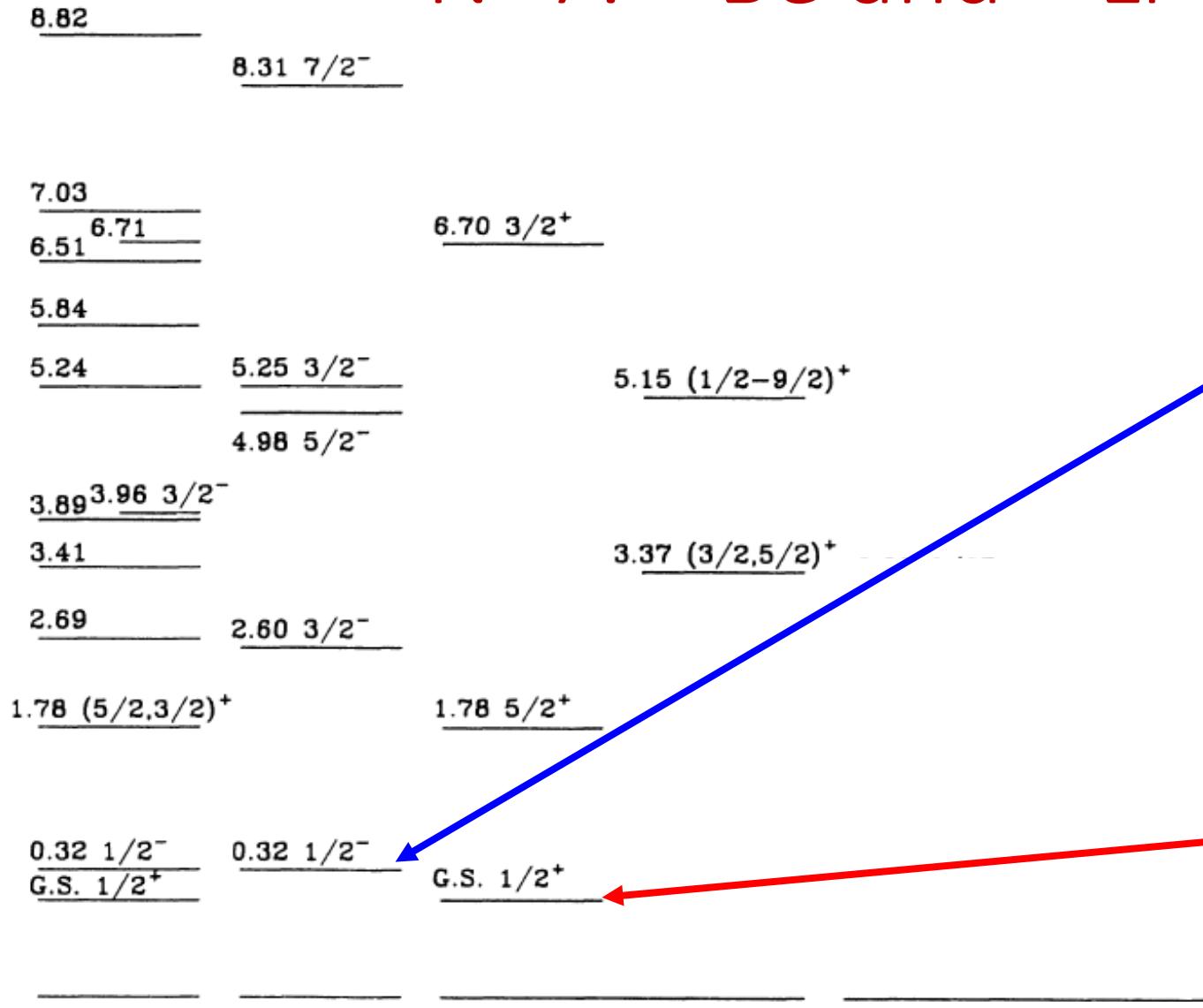


# Light-exotic nuclei studied with the $(t,p)$ reaction in inverse kinematics using HELIOS

- Well-known shifts in neutron-rich  $p$ - $sd$  shell-model orbitals
- Examples:
  - N=7:  $^{11}\text{Be}$   $1/2^+$  ground state
  - N=8:  $^{11}\text{Li}$  2n-halo,  $^{12}\text{Be}$   $\nu(sd)^2$  ground state
  - N=9:  $^{17}\text{O}$ - $^{15}\text{C}$   $0d_{5/2}$ - $1s_{1/2}$  inversion
- Object: Use  $(t,p)$  reactions in inverse kinematics to probe  $(sd)^2$  and other states in N=7  $^{10}\text{Li}$ , N=9  $^{14}\text{B}$ .
- Compare results to shell-model calculations



# N=7: $^{11}\text{Be}$ and $^{10}\text{Li}$



EXP  $^{10}\text{Be}(\text{gs}) \otimes (\text{p})$   $^{10}\text{Be}(\text{gs}) \otimes (\text{sd})$   $^{10}\text{Be}(2^+) \otimes (\text{sd})$   
 $^{9}\text{Be}(\text{t},\text{p})^{11}\text{Be}$ : Liu and Fortune, PRC 42, 167 (1990)

$^{10}\text{Li}$

# N=7: $^{11}\text{Be}$ and $^{10}\text{Li}$

8.82

8.31 7/2<sup>-</sup>

7.03  
6.51 6.71

5.84

5.24

6.70 3/2<sup>+</sup>

5.25 3/2<sup>-</sup>

4.98 5/2<sup>-</sup>

3.89 3.96 3/2<sup>-</sup>

3.41

2.69

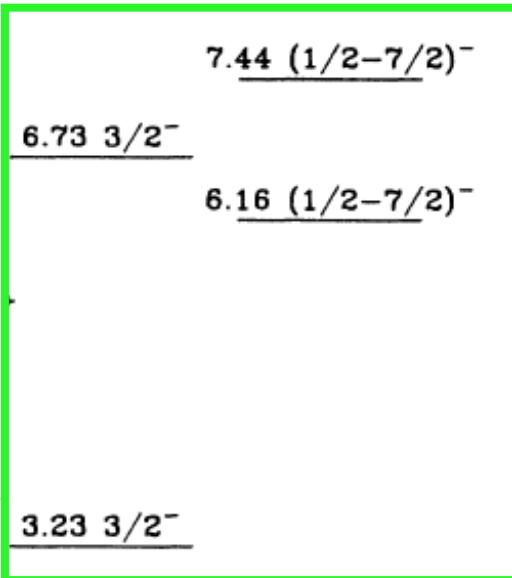
1.78 (5/2,3/2)<sup>+</sup>

1.78 5/2<sup>+</sup>

0.32 1/2<sup>-</sup>  
G.S. 1/2<sup>+</sup>

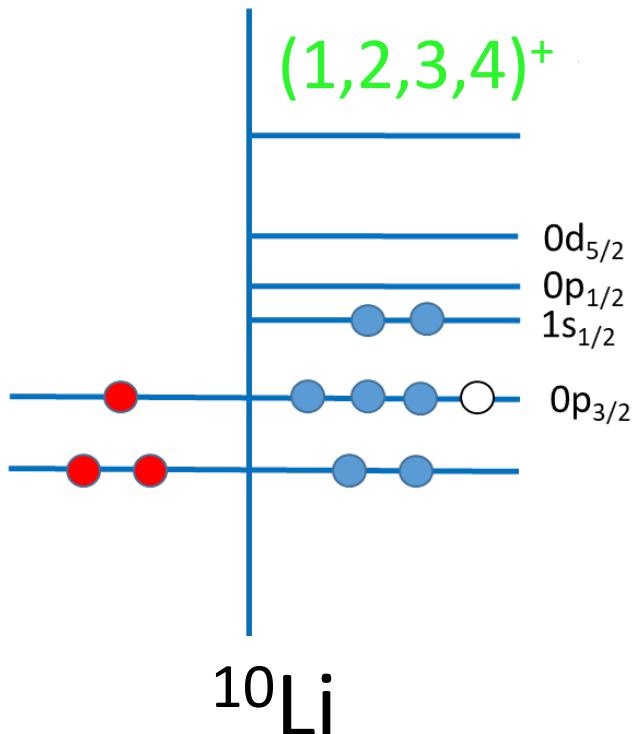
0.32 1/2<sup>-</sup>

G.S. 1/2<sup>+</sup>



$^9\text{Be}(\text{gs}) \otimes (\text{sd})^2_0 \ ^9\text{Be}(\text{gs}) \otimes (\text{sd})^2_2$

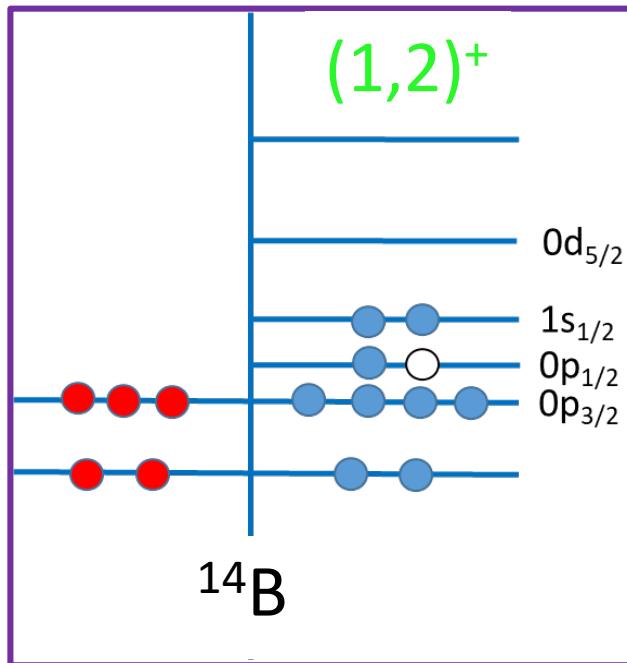
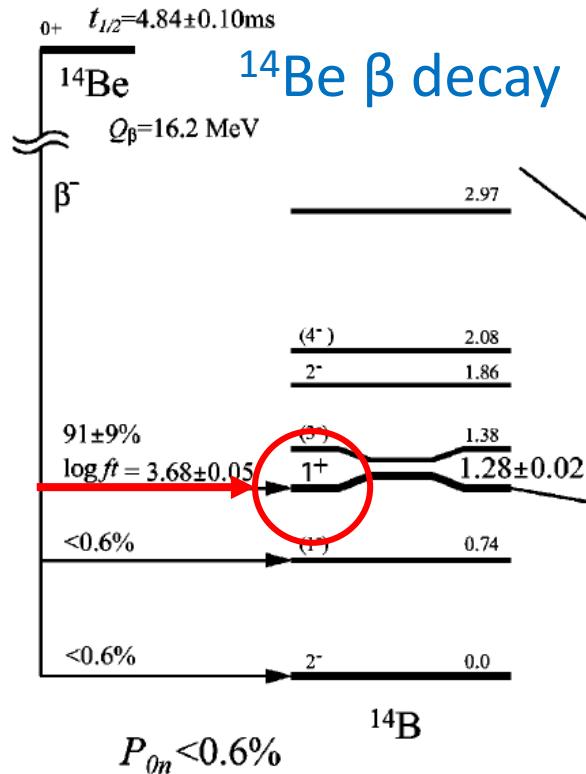
Populate only in  $(t,p)$



