Neutron *sd*-shell excitations in exotic nuclei near N=8

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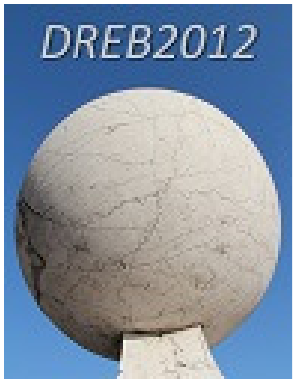
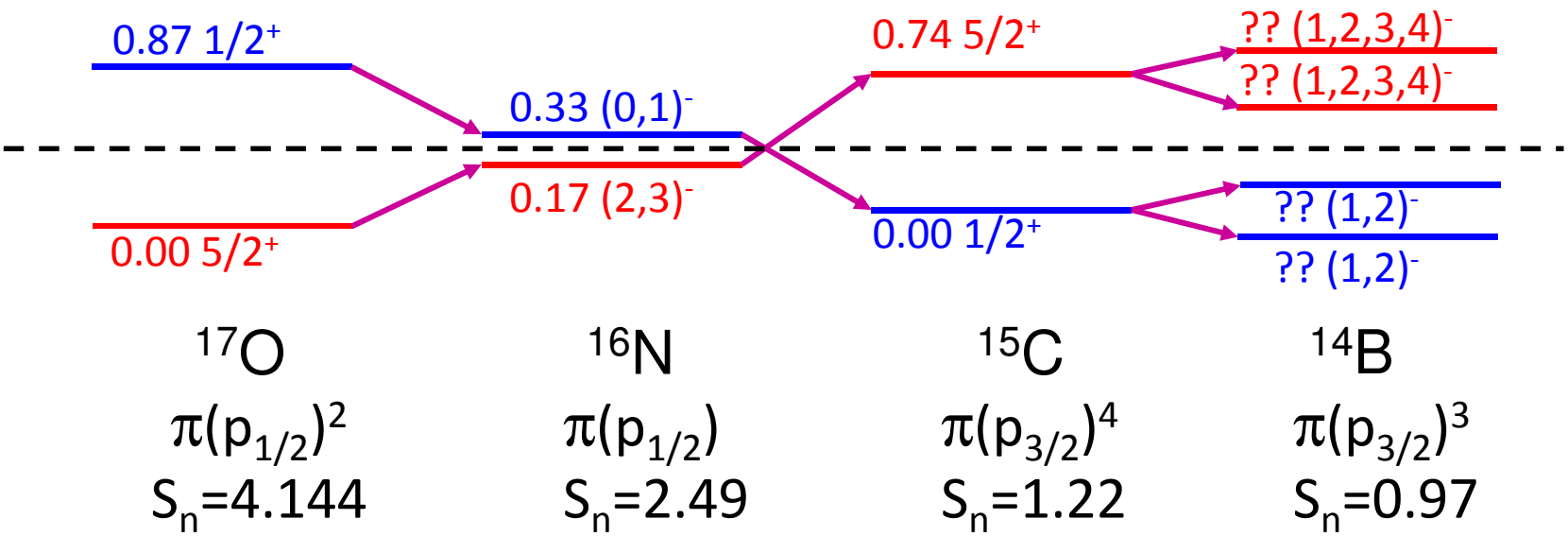
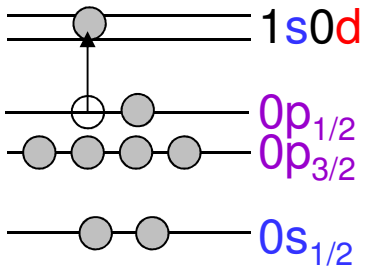


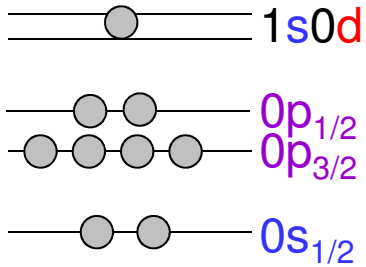
Evolution of $1s_{1/2}$-$0d_{5/2}$ splitting outside N=8

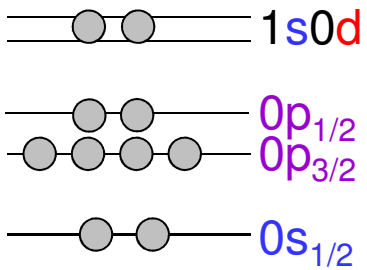


Gross behavior from p-n tensor attraction/repulsion

Neutron configurations around N=8







N=8 (^{13}B)
Positive-parity states
are $\nu(p_{1/2})^{-1}(sd)\otimes\pi(p_{3/2})^{-1}$

N=9 (^{14}B)
Negative-parity states
are $\nu(sd)\otimes\pi(p_{3/2})^{-1}$

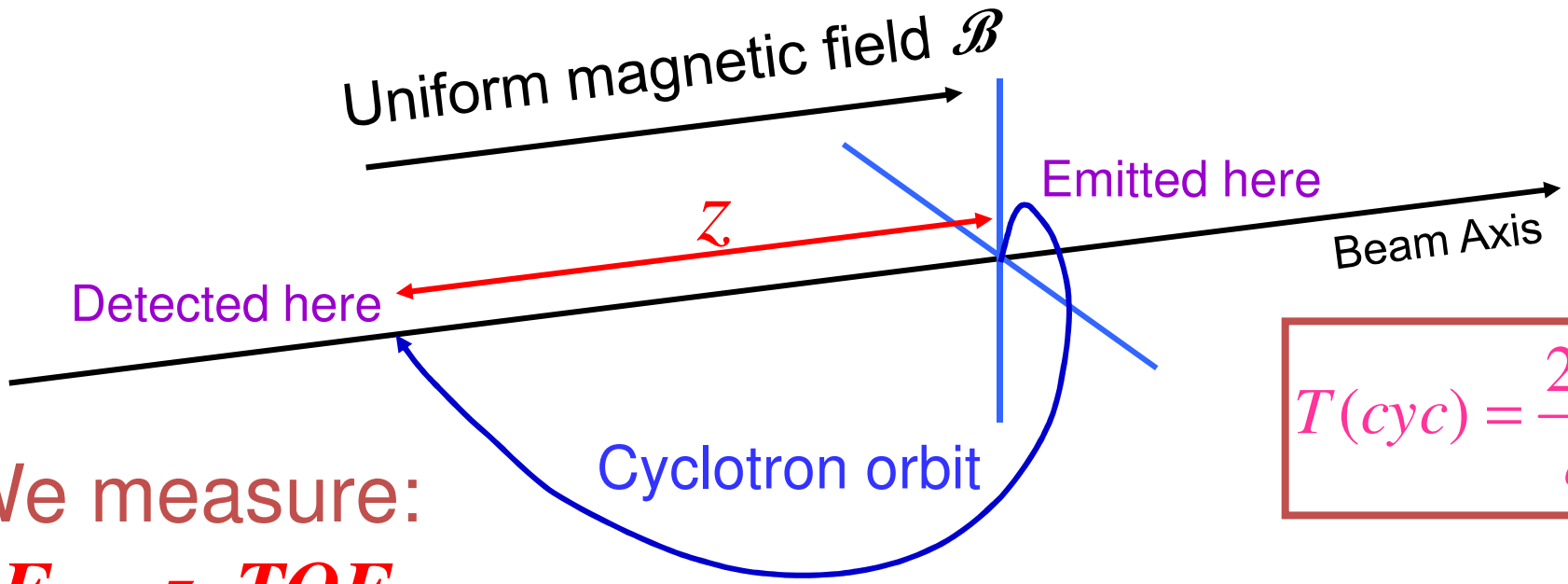
N=10 (^{16}C)
Positive-parity states
are $\nu(sd)^2 \otimes {}^{14}$C

^{12}B(d,p)^{13}B
^{12}B from ^{11}B(d,p)
At 6 MeV/u

^{13}B(d,p)^{14}B
^{13}B from ^{14}C(^{9}Be,^{10}B)
At 15.7 MeV/u

^{15}C(d,p)^{16}C
^{15}C from ^{14}C(d,p)
At 8.5 MeV/u

The HELIOS approach to inverse kinematics



$$T(cyc) = \frac{2\pi m}{qB}$$

We measure:

E_{lab}, z, TOF

We deduce:

E_{CM}, θ_{CM}

$$z \propto \cos\theta_{CM}$$

$$E_{lab} = E_{CM} - A + Bz$$

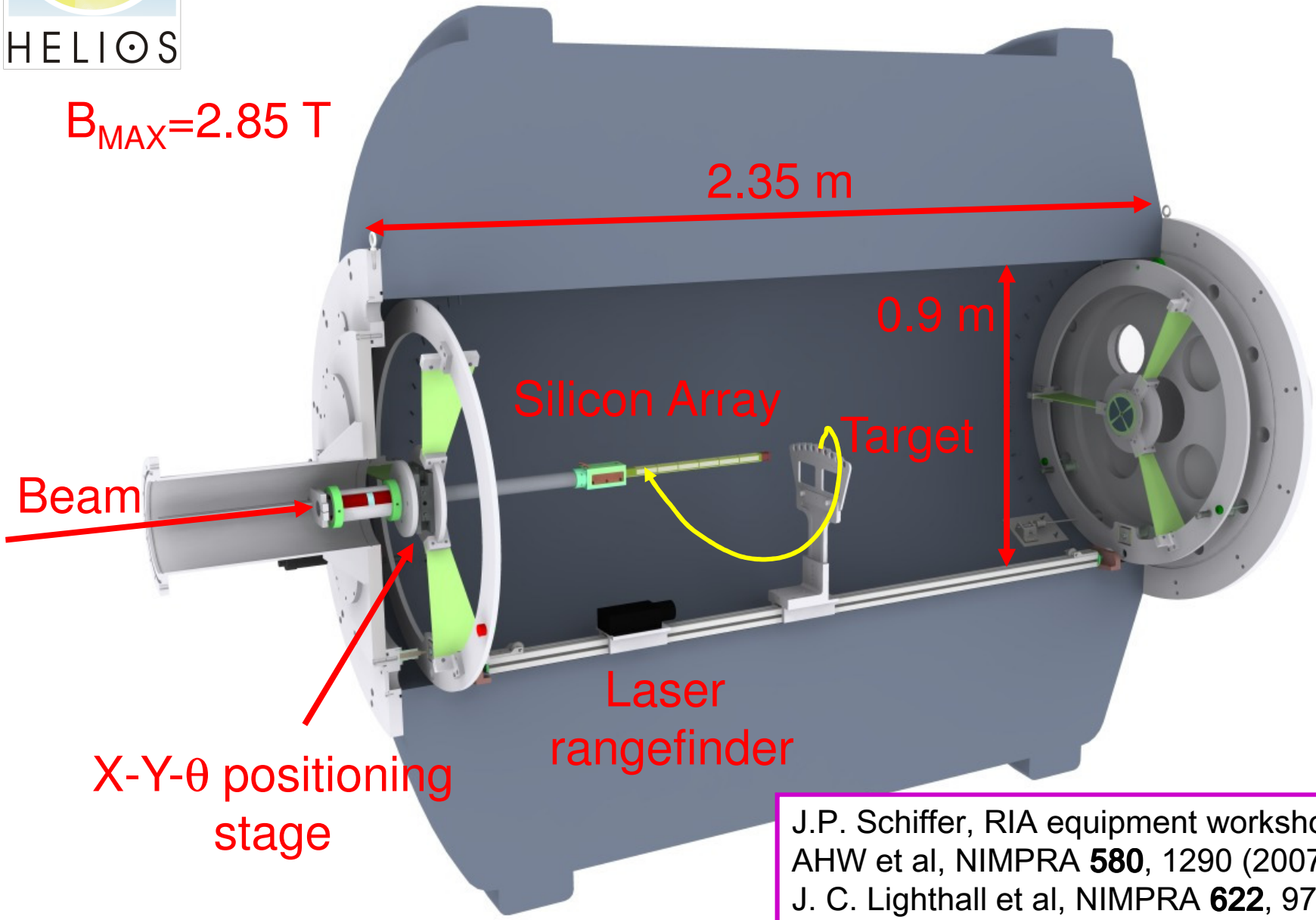
For a given state

$$\Delta E_{lab} = \Delta E_{CM}$$

For two states at fixed z

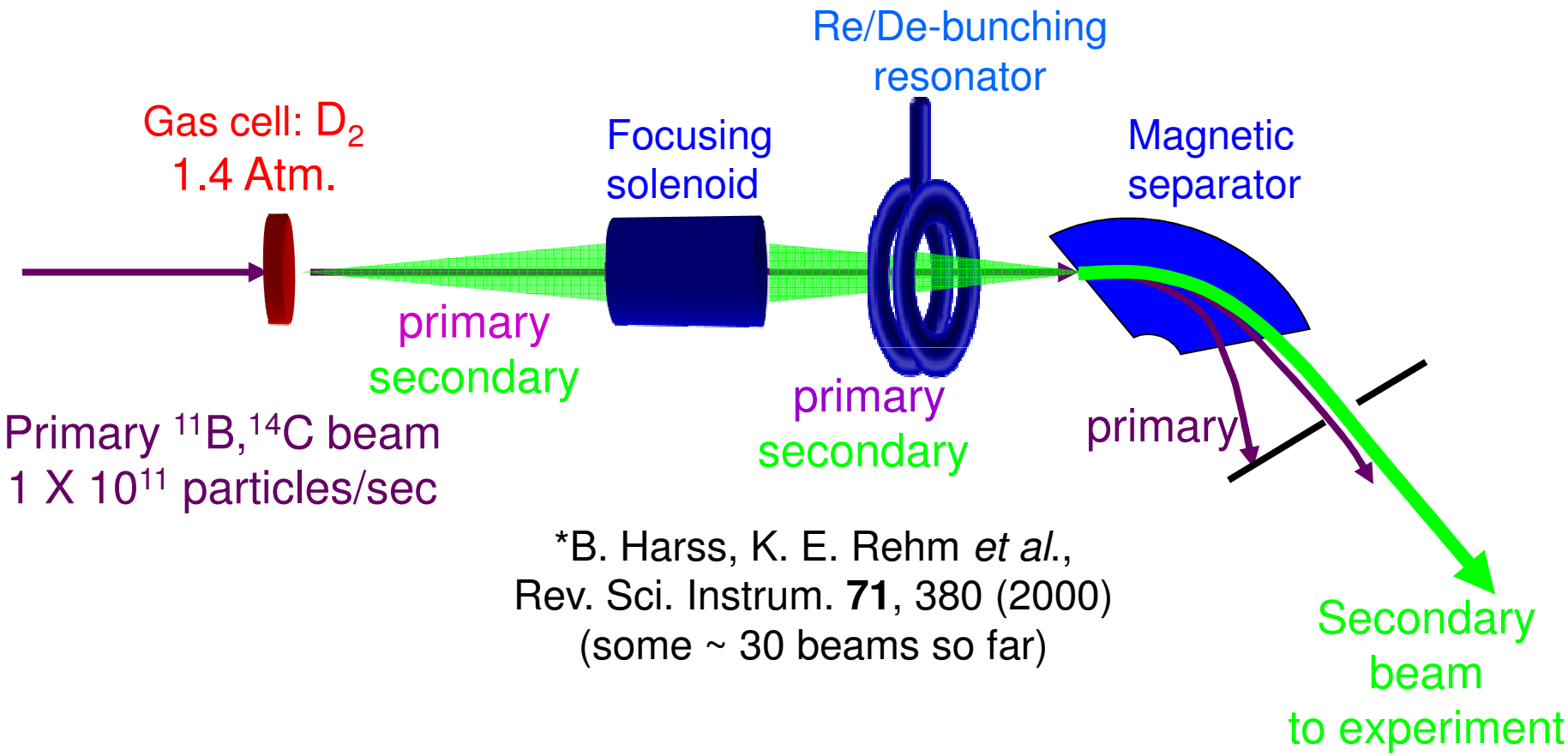
HELIOS

HELIcal Orbit Spectrometer -HELIOS



J.P. Schiffer, RIA equipment workshop 1999,
AHW et al, NIMPRA **580**, 1290 (2007)
J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