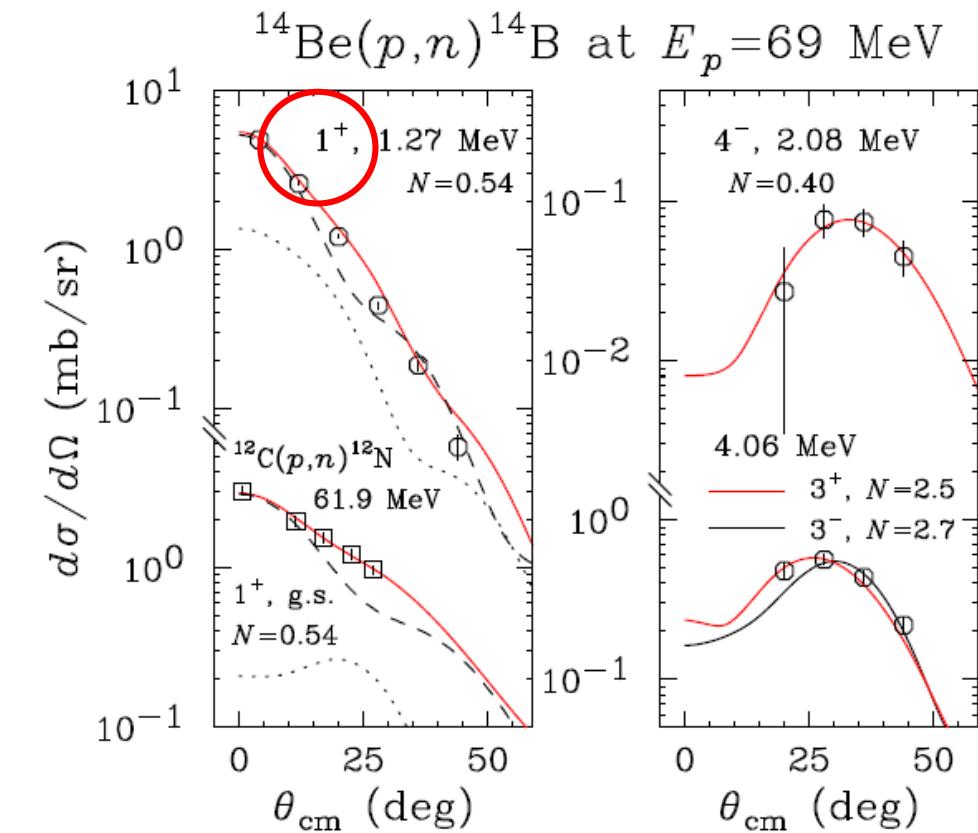
EXP  $^{10}\text{Be}(\text{gs}) \otimes (\text{p})$   $^{10}\text{Be}(\text{gs}) \otimes (\text{sd})$   $^{10}\text{Be}(2^+) \otimes (\text{sd})$

$^9\text{Be}(\text{t},\text{p})^{11}\text{Be}$ : Liu and Fortune, PRC 42, 167 (1990)

# Intruder $v(sd)^2$ states in $^{14}\text{B}$ N=9



N. Aoi et al.,  
PHYSICAL REVIEW C 66, 014301 (2002)

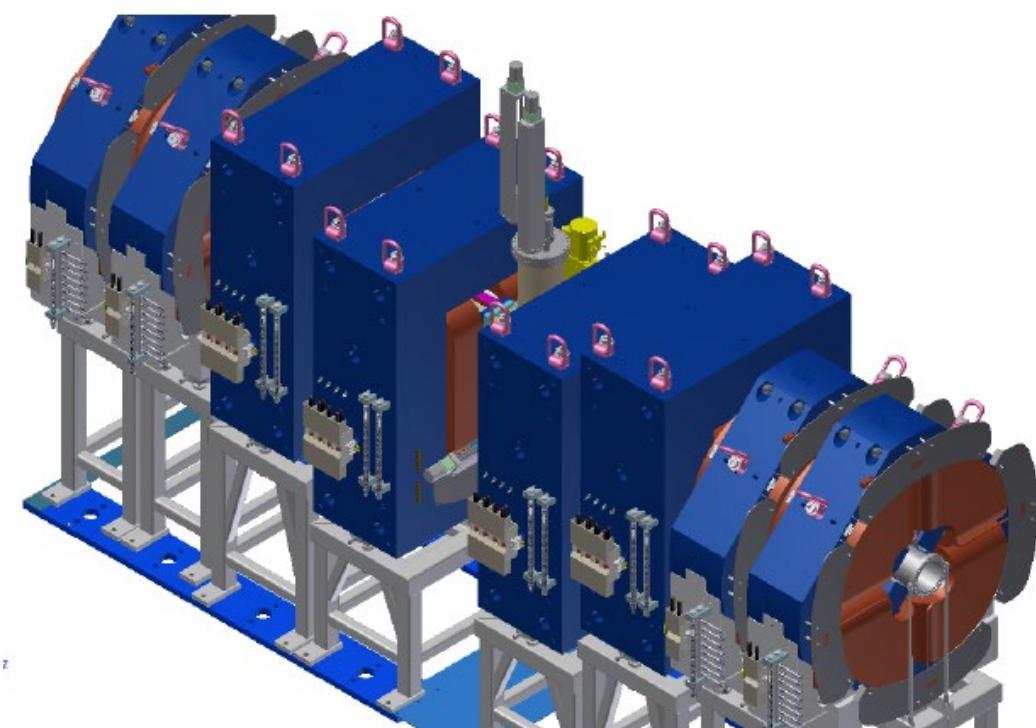
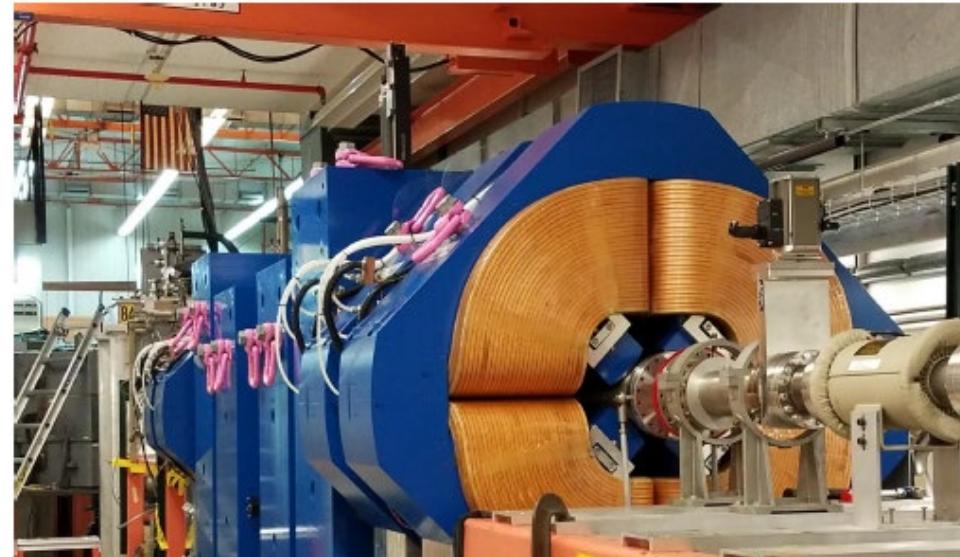


Y. Satou et al. / Physics Letters B 697 (2011) 459–462

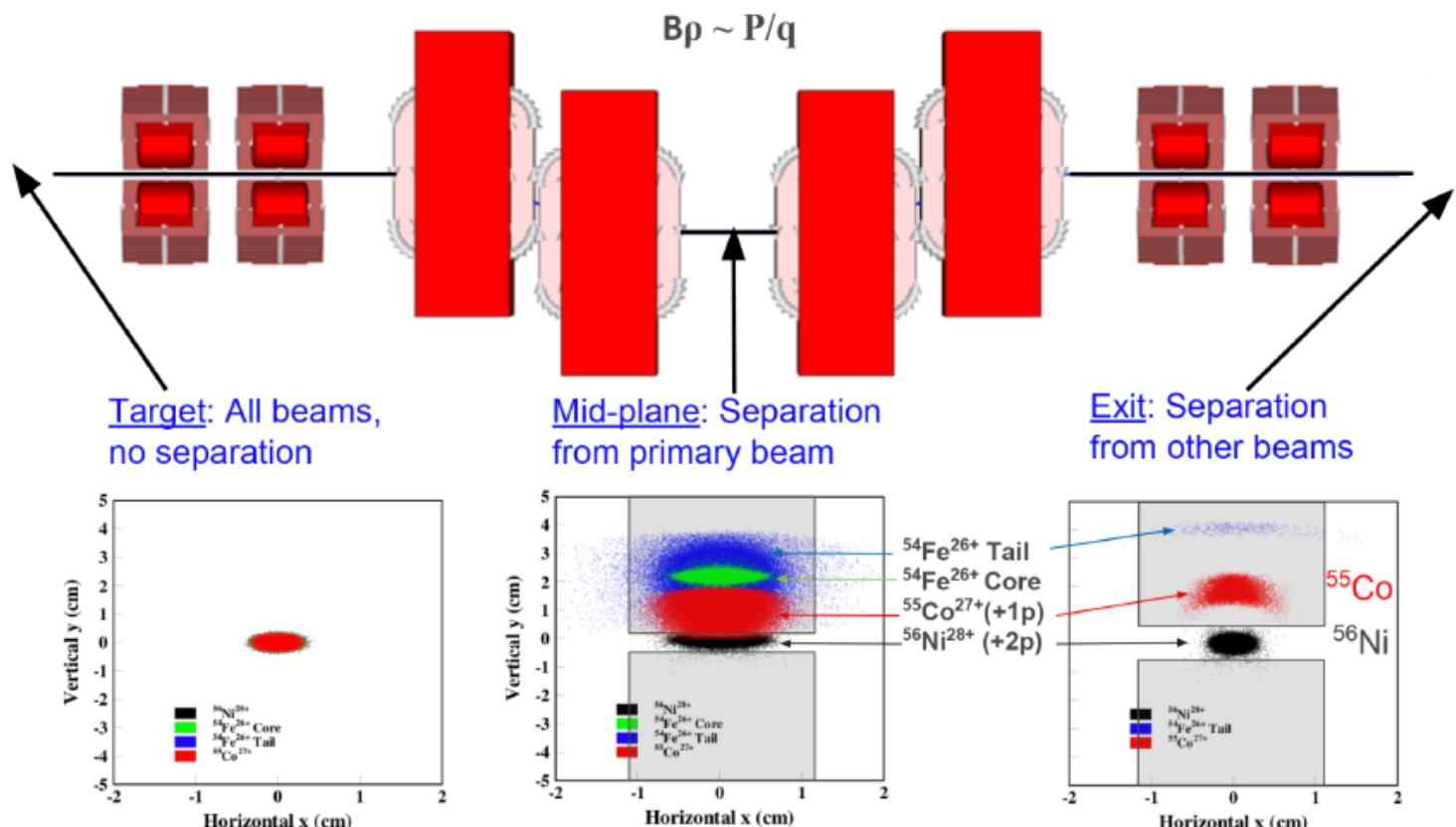
Corresponding states in  $^{15}\text{C}$ :  $E_x > 3 \text{ MeV}$  from  $^{13}\text{C}(t,p)^{15}\text{C}$   
Truong and Fortune, PRC 28, 977 (1983)

# Secondary beams at ATLAS

- ${}^8\text{Li}, {}^{12}\text{B}$  beams from ATLAS/RAISOR
- ${}^8\text{Li}$ :  ${}^7\text{Li}(d,p){}^8\text{Li}$ ,  $E=8.5 \text{ AMeV}$ ,  $10^5 \text{ pps}$
- ${}^{12}\text{B}$ :  ${}^{11}\text{B}(d,p){}^{12}\text{B}$ ,  $E=7.8 \text{ AMeV}$ ,  $3\times 10^5 \text{ pps}$