Producing secondary beams: "In-flight" production at ANL*

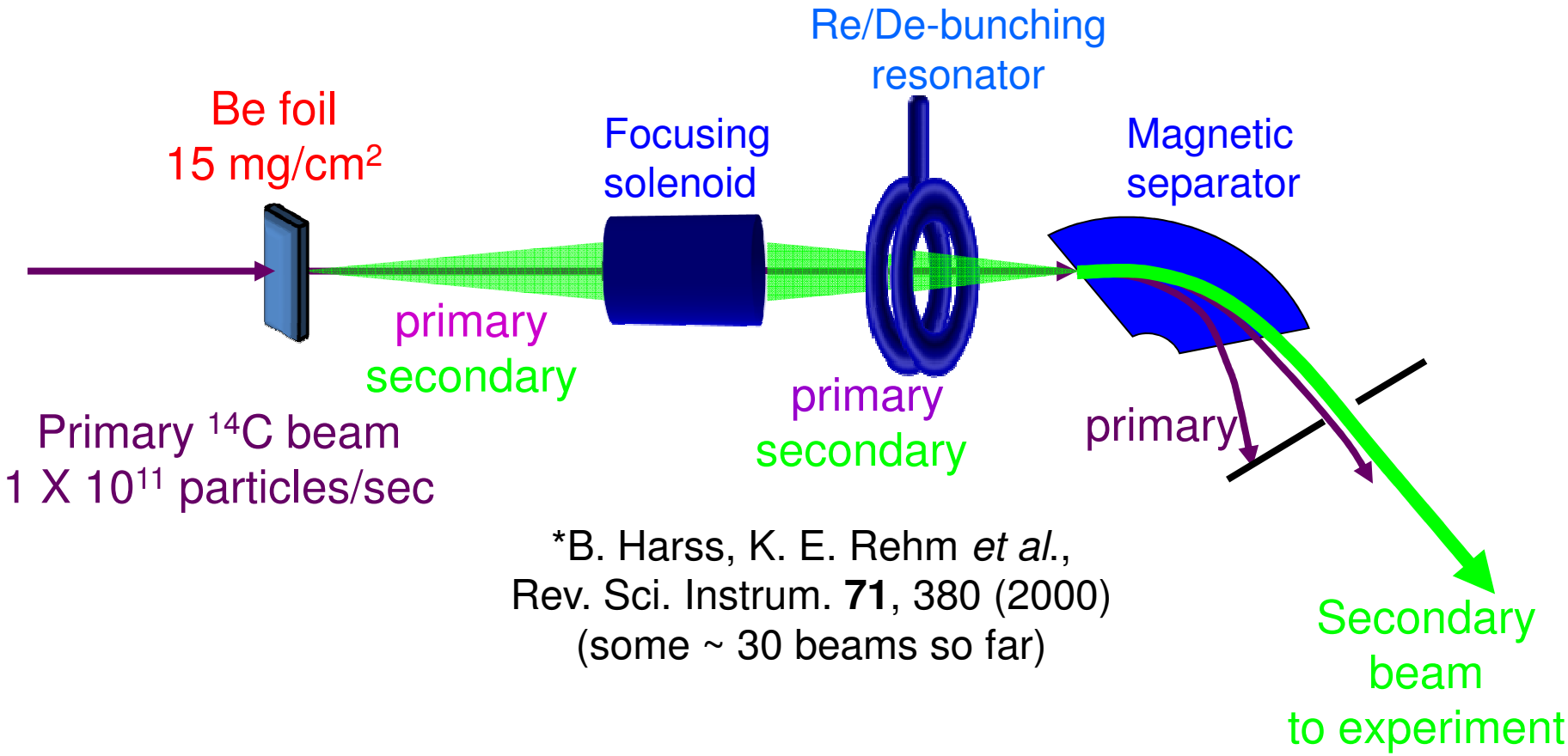


*B. Harss, K. E. Rehm *et al.*, Rev. Sci. Instrum. **71**, 380 (2000) (some ~ 30 beams so far)

^{12}B intensity ~ 6 X 10^5 /sec at 6.25 MeV/u

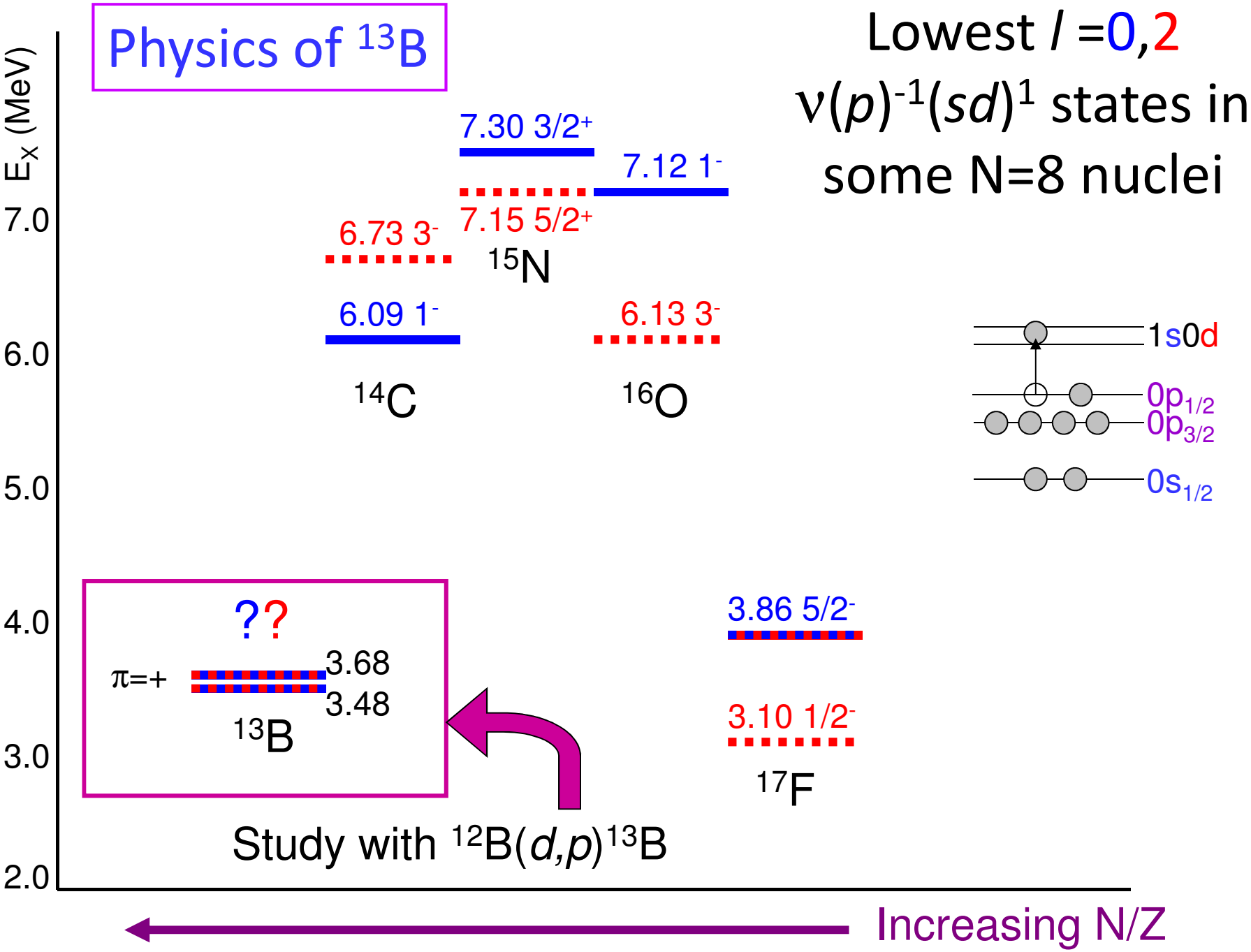
^{15}C intensity ~ 1.5 X 10^6 /sec at 8.2 MeV/u

Producing secondary beams: "In-flight" production at ANL*

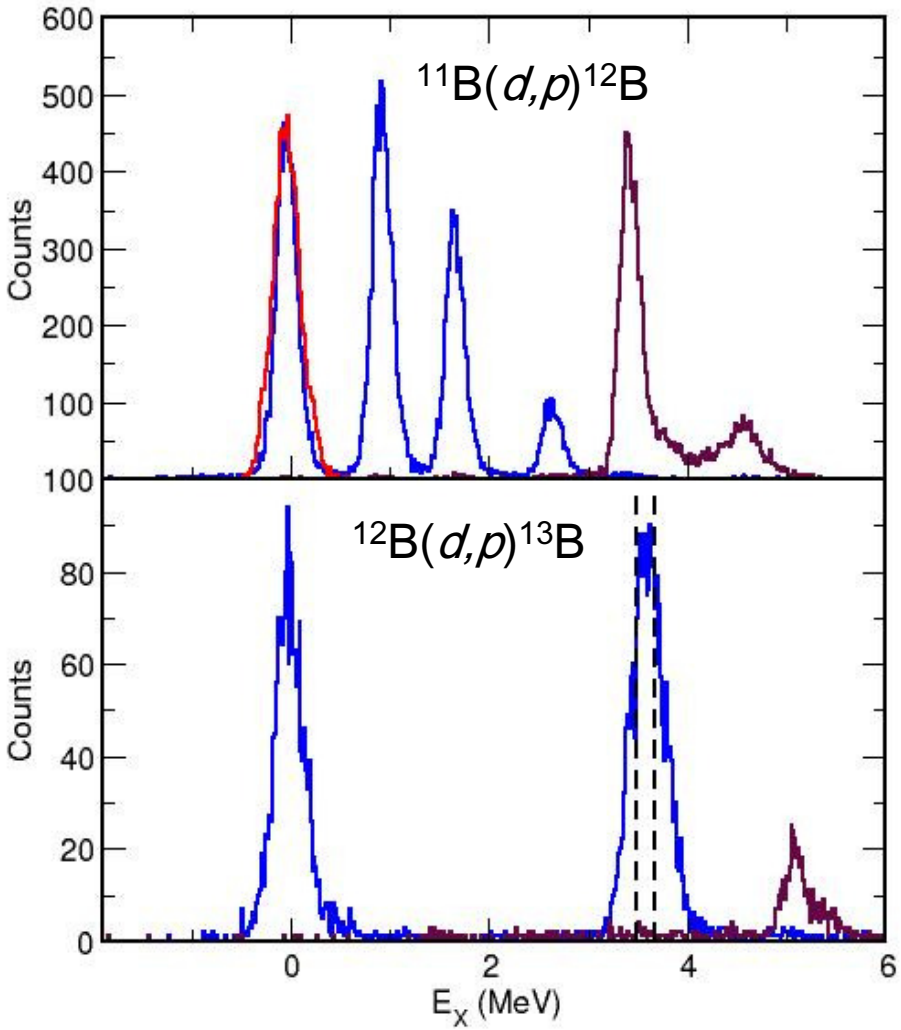


*B. Harss, K. E. Rehm *et al.*, Rev. Sci. Instrum. **71**, 380 (2000) (some ~ 30 beams so far)

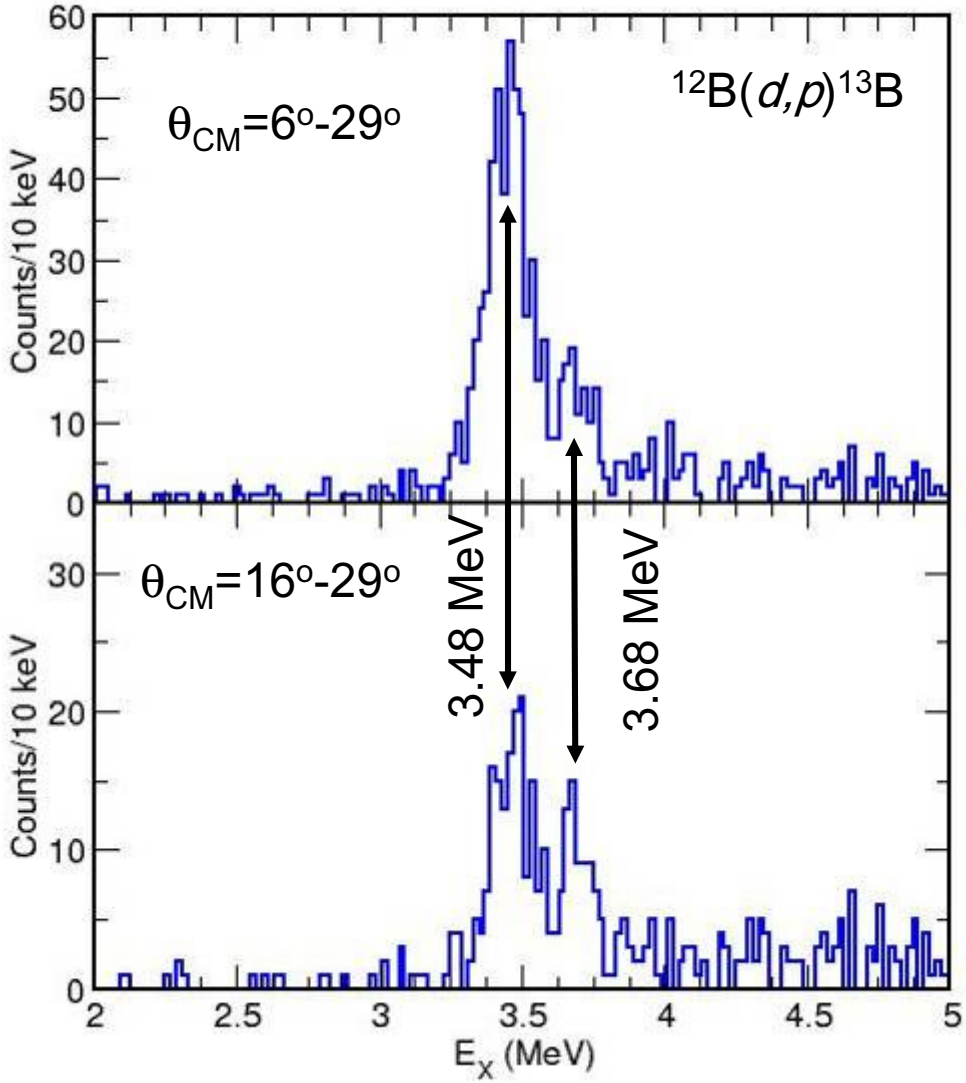
^{13}B intensity ~ 4 X 10^4 /sec at 15.7 MeV/u


Physics of ^{13}B
Lowest l =0,2
$\nu(p)^{-1}(sd)^{1}$ states in
some N=8 nuclei
E_X (MeV)
7.0
6.0
5.0
4.0
3.0
2.0
7.30 3/2+
7.12 1-
7.15 5/2+
6.73 3-
^{15}N
6.09 1-
6.13 3-
^{14}C
^{16}O
1s0d
0p1/2
0p3/2
0s1/2
3.86 5/2-
3.10 1/2-
^{17}F
??
π=+
3.68
3.48
^{13}B
Study with ^{12}B(d,p)^{13}B
Increasing N/Z

First HELIOS RIB results with $^{12}B(d,p)^{13}B$



"Conventional"

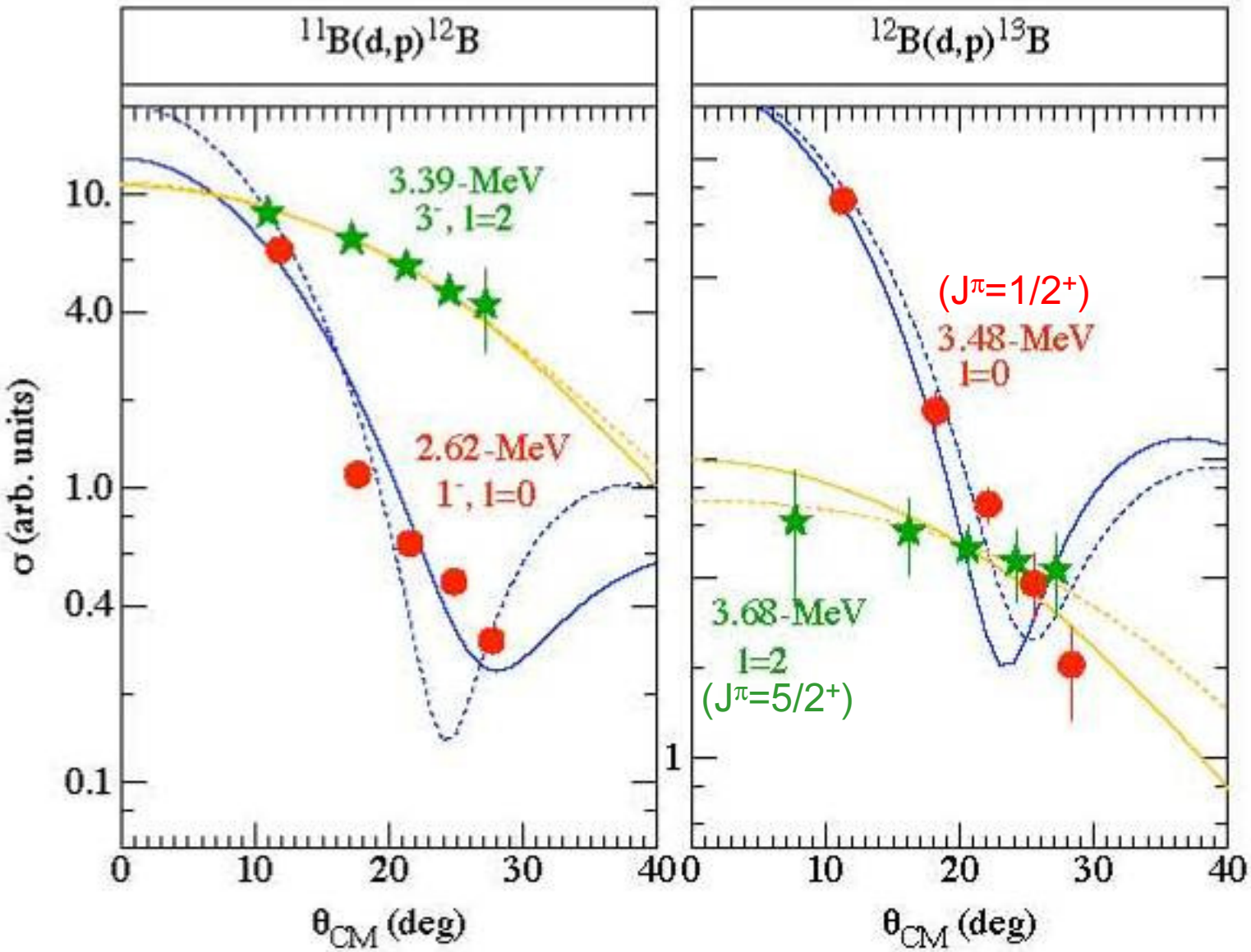


HELIOS

H. Y. Lee et al., PRC **81**, 015802 (2010)

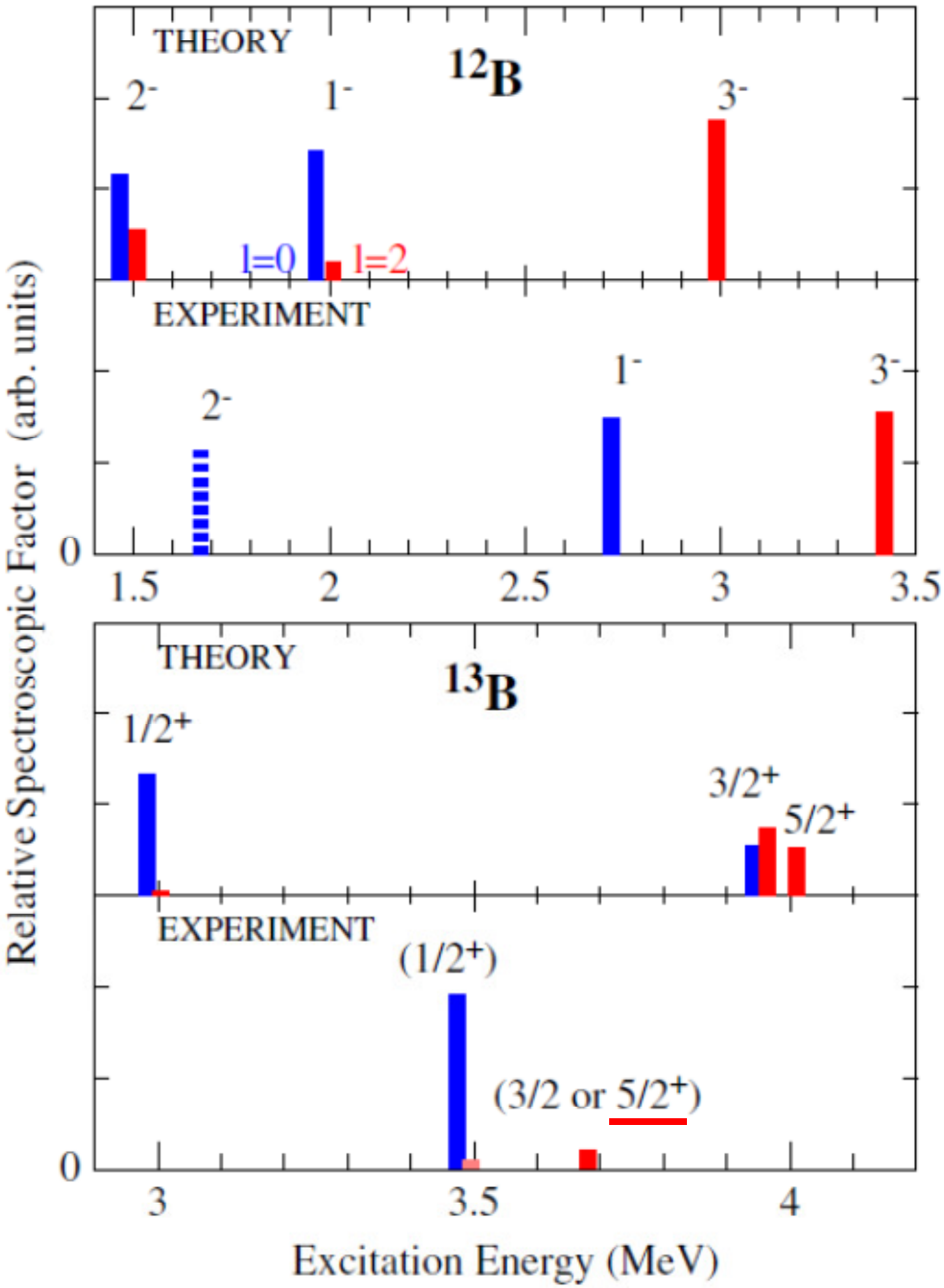
B. B. Back et al., PRL **104**, 132501 (2010)

$^{11,12}B(d,p)^{12,13}B$ angular distributions



B. B. Back et al., PRL **104**, 132501 (2010)

Theory versus experiment for ^{13}B



Excitation energies and relative spectroscopic factors from the shell model

Blue: L=0

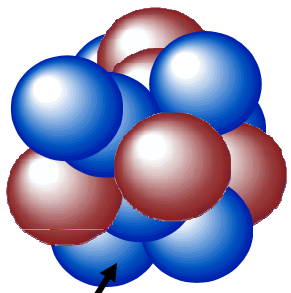
Red: L=2

$5/2^+$ L=2 is reduced, no nearby $3/2^+$ is observed

B. B. Back et al., PRL **104**, 132501 (2010)

Exotic behavior in ^{16}C?

Valence neutrons



Core ^{16}C

VOLUME 92, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2004

Anomalously Hindered $E2$ Strength $B(E2; 2_1^+ \rightarrow 0^+)$ in ^{16}C

N. Imai,[1,*] H. J. Ong,[2] N. Aoi,[1] H. Sakurai,[2] K. Demichi,[3] H. Kawasaki,[3] H. Baba,[3] Zs. Dombrádi,[4] Z. Elekes,[1,†] N. Fukuda,[1] Zs. Fülöp,[4] A. Gelberg,[5] T. Gomi,[3] H. Hasegawa,[3] K. Ishikawa,[6] H. Iwasaki,[2] E. Kaneko,[3] S. Kanno,[3] T. Kishida,[1] Y. Kondo,[6] T. Kubo,[1] K. Kurita,[3] S. Michimasa,[7] T. Minemura,[1] M. Miura,[6] T. Motobayashi,[1] T. Nakamura,[6] M. Notani,[7] T. K. Onishi,[2] A. Saito,[3] S. Shimoura,[7] T. Sugimoto,[6] M. K. Suzuki,[2] E. Takeshita,[3] S. Takeuchi,[1] M. Tamaki,[7] K. Yamada,[3] K. Yoneda,[1,‡] H. Watanabe,[1] and M. Ishihara[1]

Physics Letters B 586 (2004) 34–40

Decoupling of valence neutrons from the core in ^{16}C

Z. Elekes [a,1], Zs. Dombrádi [b], A. Krasznahorkay [b], H. Baba [c], M. Csatlós [b], L. Csige [b], N. Fukuda [a], Zs. Fülöp [b], Z. Gácsi [b], J. Gulyás [b], N. Iwasa [d], H. Kinugawa [c], S. Kubono [c], M. Kurokawa [c], X. Liu [c], S. Michimasa [c], T. Minemura [c], T. Motobayashi [a], A. Ozawa [a], A. Saito [c], S. Shimoura [c], S. Takeuchi [a], I. Tanihata [a], P. Thirolf [f], Y. Yanagisawa [a], K. Yoshida [a]

PRL 100, 152501 (2008) PHYSICAL REVIEW LETTERS week ending 18 APRIL 2008

Lifetime Measurement of the First Excited 2^+ State in ^{16}C

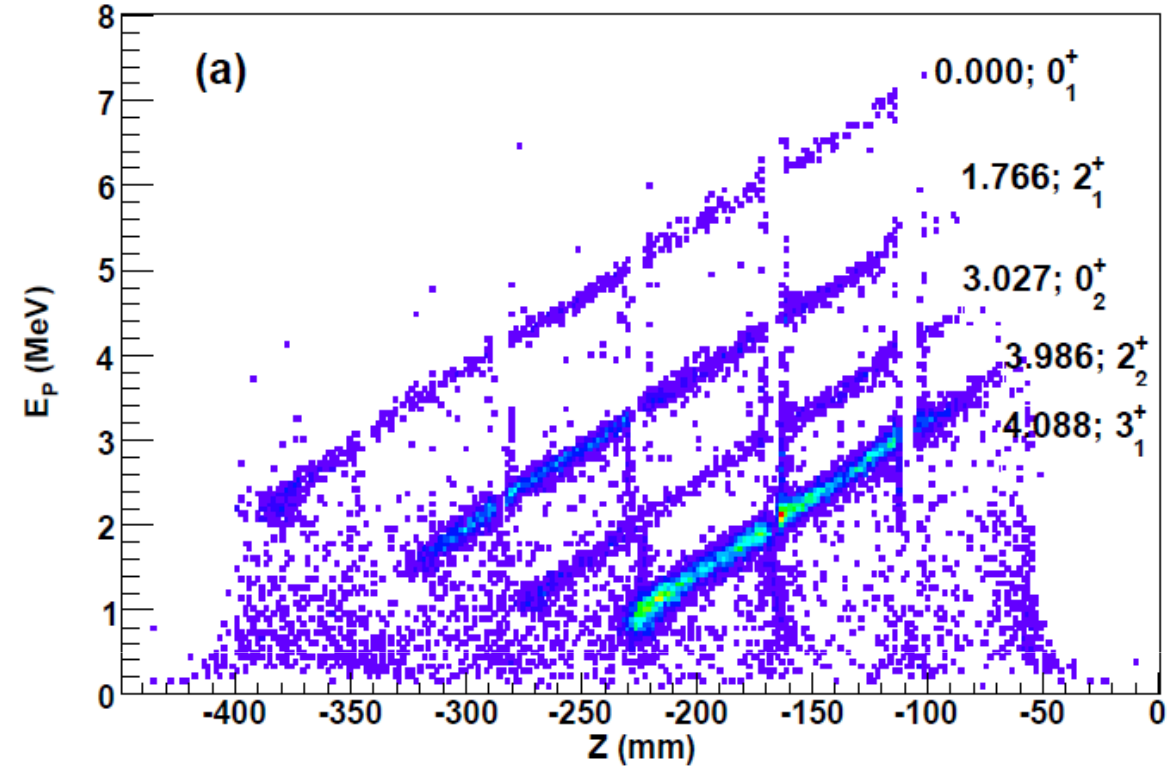
M. Wiedeking, P. Fallon, A. O. Macchiavelli, J. Gibelin, M. S. Basunia, R. M. Clark, M. Cromaz, M.-A. Deleplanque, S. Gros, H. B. Jeppesen, P. T. Lake, I.-Y. Lee, L. G. Moretto, J. Pavan, L. Phair, and E. Rodriguez-Vietiez
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

L. A. Bernstein, D. L. Bleuel, J. T. Burke, S. R. Lesher, B. F. Lyles, and N. D. Scielzo
Lawrence Livermore National Laboratory, Livermore, California 94550, USA
(Received 20 November 2007; published 16 April 2008)

No hindrance, and no exotic behavior.

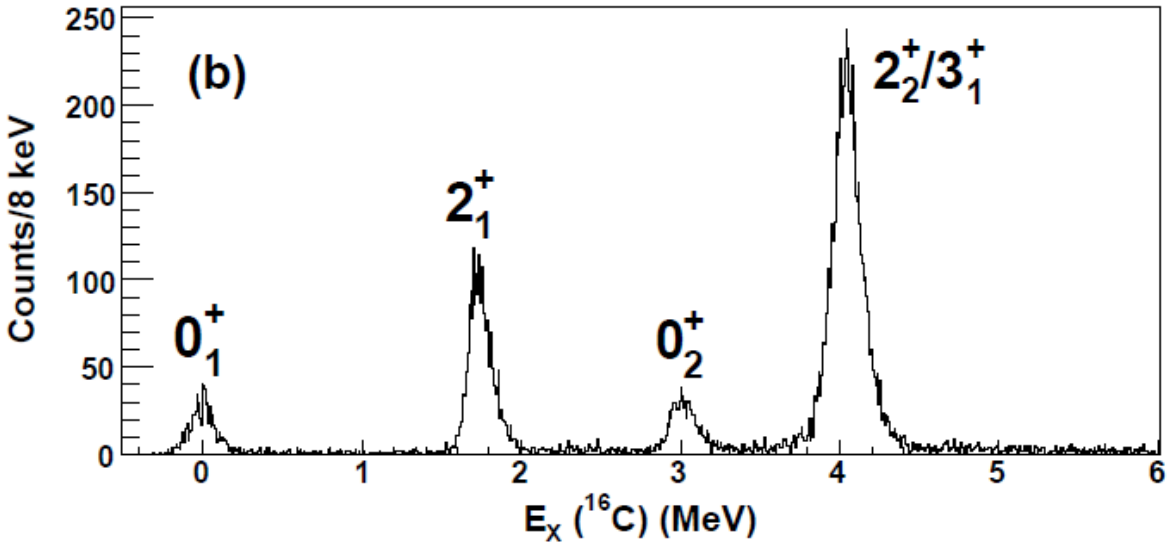
Study with $^{15}C(d,p)^{16}C$

$^{15}C(d,p)^{16}C$ with HELIOS



Proton energy-position correlation

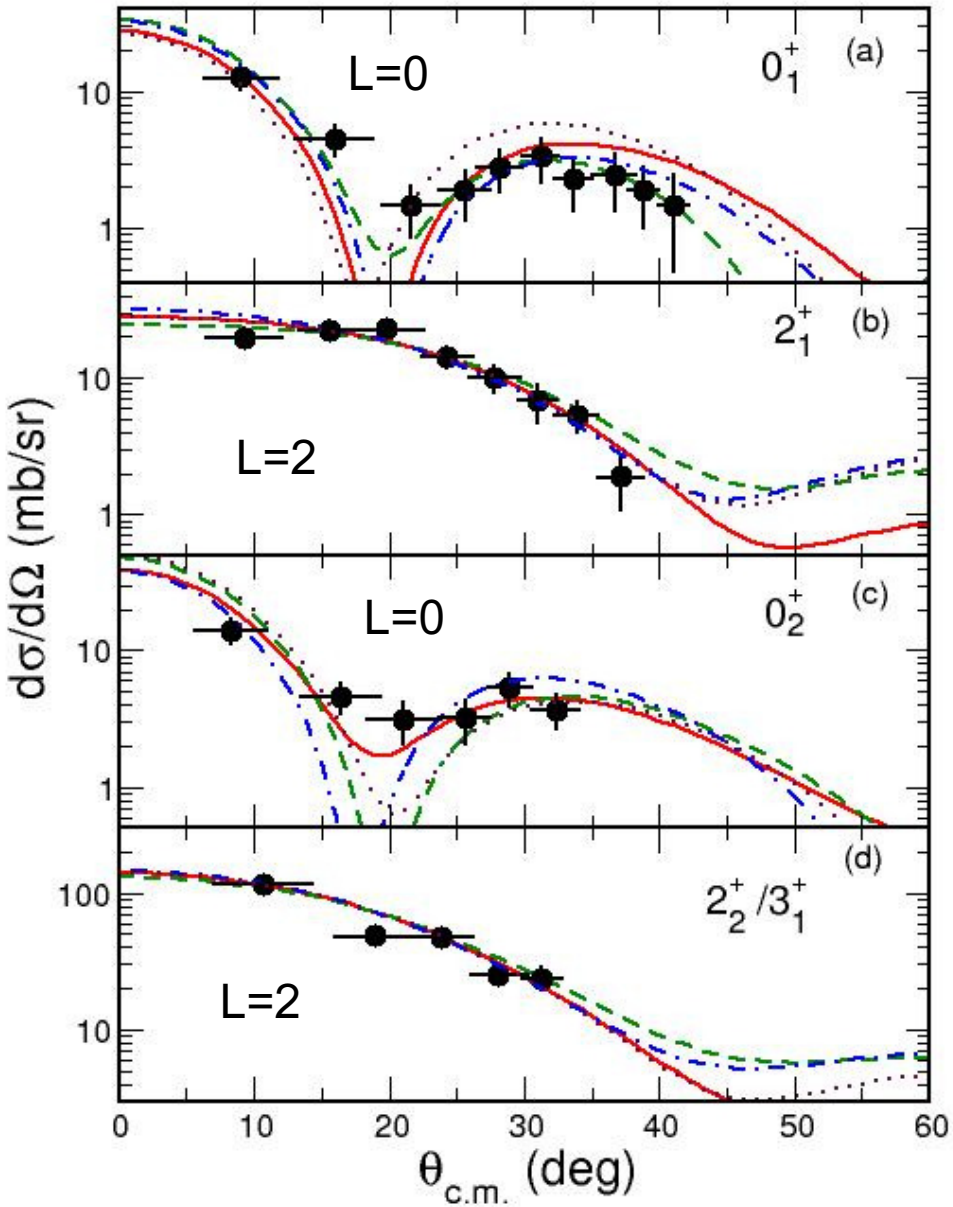
(d,p) samples the $\nu(1s_{1/2})$ content of the wave functions for positive-parity states