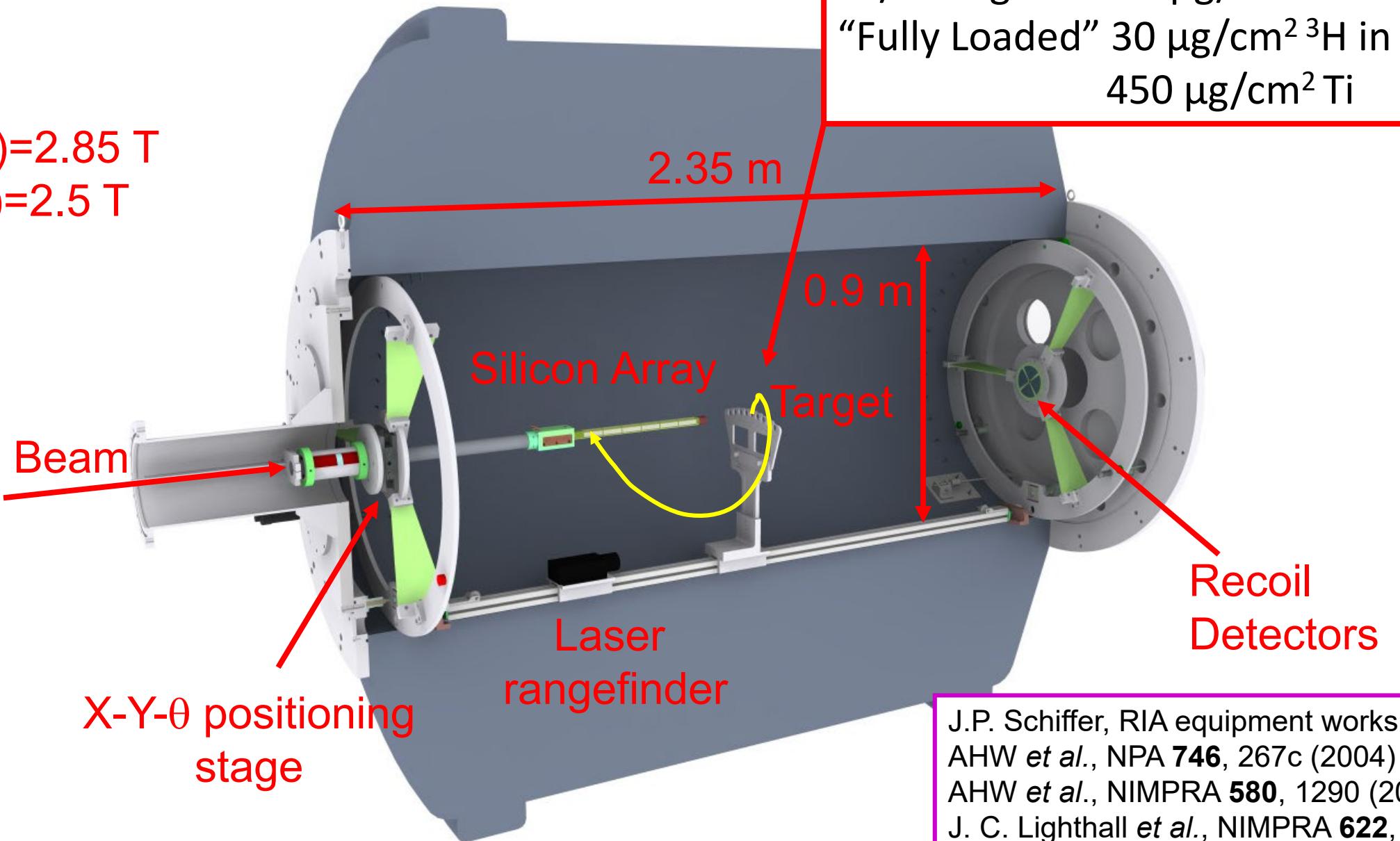
C. R. Hoffman, ANL





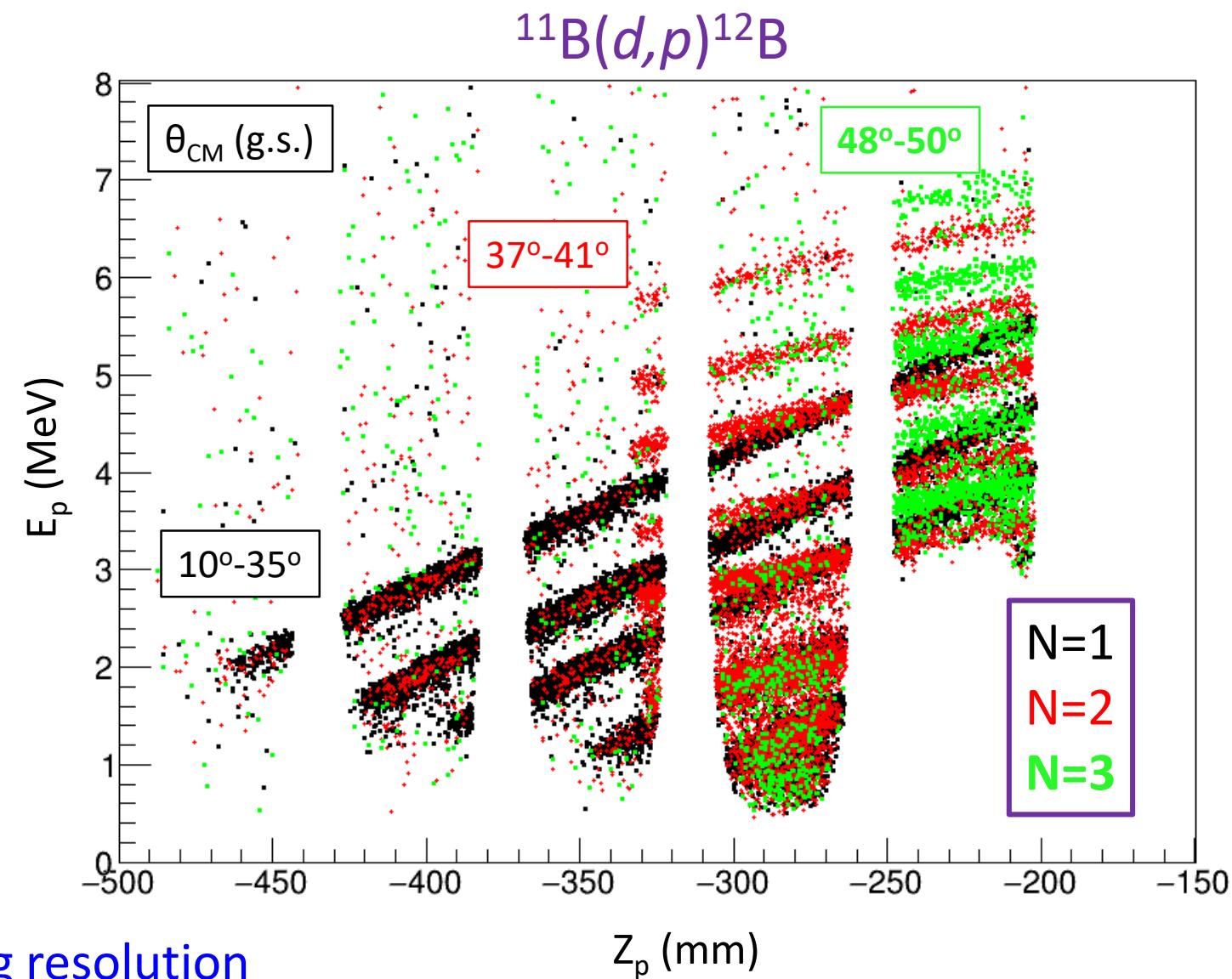
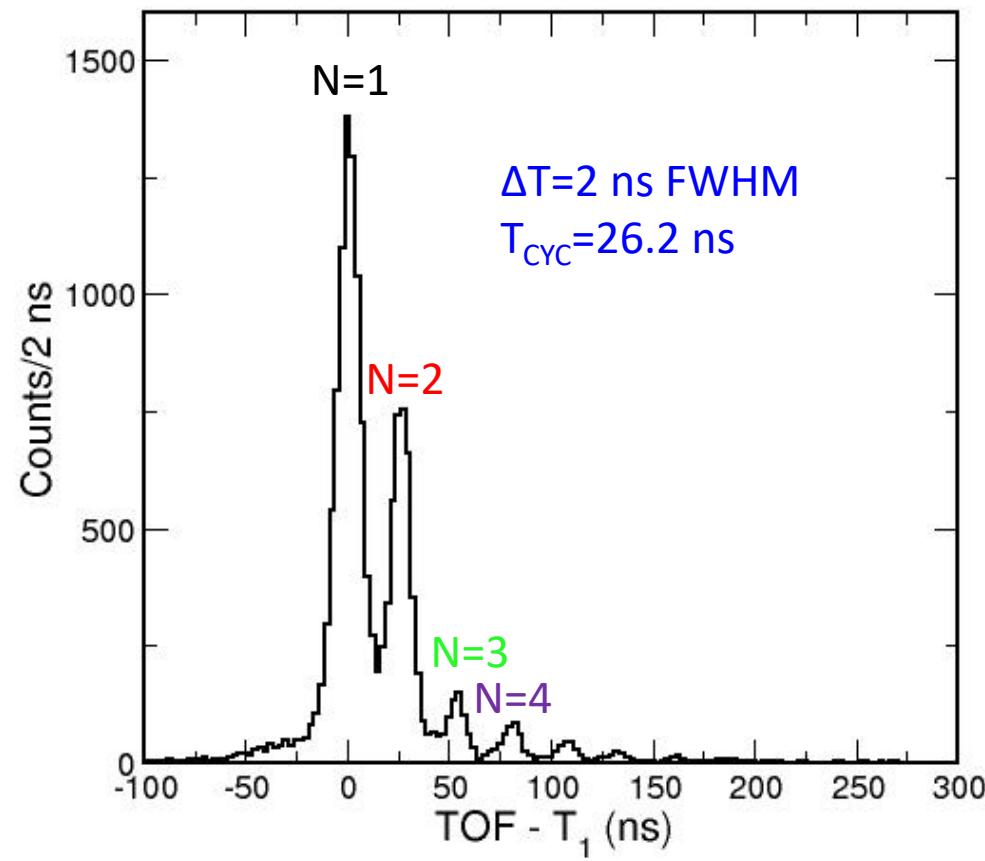
# HELIcal Orbit Spectrometer -HELIOS

$$B(^{10}\text{Li})=2.85 \text{ T}$$
$$B(^{14}\text{B})=2.5 \text{ T}$$



J.P. Schiffer, RIA equipment workshop 1999  
AHW *et al.*, NPA **746**, 267c (2004) ([RNB6](#))  
AHW *et al.*, NIMPRA **580**, 1290 (2007)  
J. C. Lighthall *et al.*, NIMPRA **622**, 97 (2010)

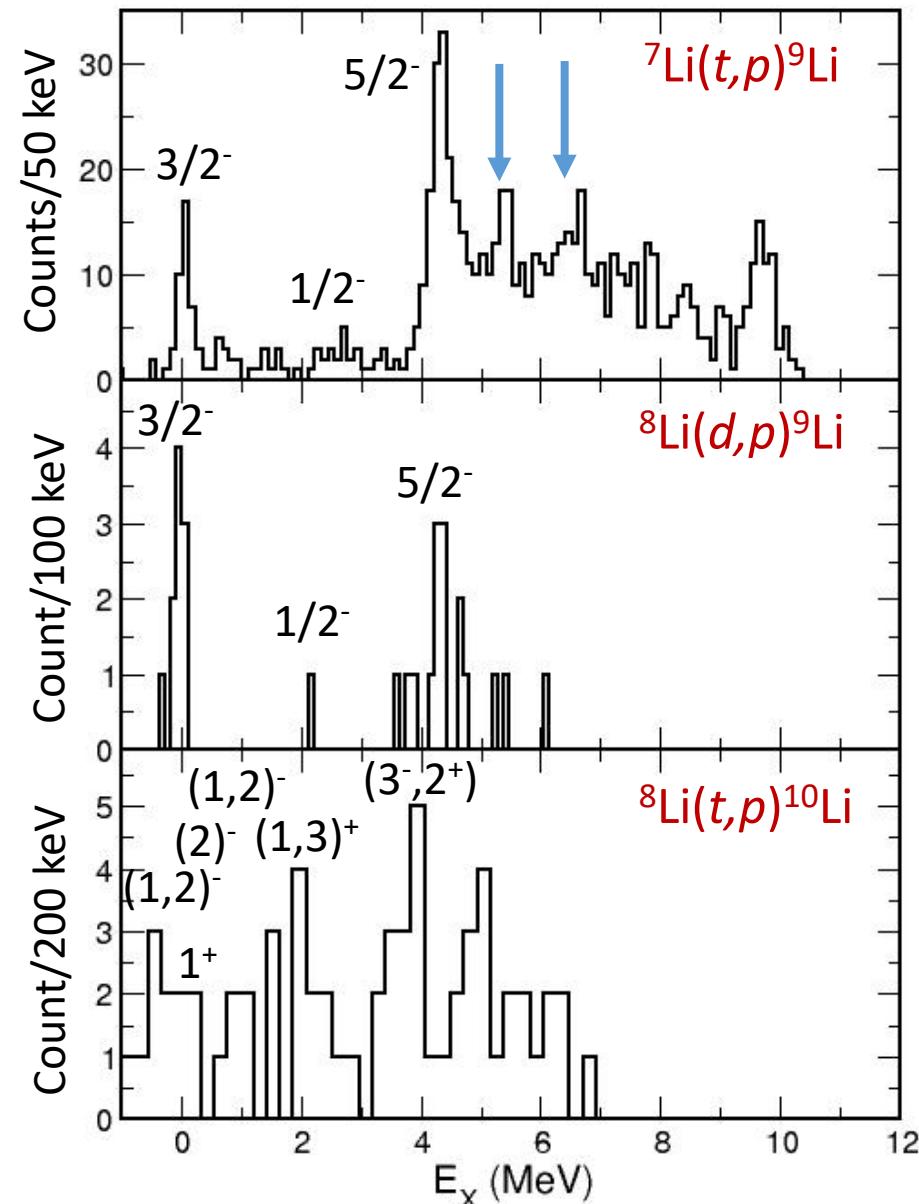
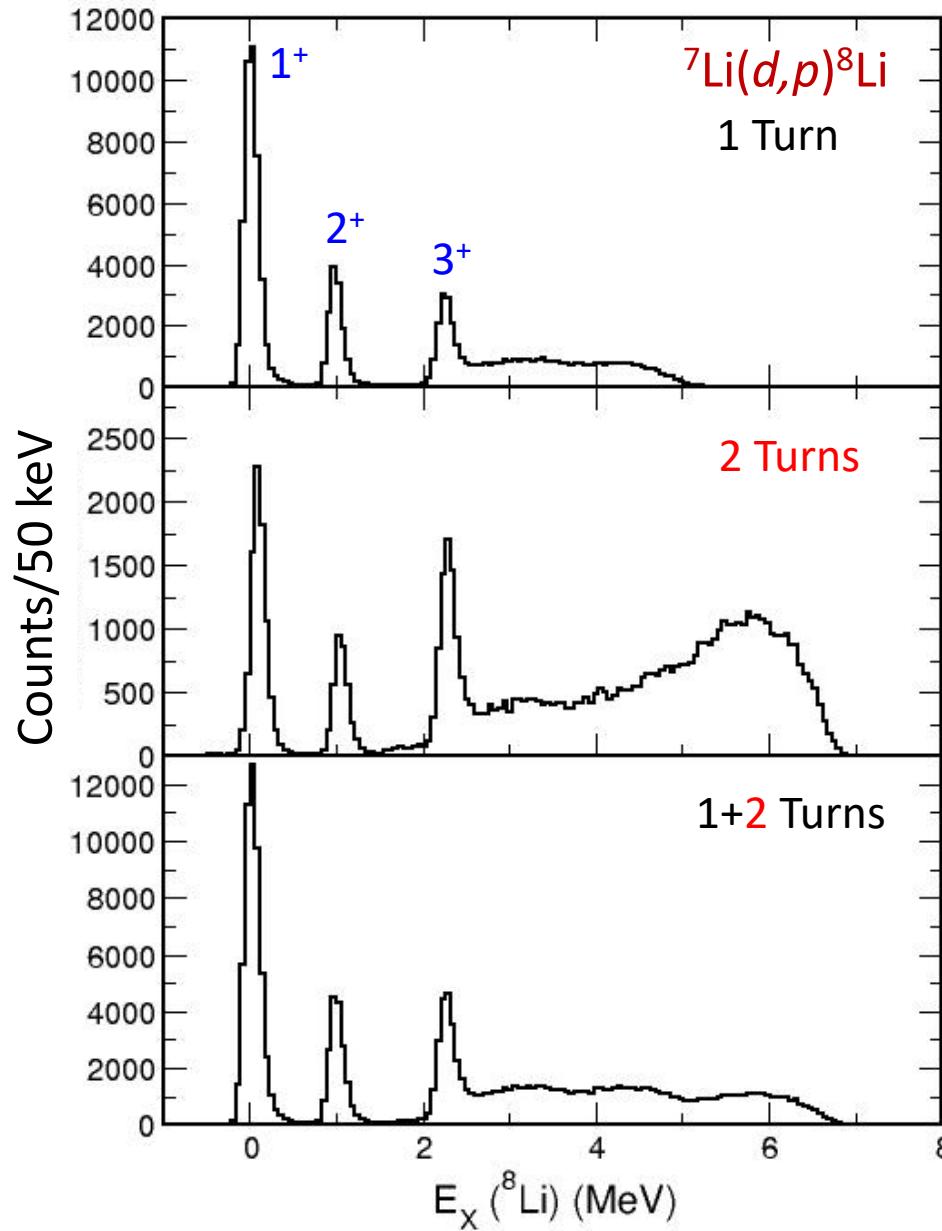
# Timing is important: multiple orbits are possible



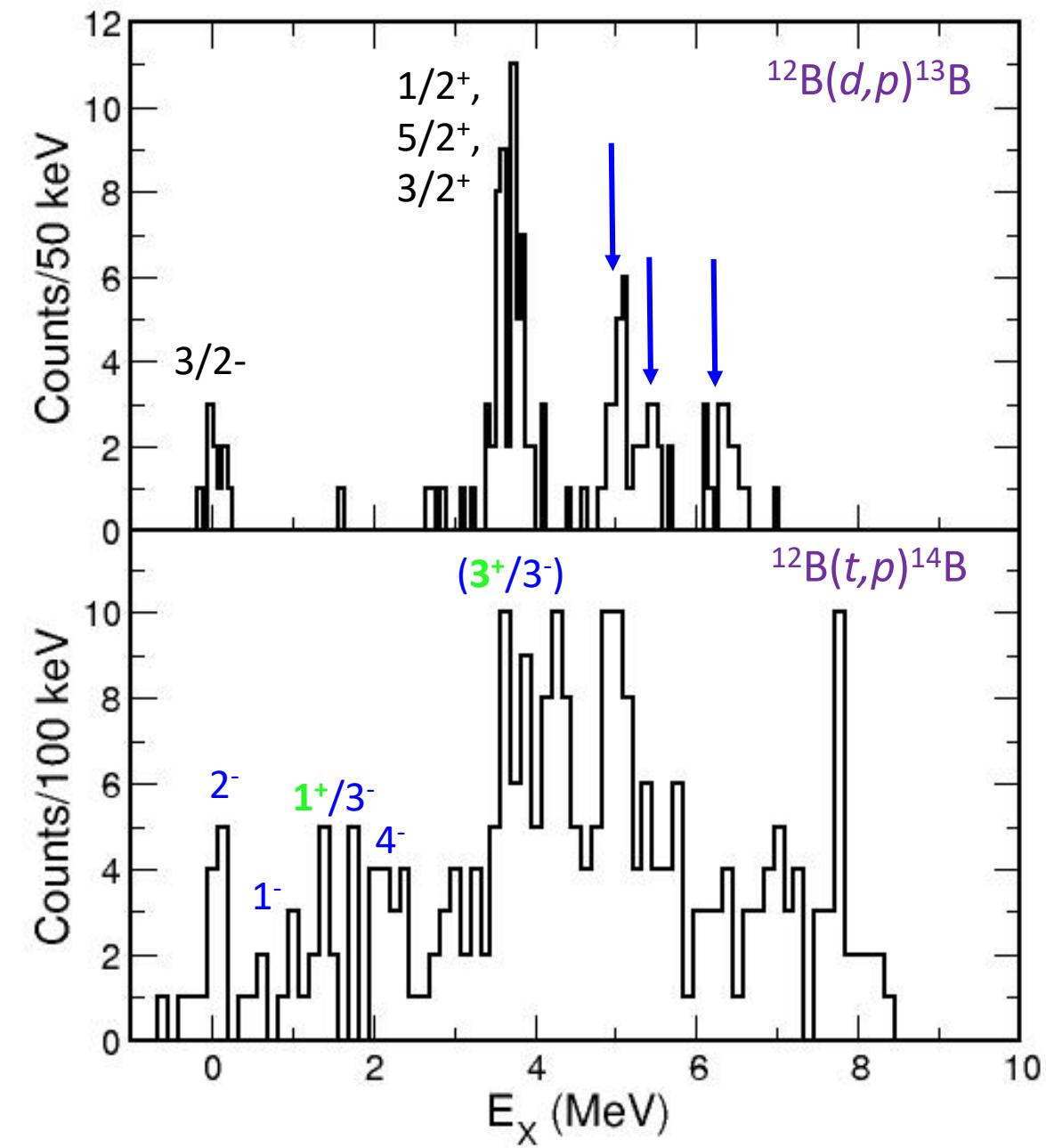
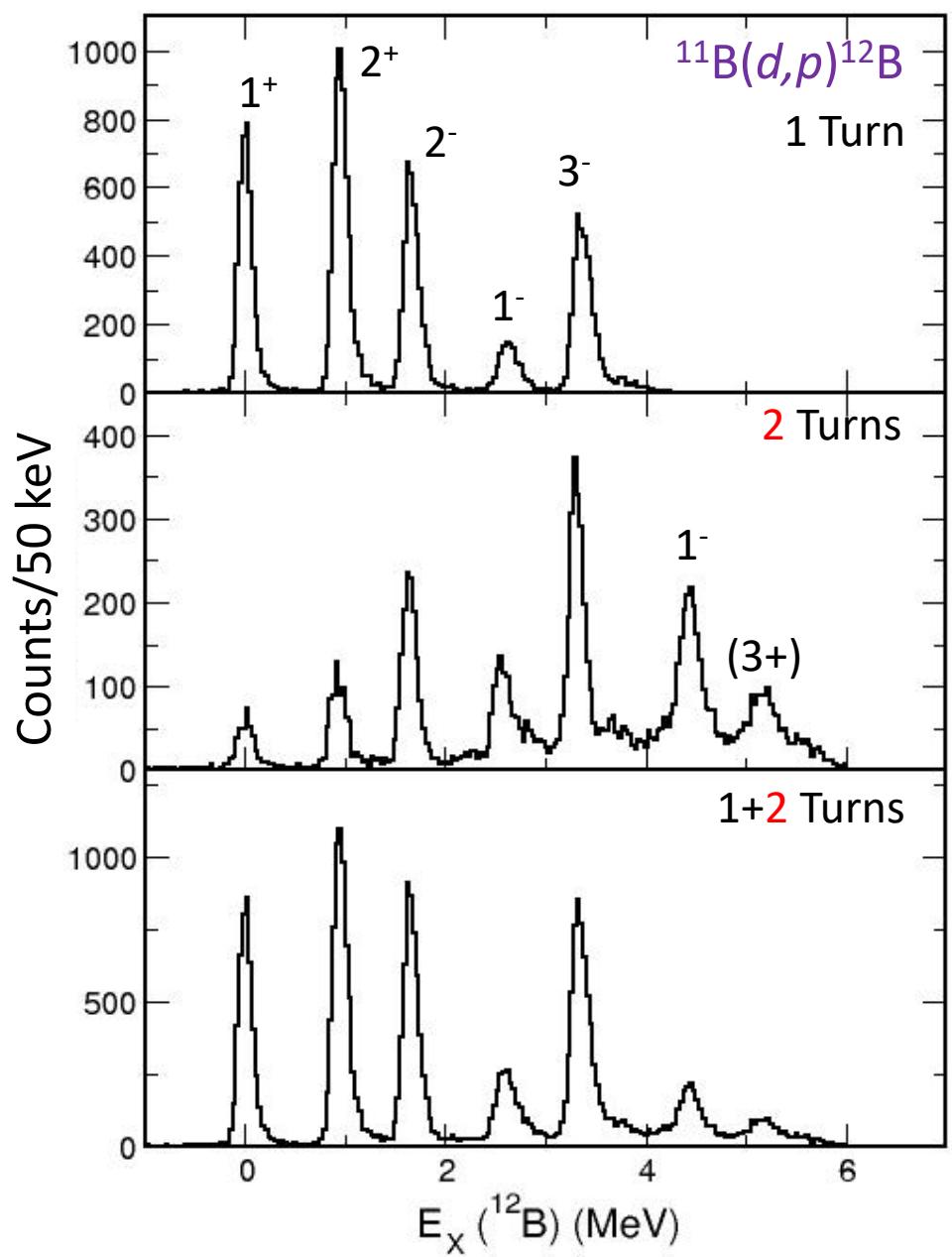
Use DSP trace analysis to improve timing resolution

$\Delta T \text{ (DAQ)} = 10 \text{ ns}$  (D. G. McNeel *et al.*, PRC **103**, 064320 2021)