^{16}C Excitation-energy spectrum

PRL **105**, 132501 (2010)

$^{15}C(d,p)^{16}C$ angular distributions



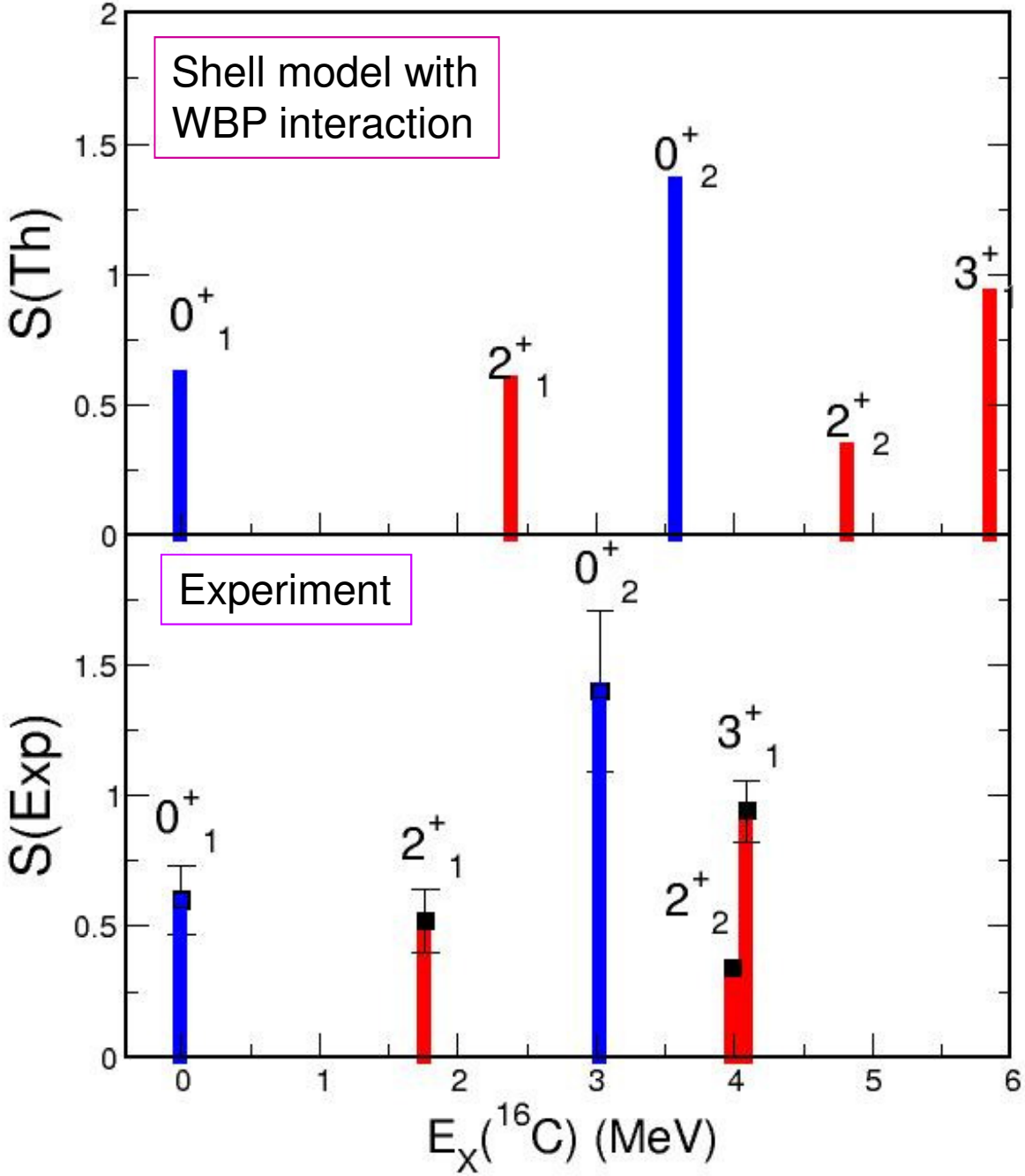
Curves are DWBA calculations with various optical-model potentials.

Spectroscopic factors obtained from the average over four sets of OMP.

Relative uncertainties in SF dominated by OMP variations
Absolute uncertainty (~30%) from beam-integration uncertainty

PRL **105**, 132501 (2010)

$^{15}C(d,p)^{16}C$ Spectroscopic factors



Excitation energies and relative spectroscopic factors from the shell model

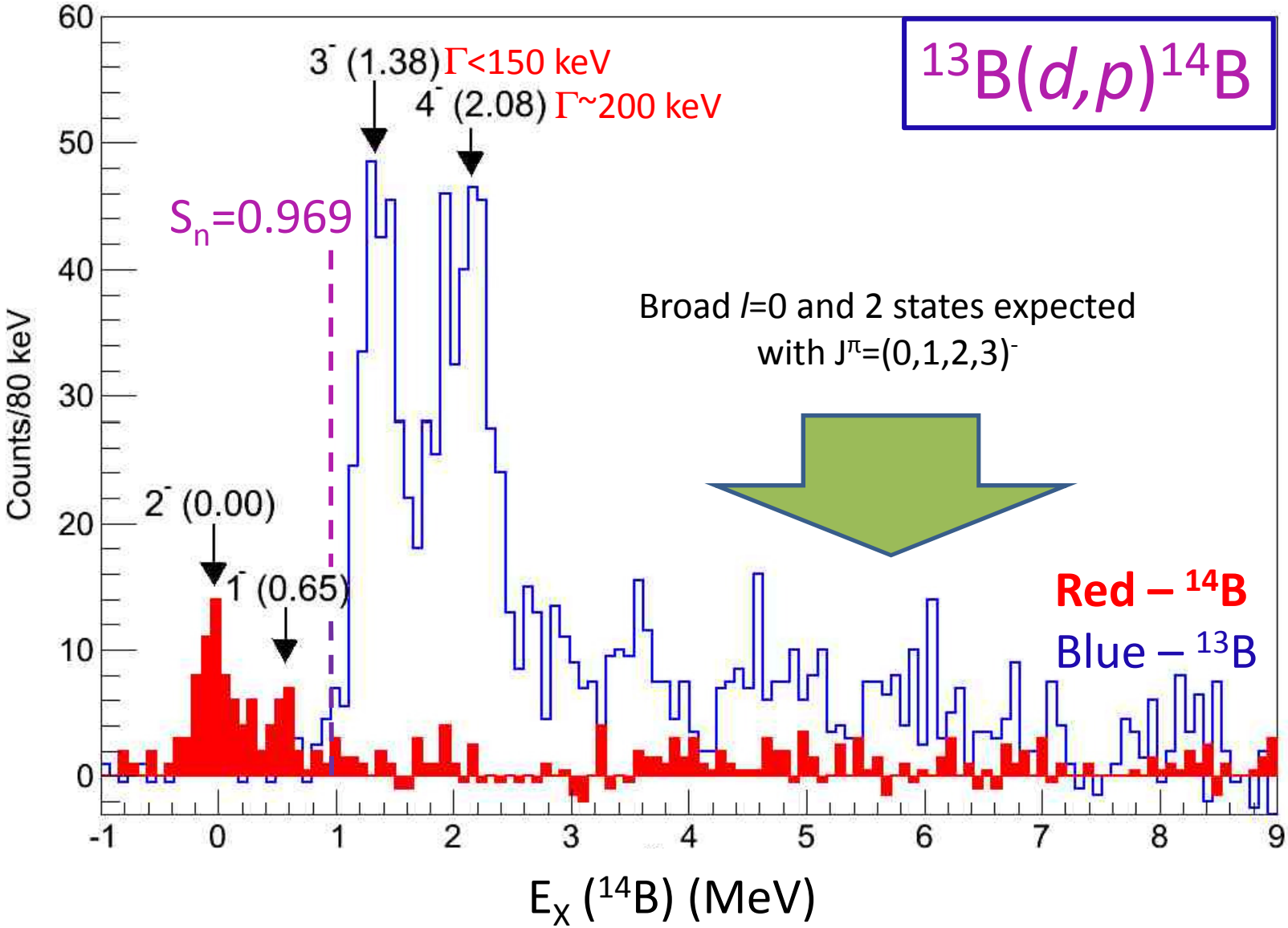
Blue: L=0

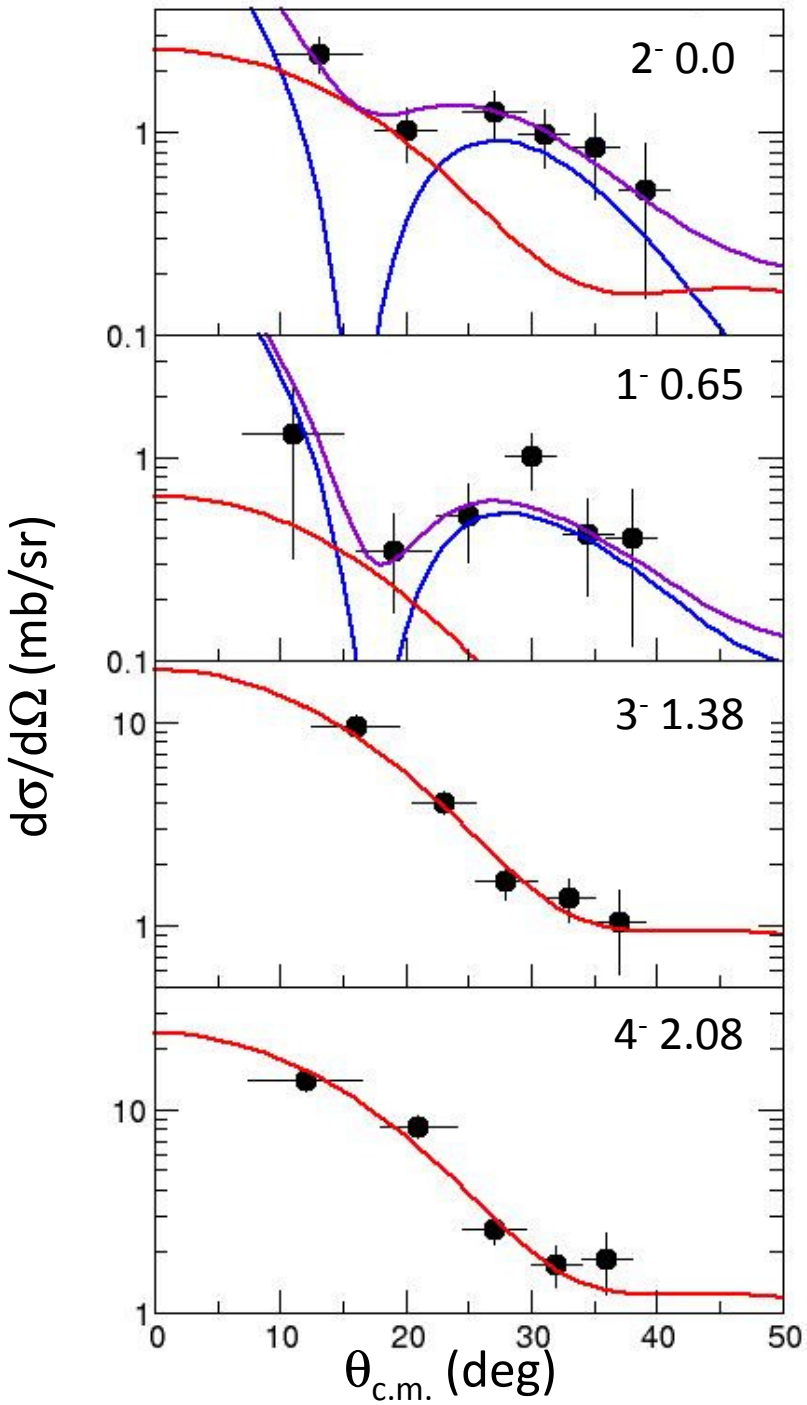
Red: L=2

Agreement for SF is excellent!
No need for exotica

PRL **105**, 132501 (2010)

Preliminary excitation-energy spectrum





Preliminary

$^{13}B(d,p)^{14}B$ angular distributions

Blue: L=0

Red: L=2

Violet: L=0 + L=2

$2^-(0.00)$: S_0=.71 S_2=.17

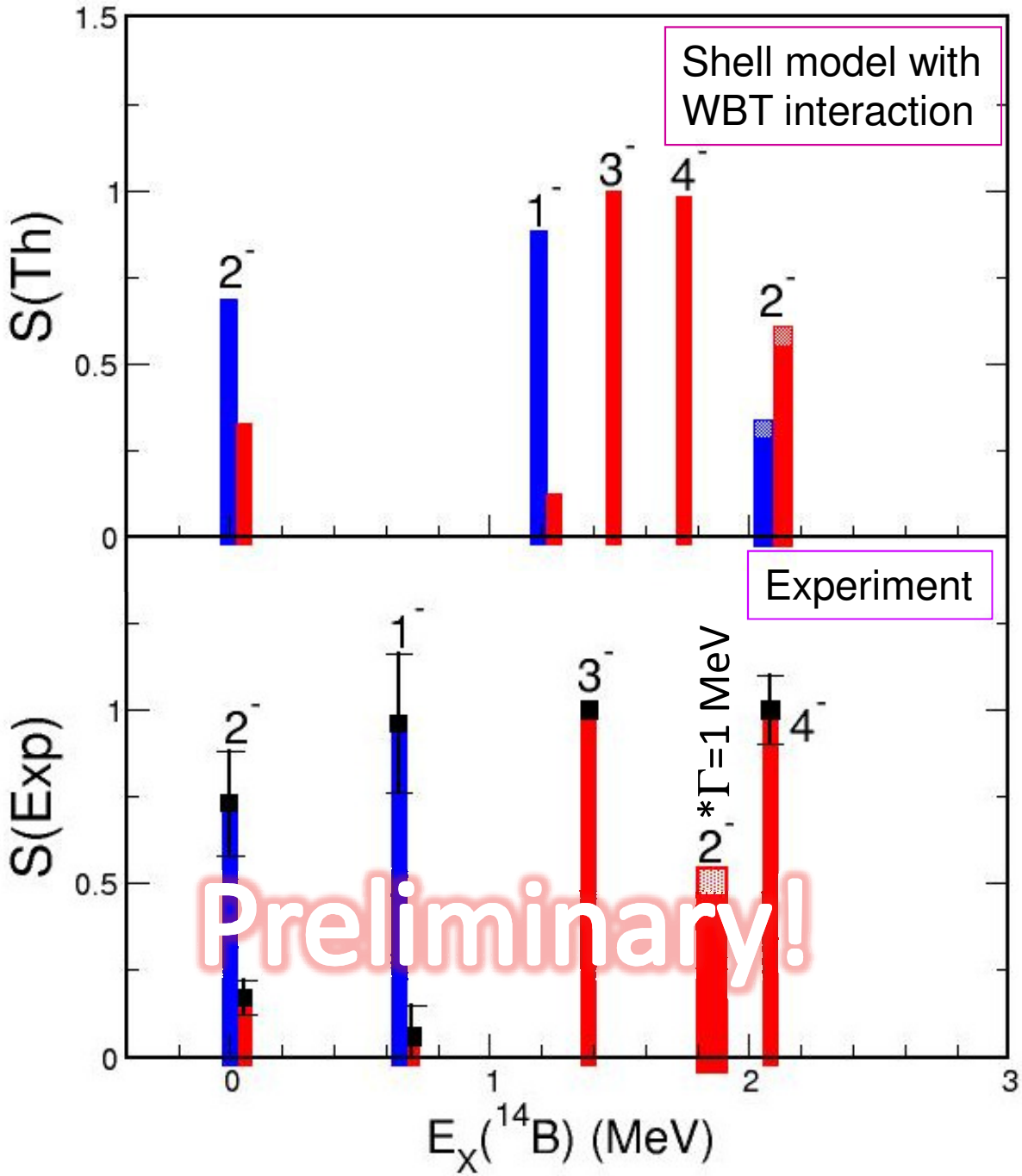
$1^-(0.65)$: S_0=0.96 S_2=.06

$3^-(1.38)$: S_2=1.00 (fixed)

$4^-(2.08)$: S_2=1.00

OMPs fit 30 MeV d+^{12}C, p+^{12,13}C elastic scattering

$^{13}B(d,p)^{14}B$ Spectroscopic factors



Excitation energies and relative spectroscopic factors from the shell model

Blue: L=0, $1s_{1/2}$

Red: L=2, $0d_{5/2}$

2^- mixed L=0+2,
1^- pure L=0
Reasonable agreement
But *caveat emptor*!

Summary

- HELIOS provides a new approach to studying reactions in inverse kinematics
- Alleviates problems with light particle identification and gives improved excitation-energy resolution and straightforward determination of CM quantities
- Around N=8, (*d,p*) nicely probes the evolution of the $1s_{1/2}$-$0d_{5/2}$ orbitals and the p-n/n-n residual interactions
- $^{14}B(1^-)$ (S_n=.319 MeV) is mostly *s*-wave, so is as good or better a halo state than $^{11}Li_{g.s.}$ or $^{11}Be_{g.s.}$.
- Structure aspects seem reasonably well in hand, BUT: we still worry about DWBA and weakly (or un-) bound *s* states.

Acknowledgements

The HELIOS Collaboration

S. Bedoor, J. C. Lighthall, S. T. Marley, D. Shetty, J. R. Winkelbauer (SULI student), A. H. Wuosmaa

Western Michigan University

B. B. Back, S. Baker, C. M. Deibel, C. R. Hoffman, B. Kay, H. Y. Lee, C. J. Lister, P. Mueller, K.E. Rehm, **J. P. Schiffer**, K. Teh, A. Vann (SULI student)

Argonne National Laboratory

S. J. Freeman

University of Manchester

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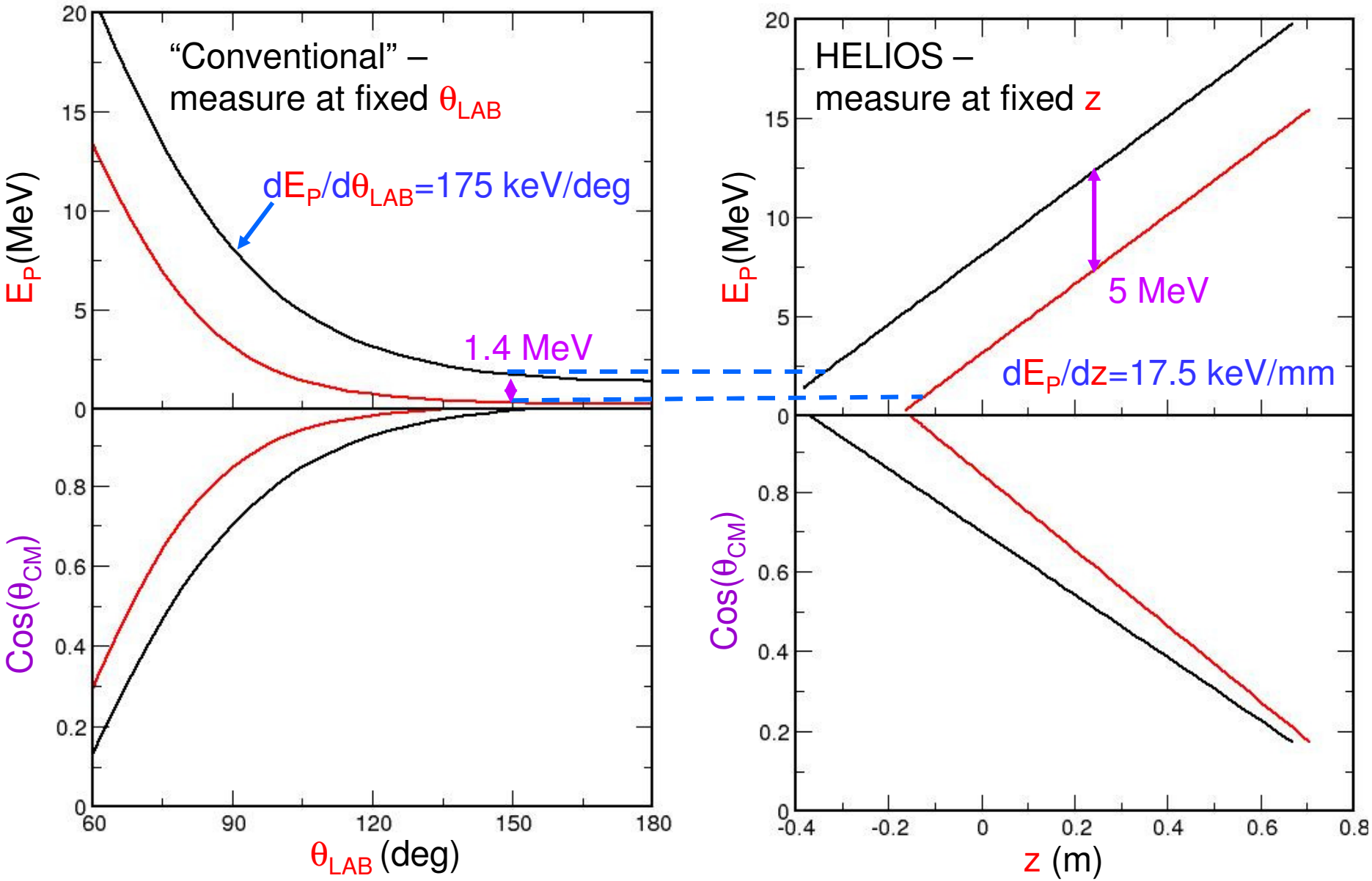
Also, special thanks to:

N. Antler, Z. Grelewicz, S. Heimsath, J. Rohrer, J. Snyder

Advantages to the HELIOS approach for (*d,p*)



Empirical v(*sd*)^2 residual interaction for 0^+

$$|0_1^+> = \alpha\,|(1s_{1/2})^2> + \beta\,|(0d_{5/2})^2>$$
$$|0_2^+> = -\beta\,|(1s_{1/2})^2> + \alpha\,|(0d_{5/2})^2>$$

$$\alpha = \sqrt{S(0_1^+)\times[J_f]/[J_i]} = 0.55$$
$$\beta = \sqrt{S(0_2^+)\times[J_f]/[J_i]} = 0.84$$

$[J]=2J+1$

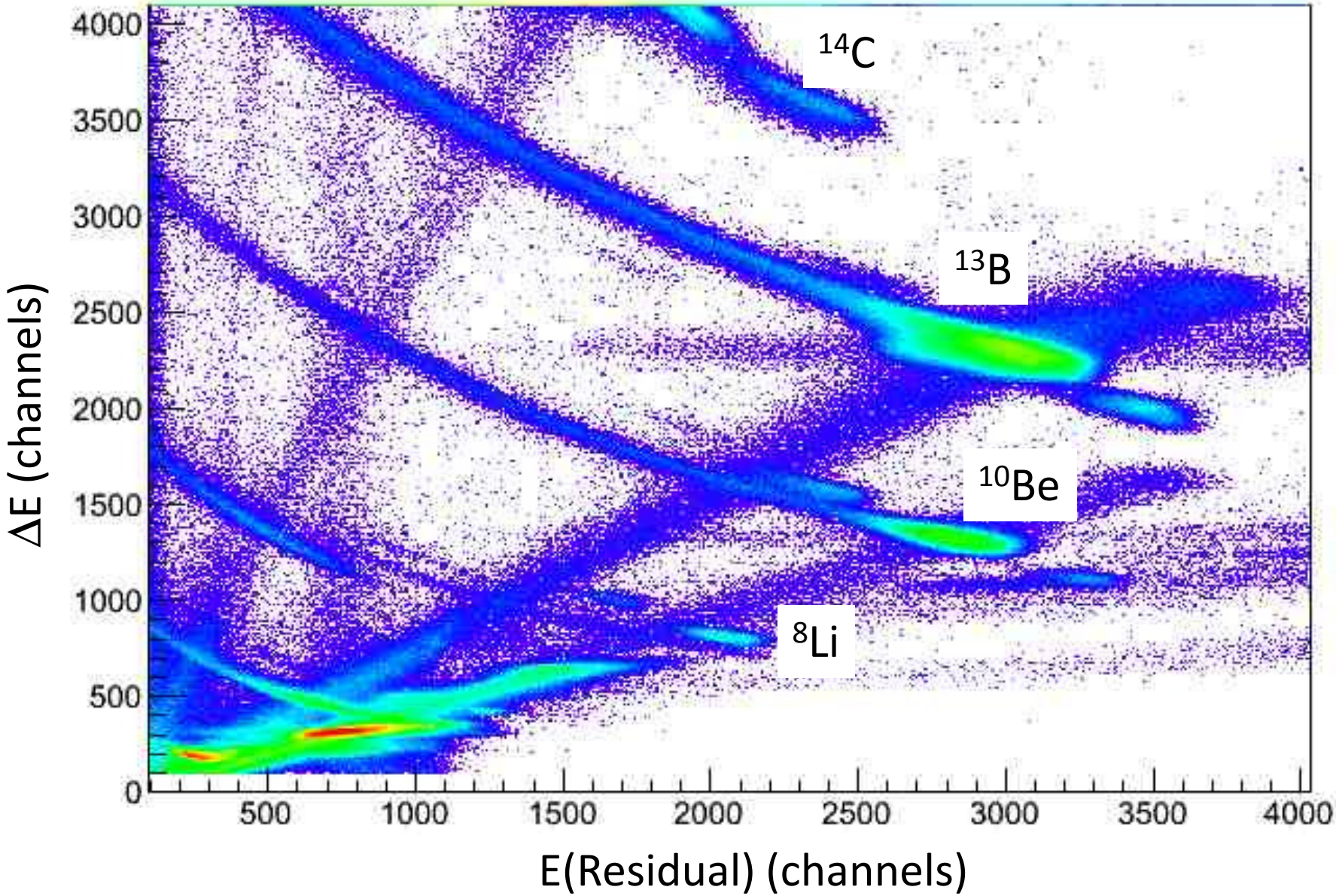
$$\begin{pmatrix} E^0_{1/2} + \delta_{1/2;1/2} & \delta_{1/2;5/2} \\ \delta_{1/2;5/2} & E^0_{5/2} + \delta_{5/2;5/2} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = E_X \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

Single-particle energies E^0 from ^{15}C.

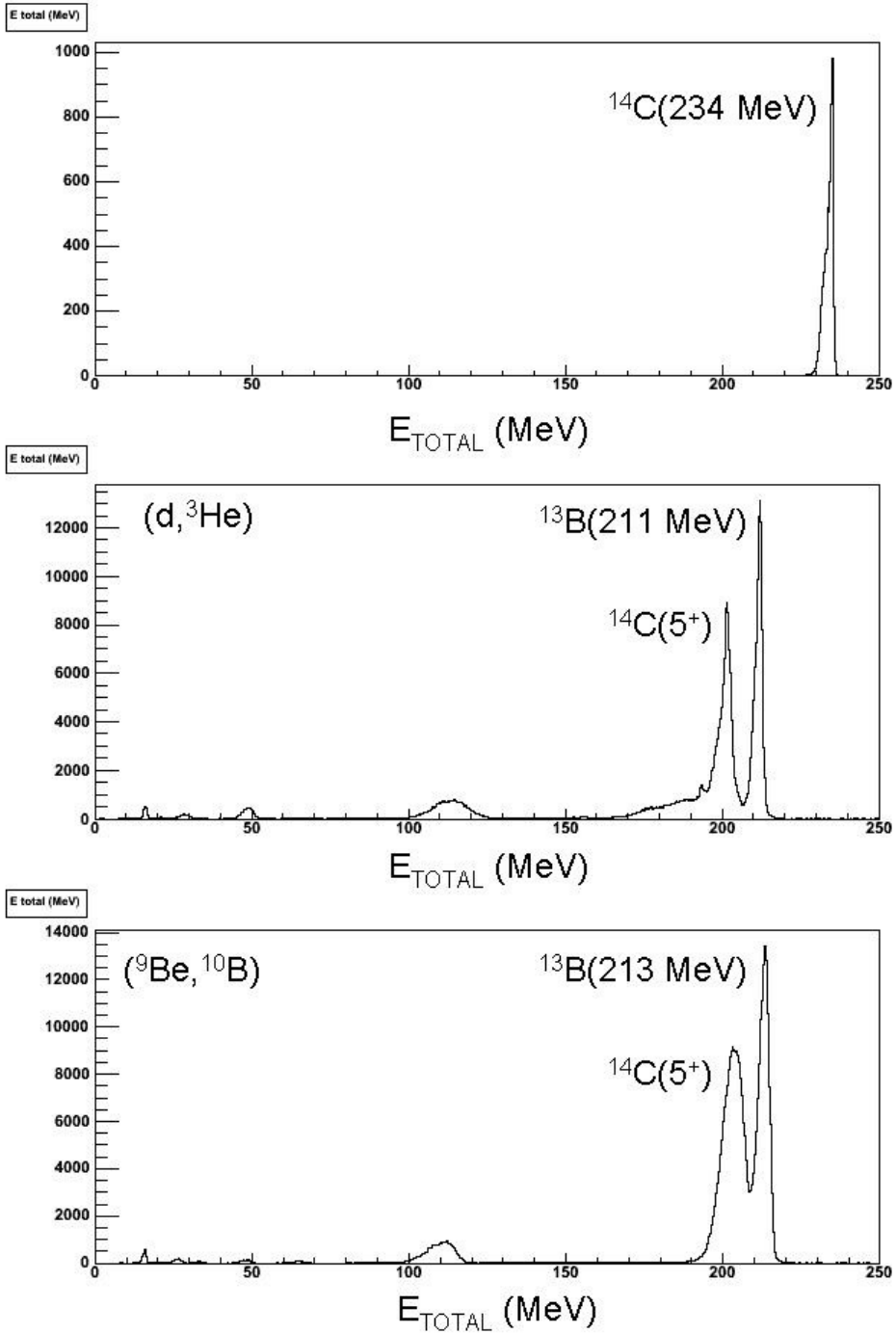
$< j_1 j_2 \| v \| j_1' j_2' >$	$(j_1 j_2, j_1' j_2')$ $(1/2\ 1/2, 1/2\ 1/2)$	$(5/2\ 5/2, 5/2\ 5/2)$	$(1/2\ 1/2, 5/2\ 5/2)$
Exp	-0.92(28)	-3.60(28)	-1.39(12)
LSF	-1.54	-2.78	-1.72
WBP	-2.12	-2.82	-1.32