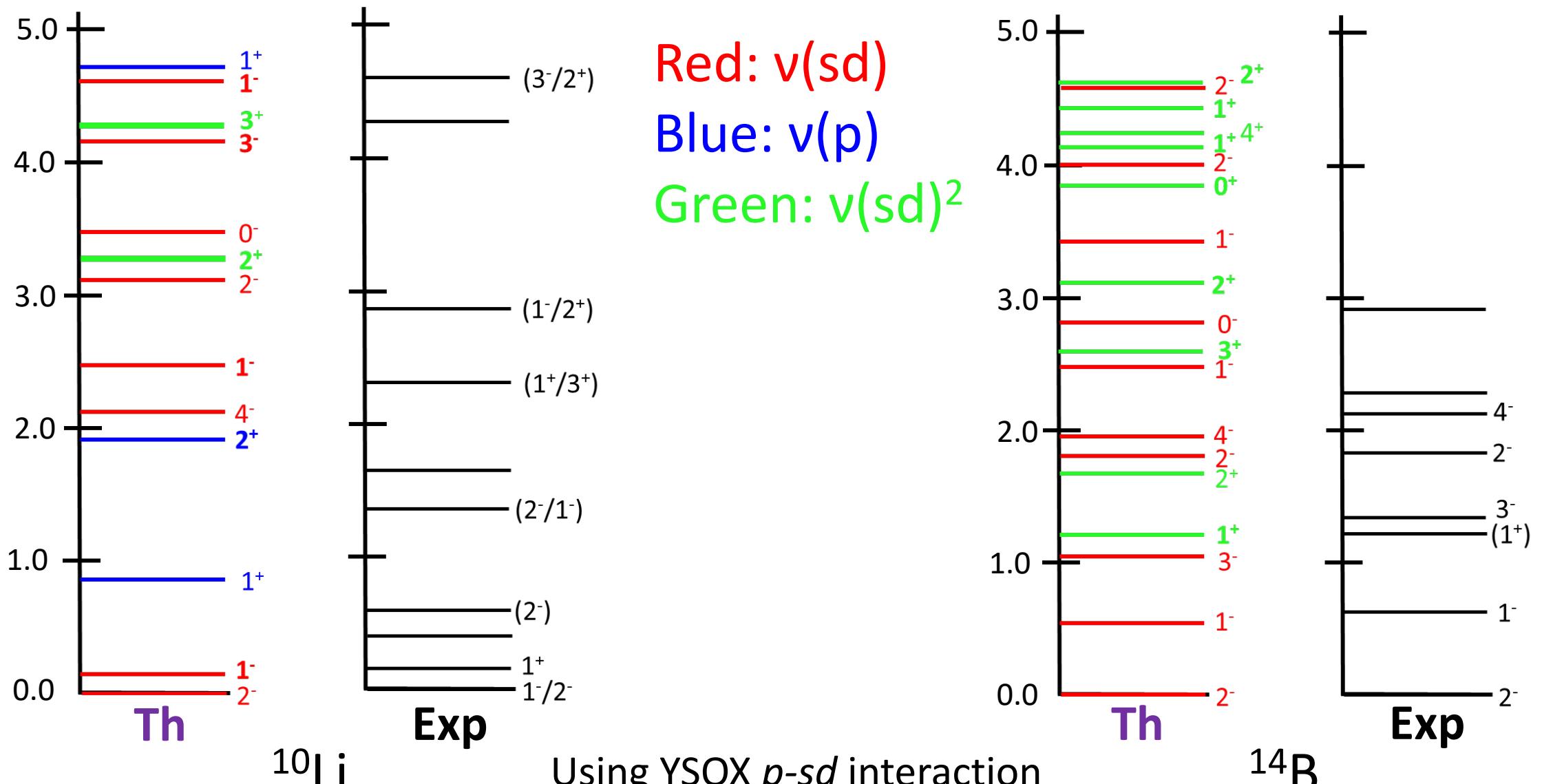
# $^{7,8}\text{Li}$ -induced reactions



# $^{11,12}\text{B}$ -induced reactions

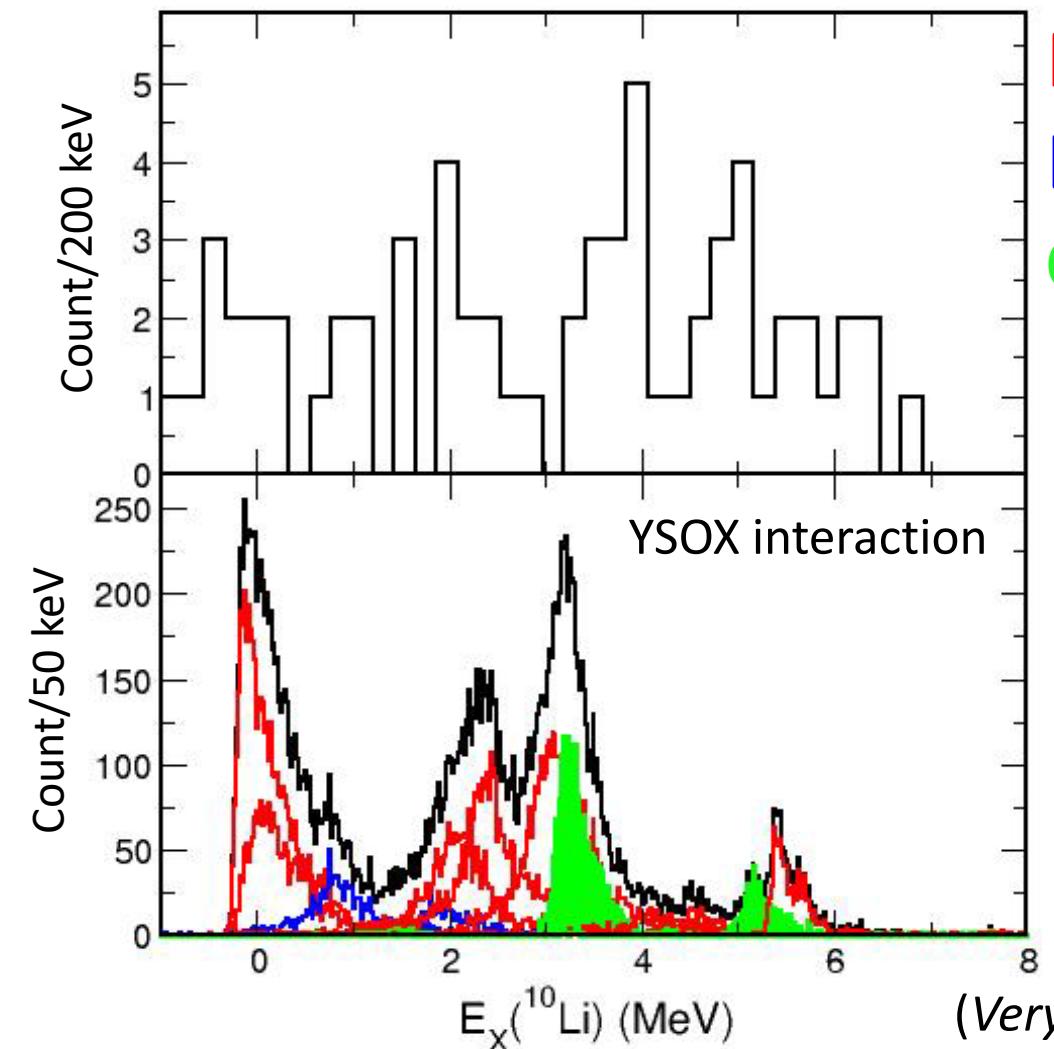


# Excitation energies: theory and experiment



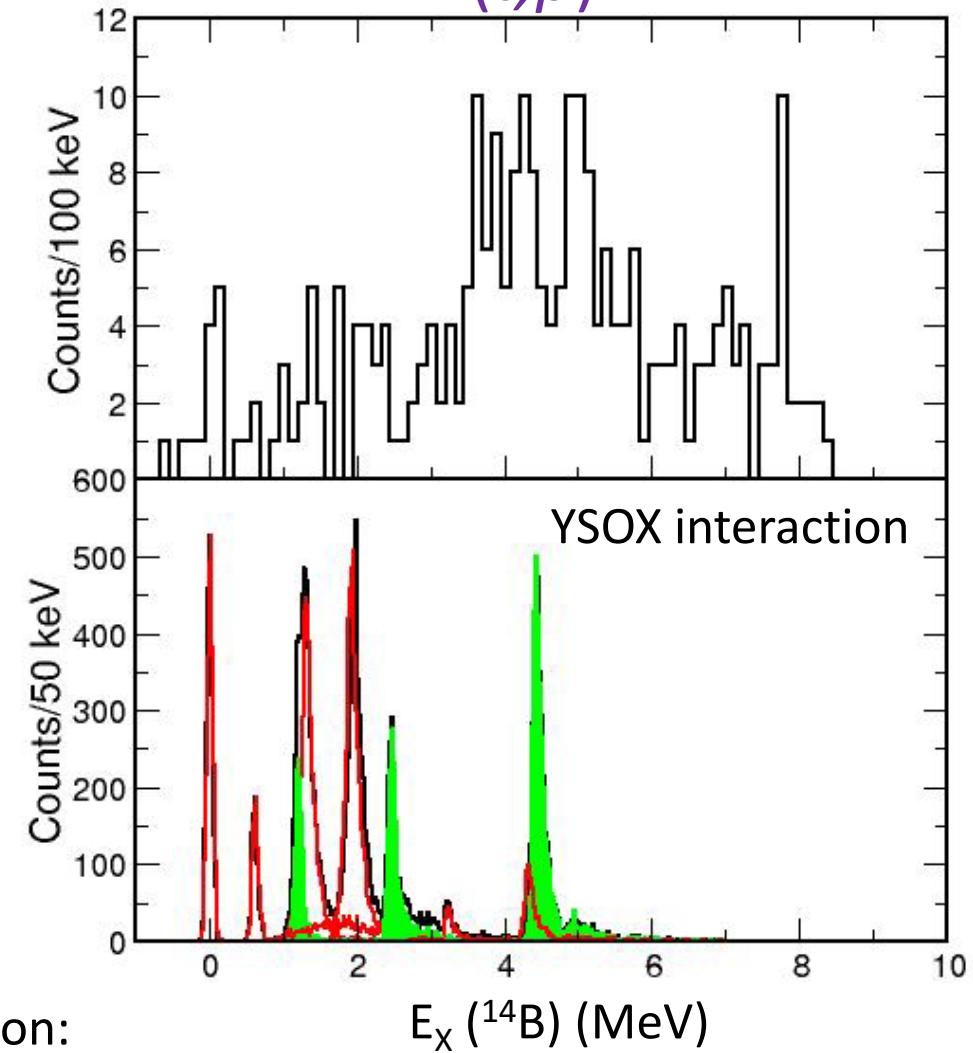
# “Theoretical” spectra

${}^8\text{Li}(t,p){}^{10}\text{Li}$



Red:  $\nu(sd)$   
Blue:  $\nu(p)$   
Green:  $\nu(sd)^2$

${}^{12}\text{B}(t,p){}^{14}\text{B}$



(Very speculative calculation:  
Strength from YSOX TNA+DWBA,  
rough estimate of widths, for  ${}^{10}\text{Li}$   
informed by  ${}^{10}\text{Li} \rightarrow {}^9\text{Li} + n$  YSOX SF)

# Conclusions and Thanks

- First studies of  ${}^8\text{Li}(t,p){}^{10}\text{Li}$  and  ${}^{12}\text{B}(t,p){}^{14}\text{B}$
- Indications of  $(sd)^2$  strength in both  ${}^{10}\text{Li}$  and  ${}^{14}\text{B}$ , but more data are needed
- New experiments are planned, awaiting new  ${}^3\text{H}$  targets
- Many thanks to all who have participated!