PRL **105**, 132501 (2010)

^{13}B and friends… from $^{14}C+^{9}Be$



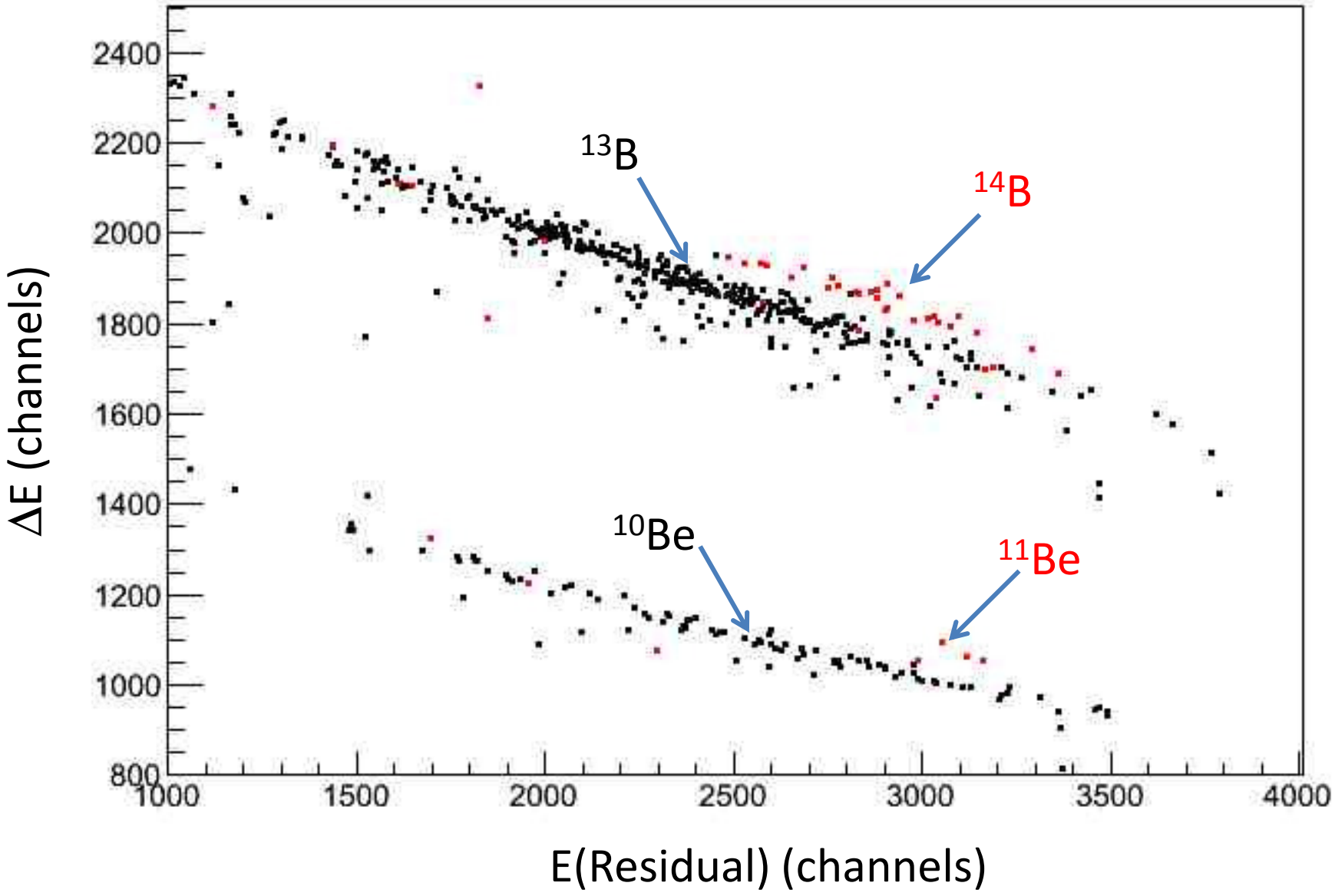
^{13}B beam quality



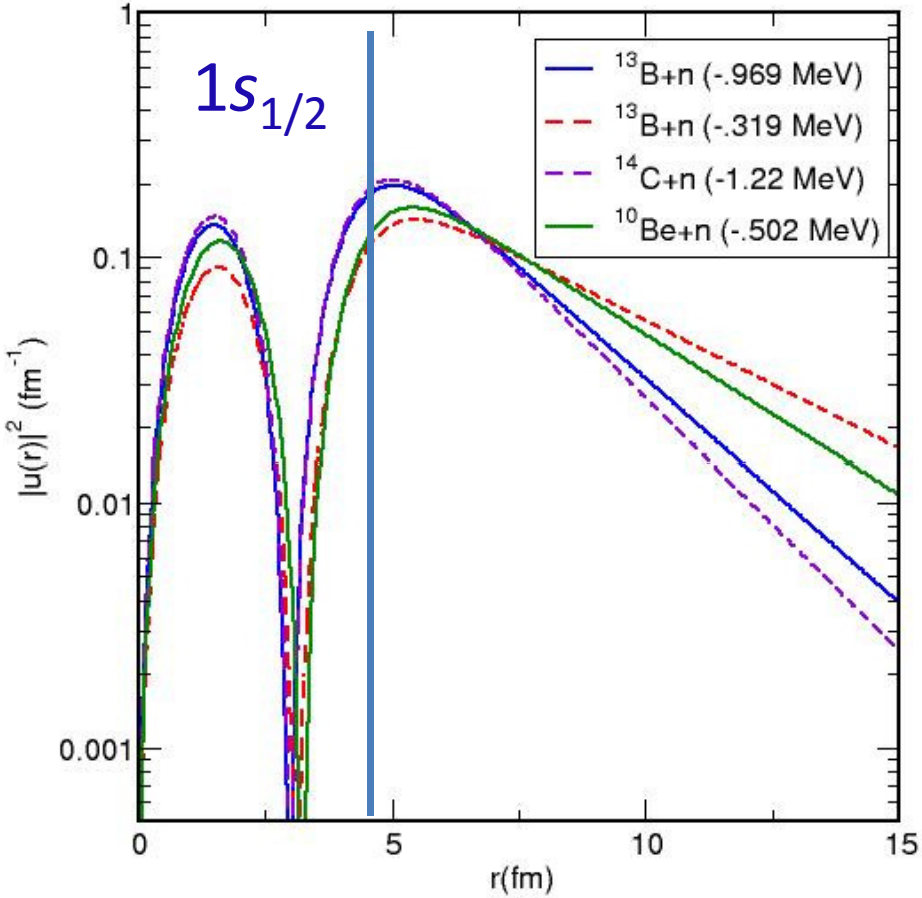
From $d(^{14}C,^{13}B)^{3}He$
$2X10^{4}$ pps

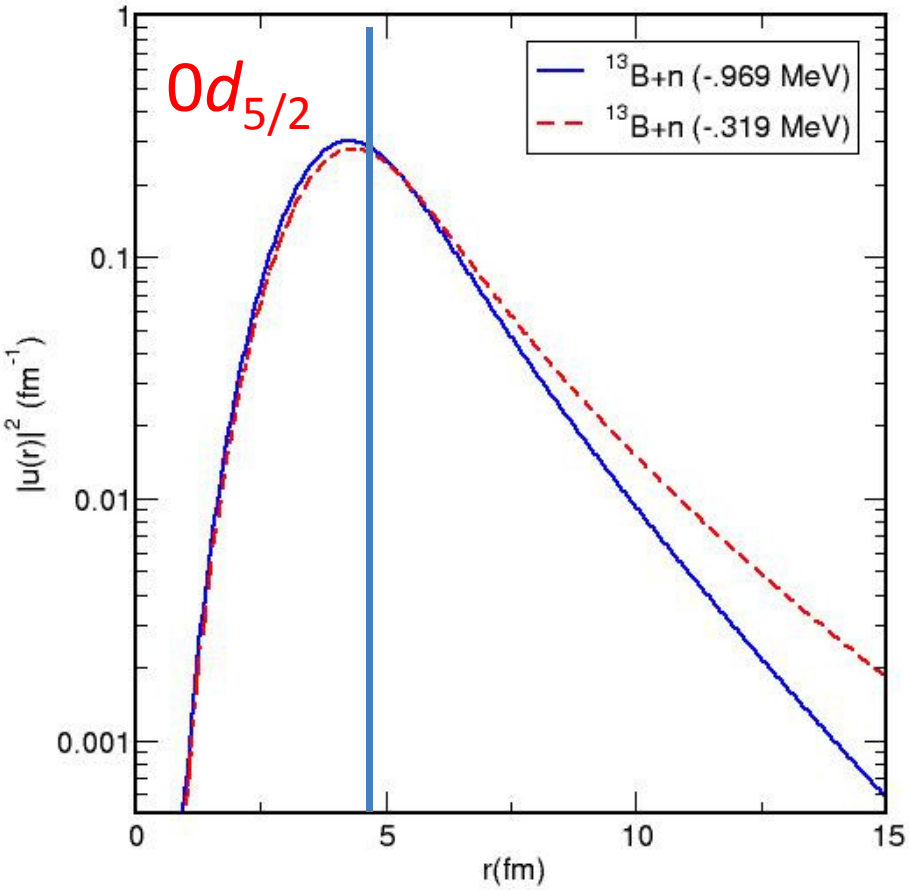
From $^{9}Be(^{14}C,^{13}B)^{10}B$
$4X10^{4}$ pps

Recoil particle identification



$1s_{1/2}$ and $0d_{5/2}$ neutron form factors



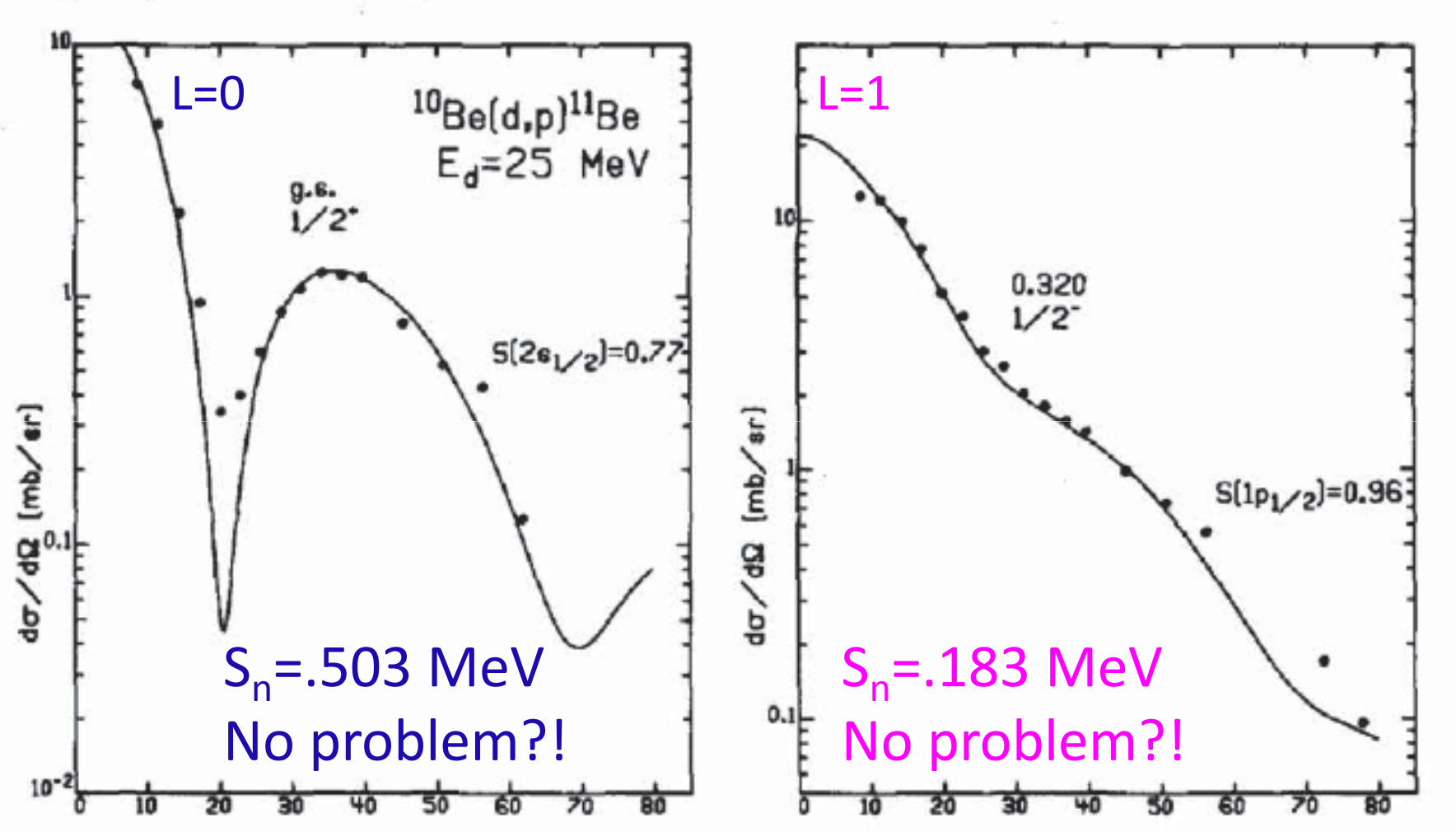


Woods-Saxon potential, r_0=1.35, a=.6, V_0 adjusted for BE

s-wave tail may cause problems for DWBA!

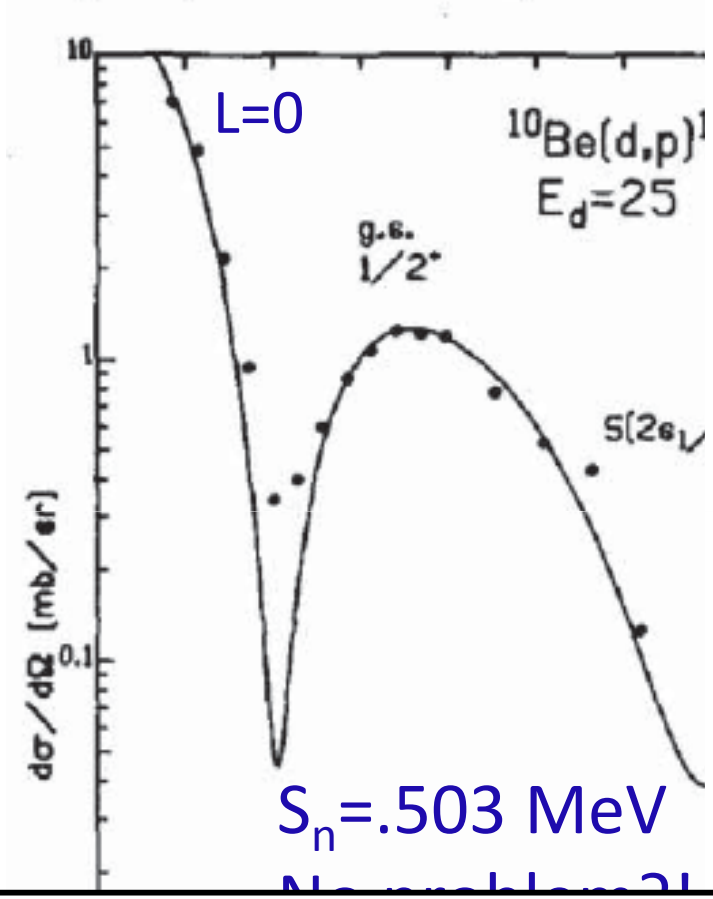
R. Huby, J. Phys. G **11**, 931 (1985)