D.G. McNeel<sup>1</sup>, J. Chen<sup>2</sup>, R. Clark<sup>3</sup>, H. Crawford<sup>3</sup>, C. M. Deibel<sup>4</sup>, R. V. F. Janssens<sup>5,6</sup>, B.P. Kay<sup>2</sup>, S.A Kuvin<sup>1</sup>, J. C. Lighthall<sup>4</sup>, A. O. Macchiavelli<sup>3</sup>, S.T. Marley<sup>4</sup>, J.P. Schiffer<sup>2</sup>, D. K. Sharp<sup>7</sup>, J. Smith<sup>1</sup>, T. Tang<sup>2</sup>, G. Wilson<sup>2,4</sup>

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<sup>4</sup>Physics Department, Louisiana State University, Baton Rouge LA 70808, USA,

<sup>5</sup>Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599, <sup>6</sup>Triangle Universities Nuclear laboratory, Duke University, Durham, NC 27708, USA,

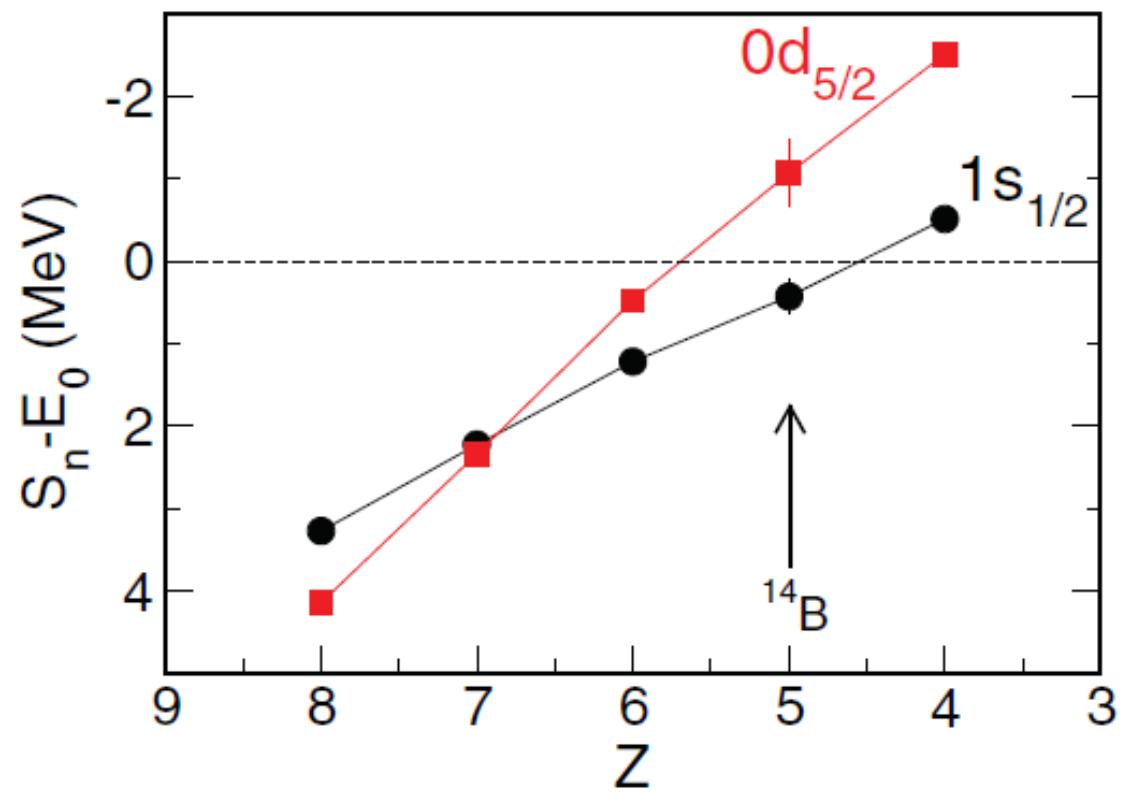
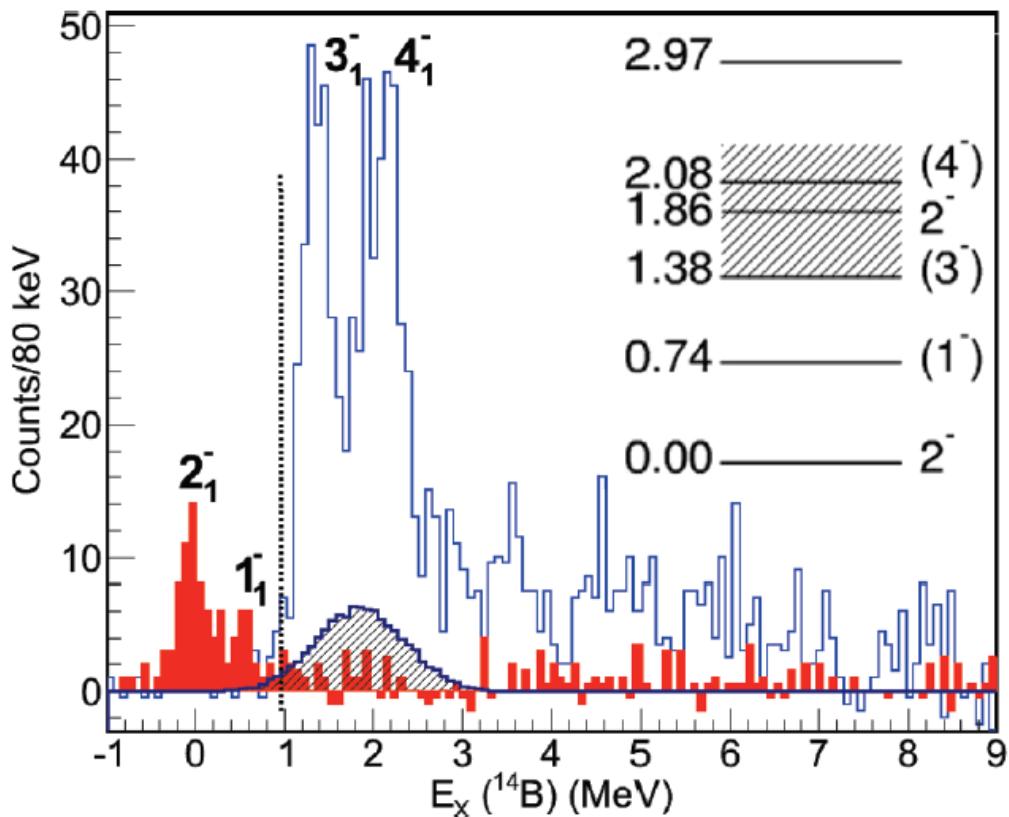
<sup>7</sup>School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK

This research was supported by the US Department of Energy, Office of Nuclear Physics, under Grants No. DESC0014552, (UConn), No. DE-FG02-96ER40978 (LSU), and No. DE-AC02-06CH11357 (ANL).

# HELIOS at ATLAS (ANL)



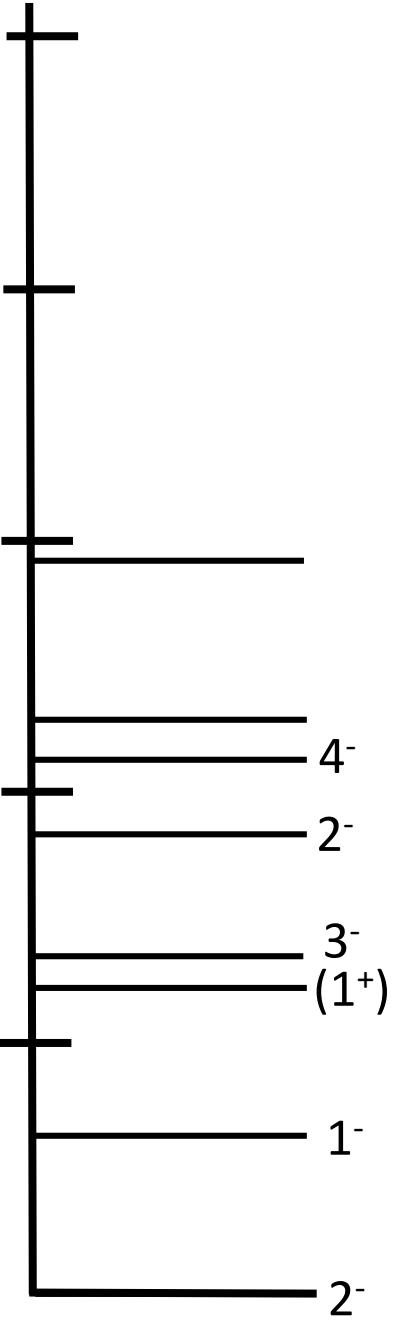
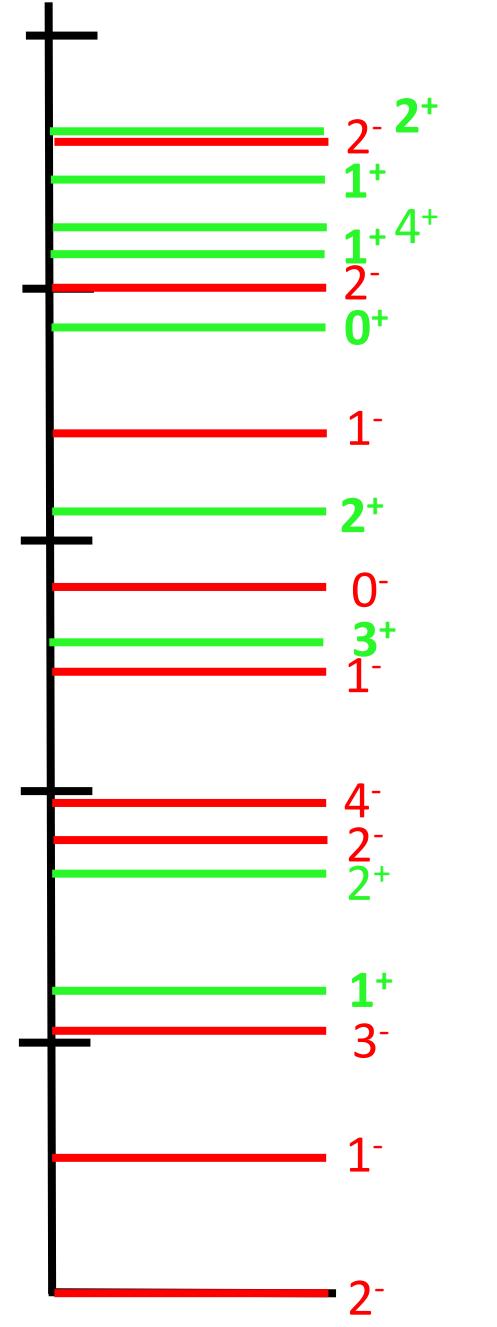
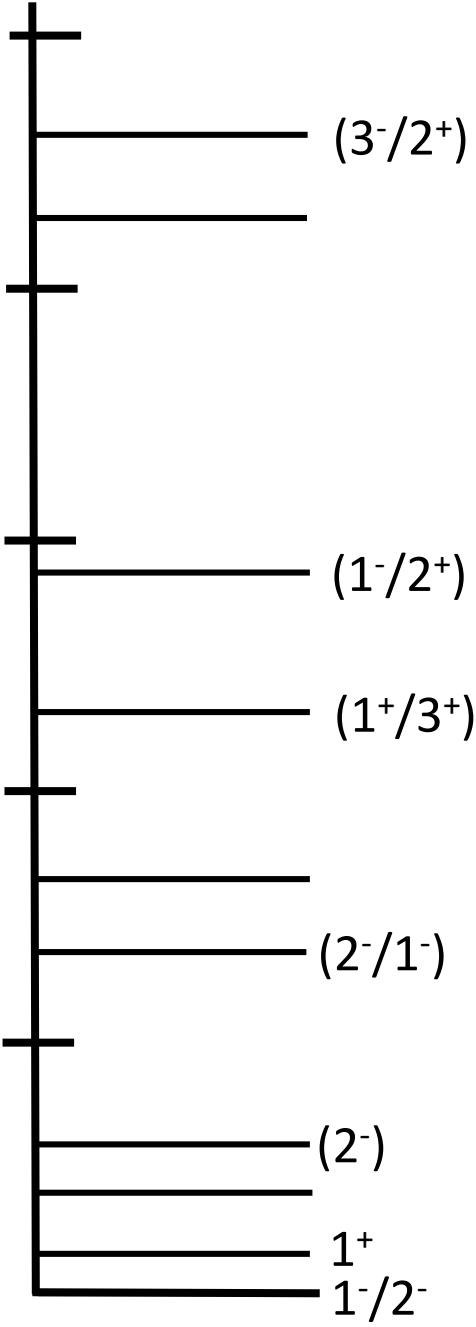
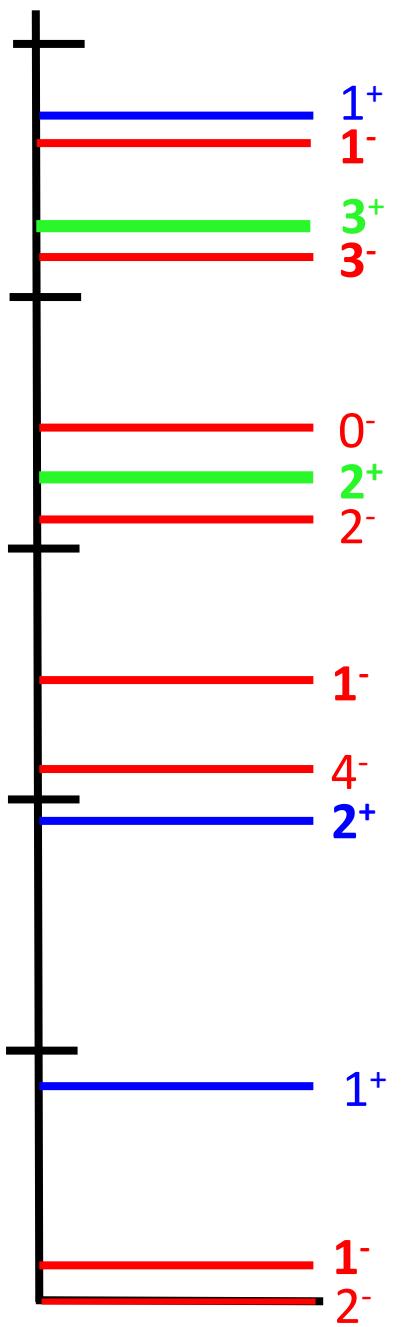
# $1s_{1/2}$ - $0d_{5/2}$ splitting in $^{14}\text{B}$ from $^{13}\text{B}(\text{d},\text{p})^{14}\text{B}$



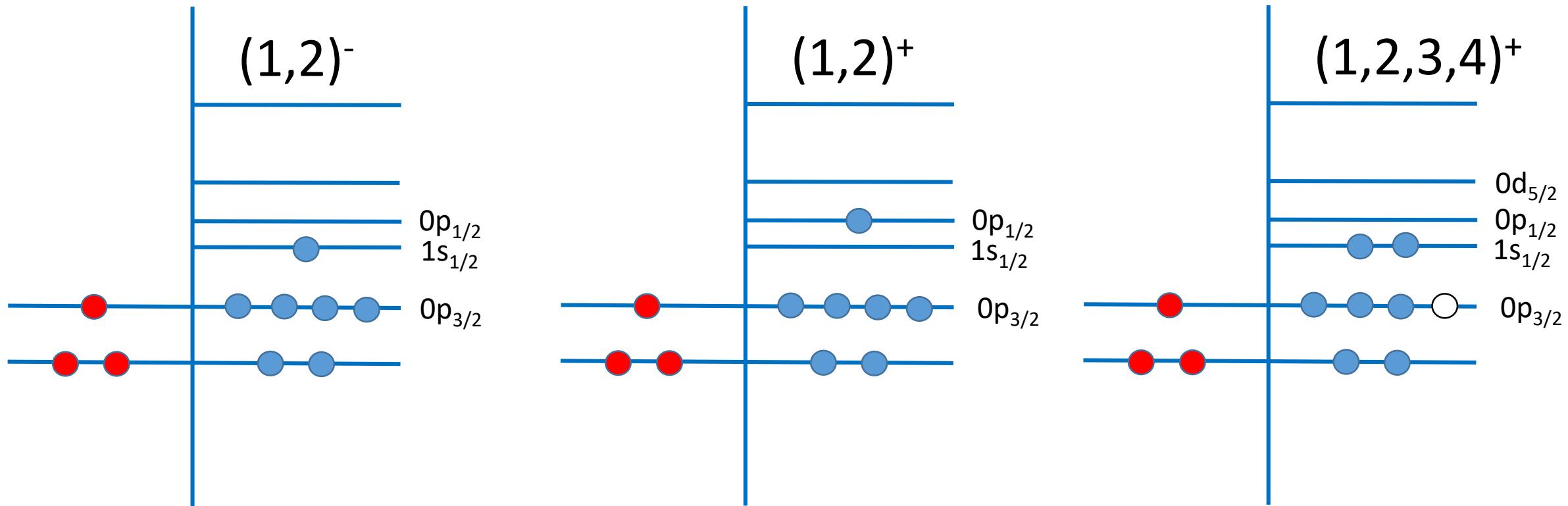
PHYSICAL REVIEW C 88, 011304(R) (2013)

## Structure of $^{14}\text{B}$ and the evolution of $N = 9$ single-neutron isotones

S. Bedoor,<sup>1</sup> A. H. Wuosmaa,<sup>1,\*</sup> J. C. Lighthall,<sup>1,†</sup> M. Alcorta,<sup>2</sup> B. B. Back,<sup>2</sup> P. F. Bertone,<sup>2,‡</sup> B. A. Brown,<sup>3</sup> C. M. Deibel,<sup>4</sup> C. R. Hoffman,<sup>2</sup> S. T. Marley,<sup>1,2,§</sup> R. C. Pardo,<sup>2</sup> K. E. Rehm,<sup>2</sup> A. M. Rogers,<sup>2</sup> J. P. Schiffer,<sup>2</sup> and D. V. Shetty<sup>1,||</sup>



# Shell-model configurations in ${}^{10}\text{Li}$



# Shell-model configurations in $^{14}\text{B}$