But: Don't forget history- $^{10}Be(d,p)^{11}Be$

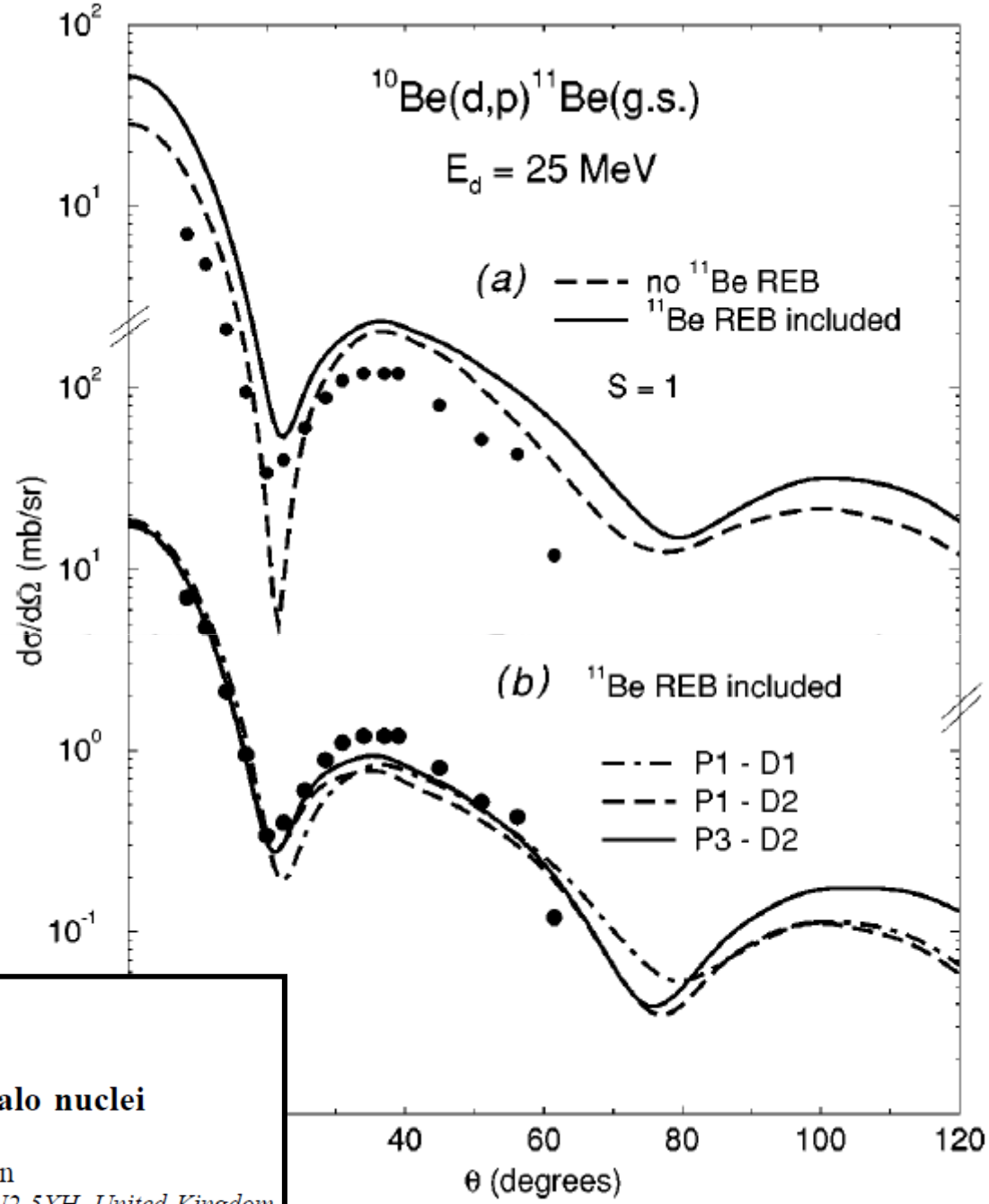


Zwieglinski, Benenson, Robertson, Coker – NP **A315**, 124 (1979)

But: Don't forg



S_n=.503 MeV



VOLUME 59, NUMBER 3

Deuteron stripping and pick-up on halo nuclei

N. K. Timofeyuk* and R. C. Johnson
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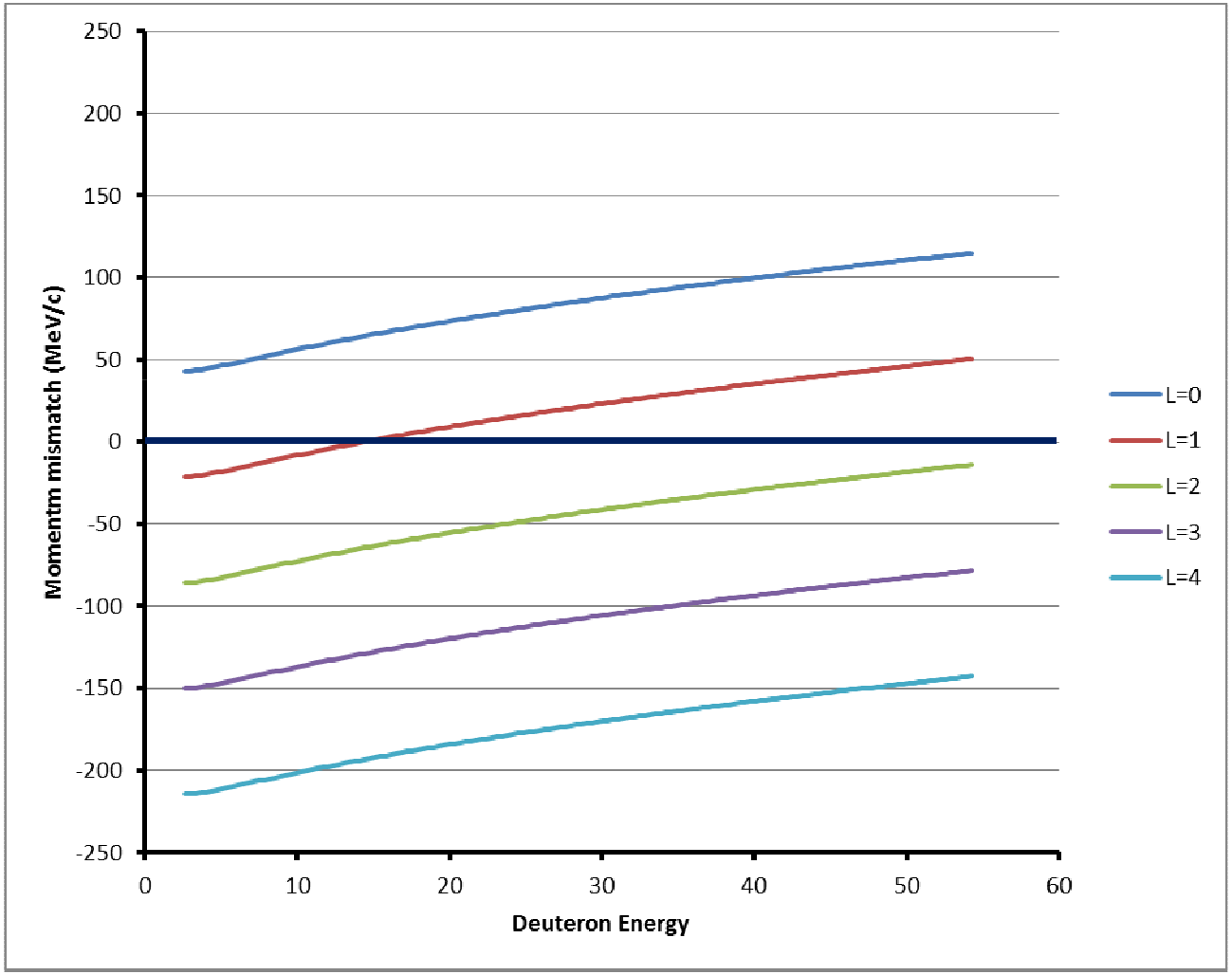
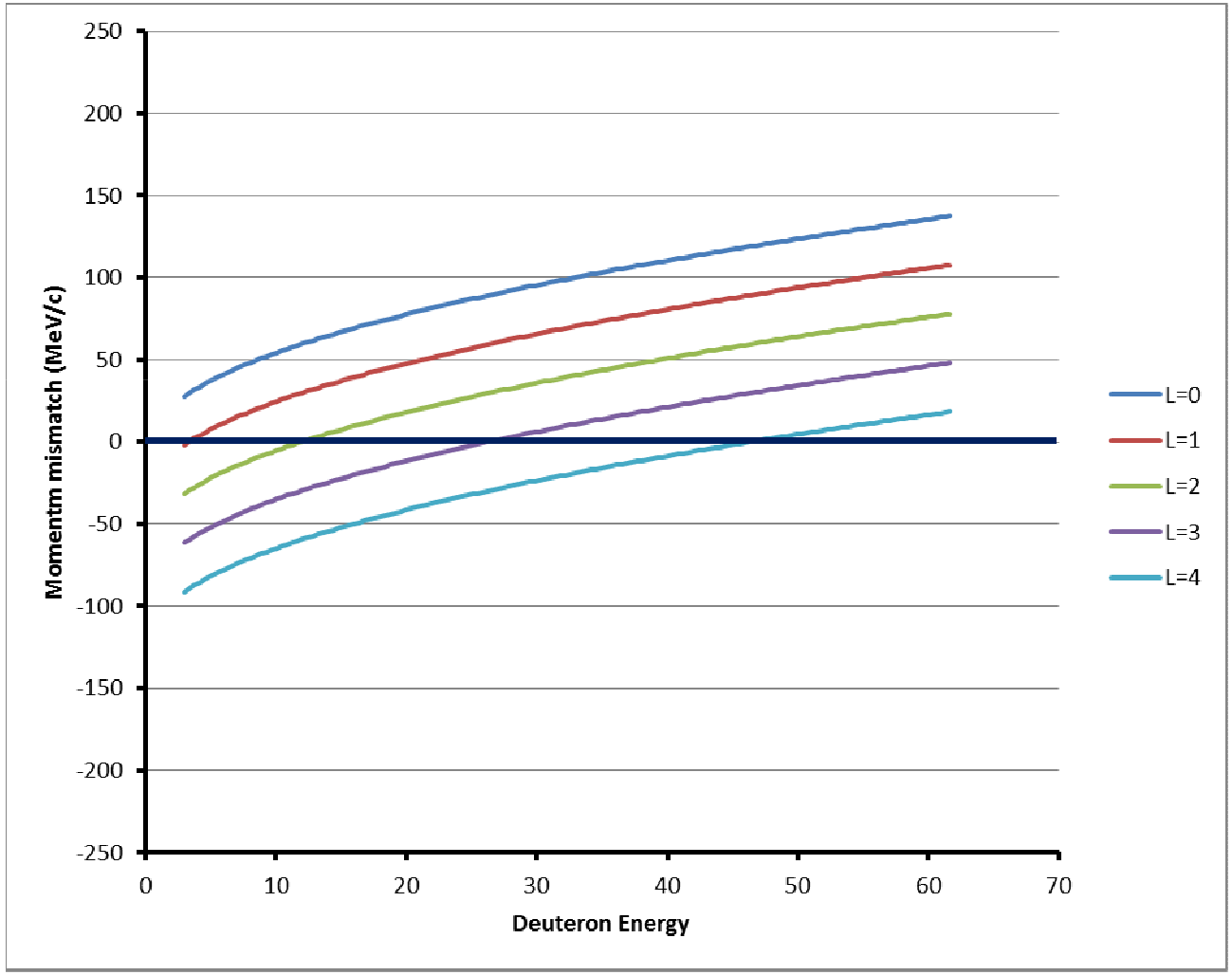
(Received 10 September 1998)

(*d,p*) momentum mismatch at 0° (A_{tgt}=13)



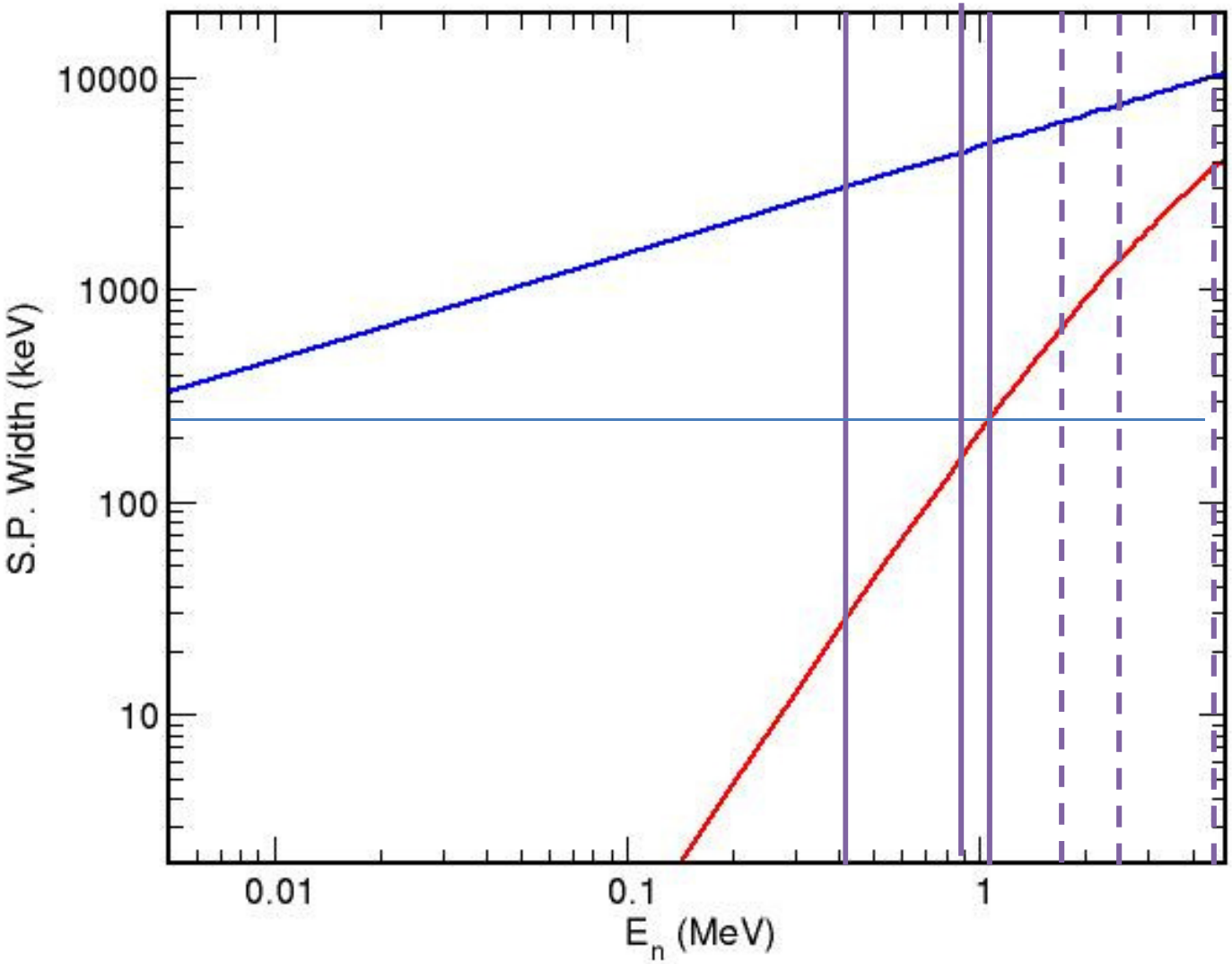
$\Delta q(1\hbar)$~65 MeV/c

(*d,p*) momentum mismatch at 0° (A_{tgt}=132)



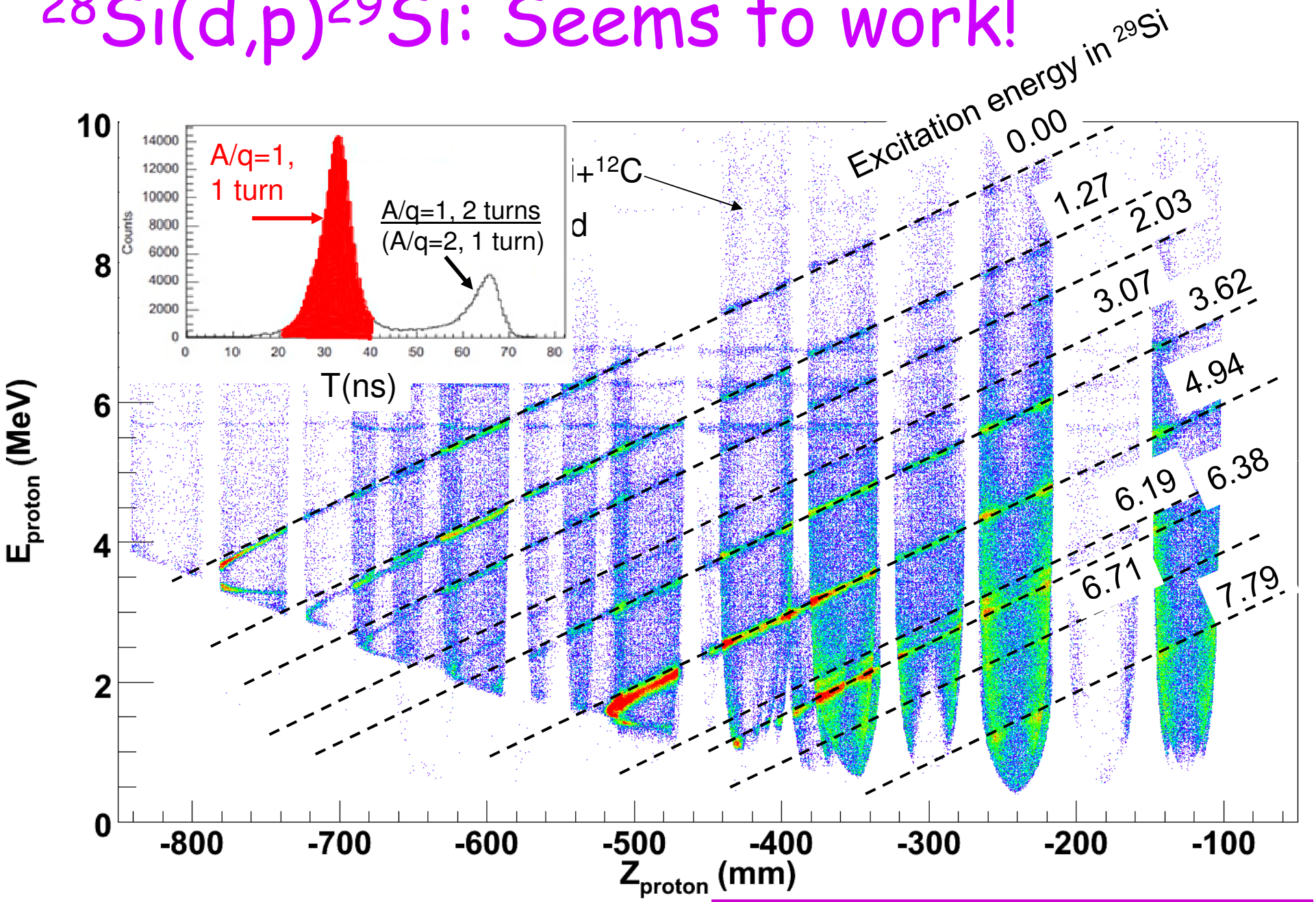
$\Delta q(1\hbar)$~30 MeV/c

Single-particle widths for $^{13}B+n$



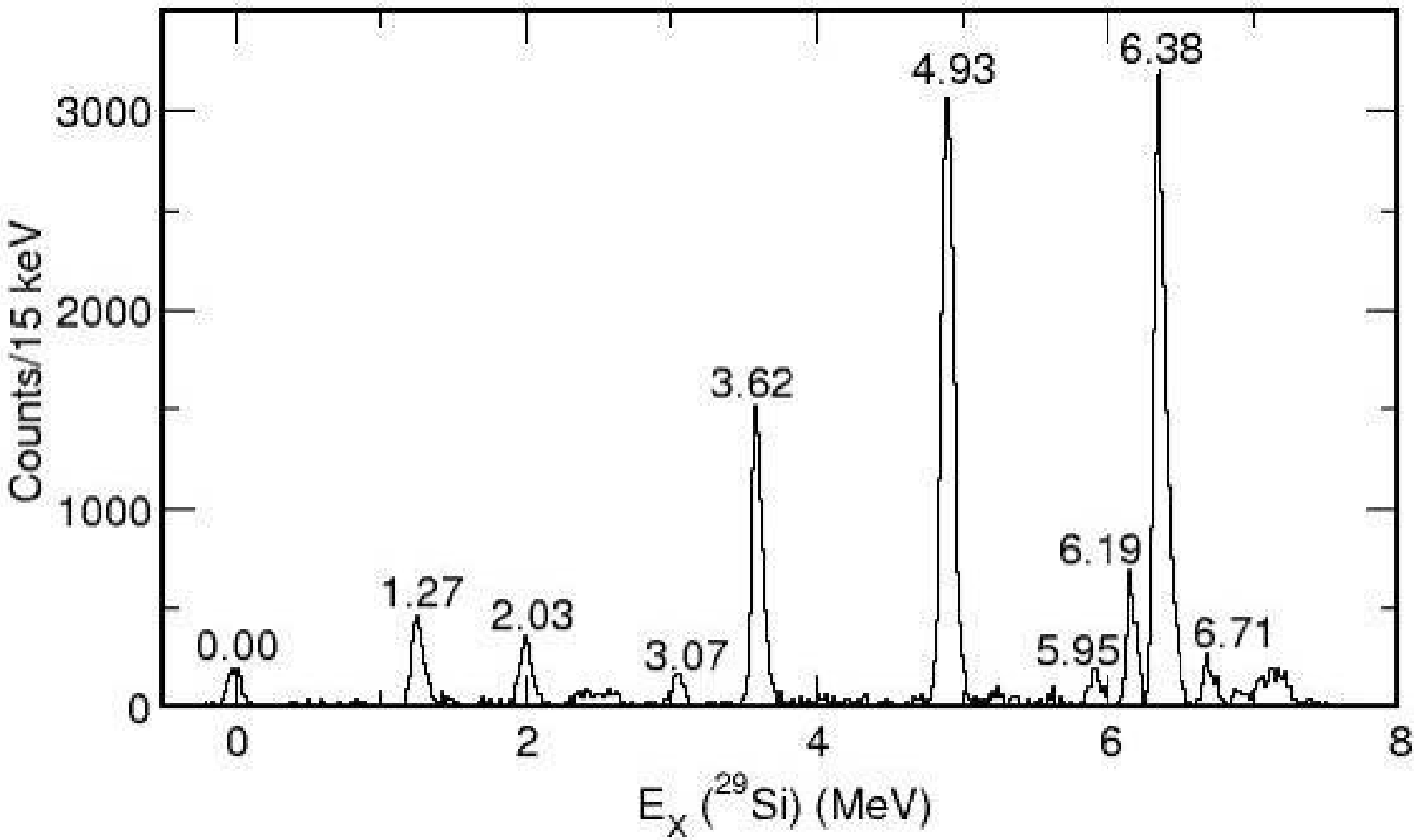
Spectrometer completed in August 2008

$^{28}Si(d,p)^{29}Si$: Seems to work!



J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

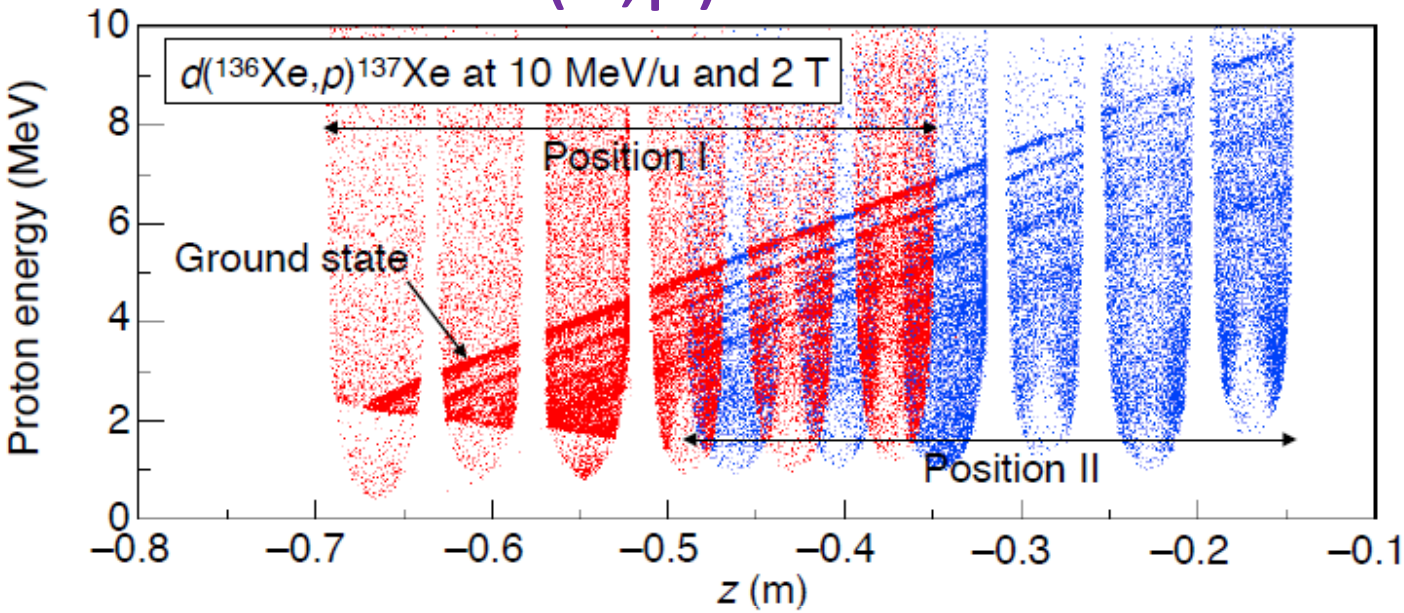
$^{28}Si(d,p)^{29}Si$ Excitation-energy spectrum

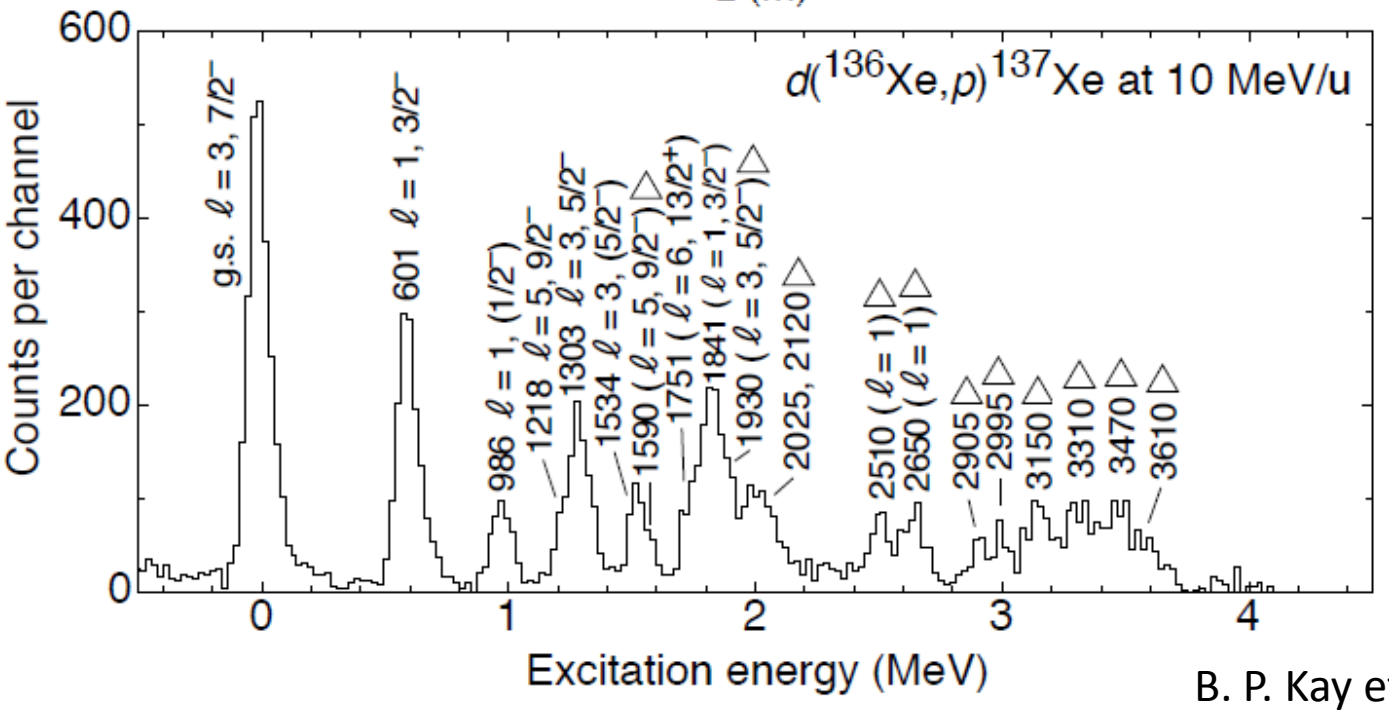


Typical resolution ~ 120 keV FWHM
Best resolution ~ 80 keV FWHM

J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

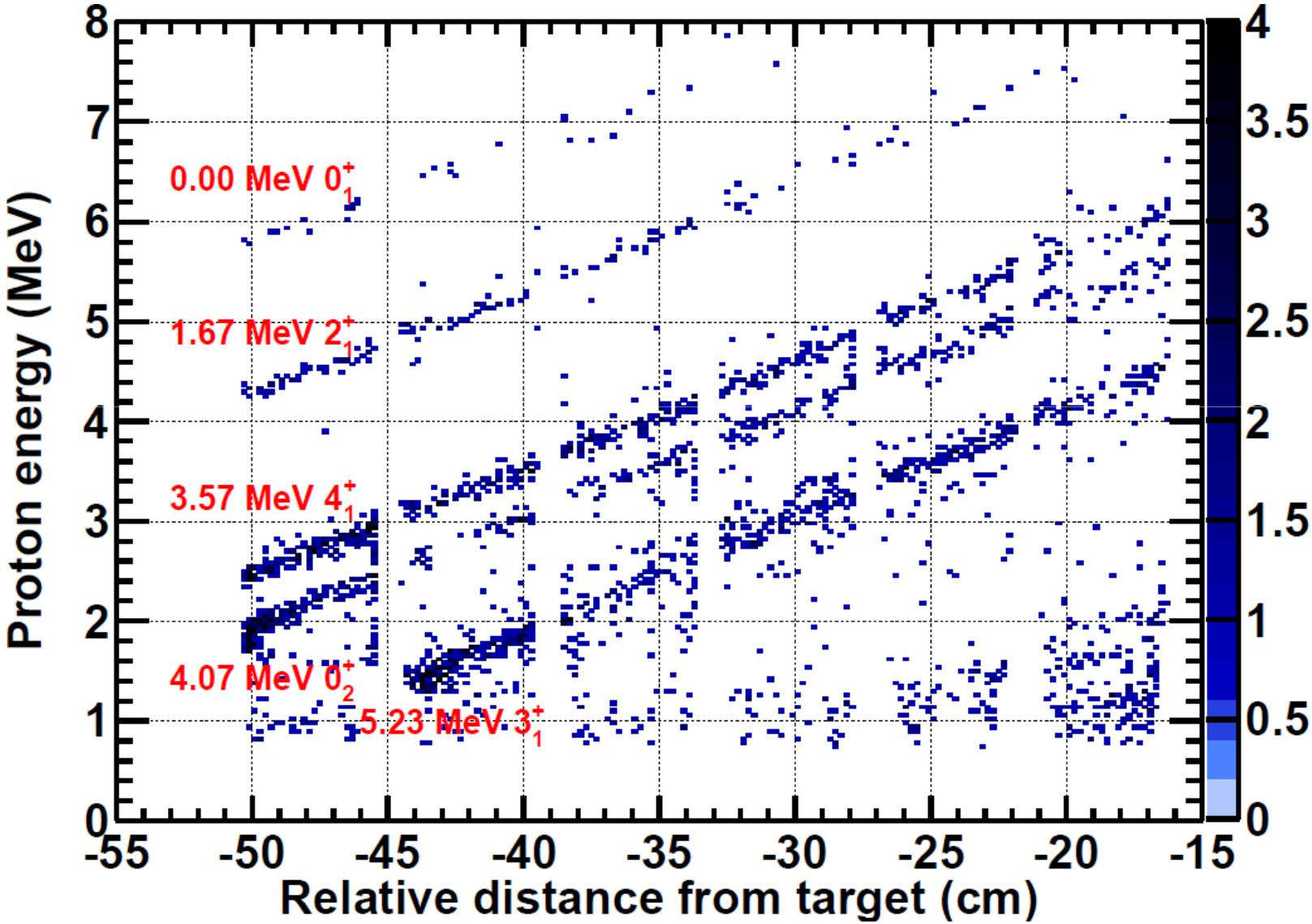
Towards ^{132}Sn(d,p)^{133}Sn with CARIBU





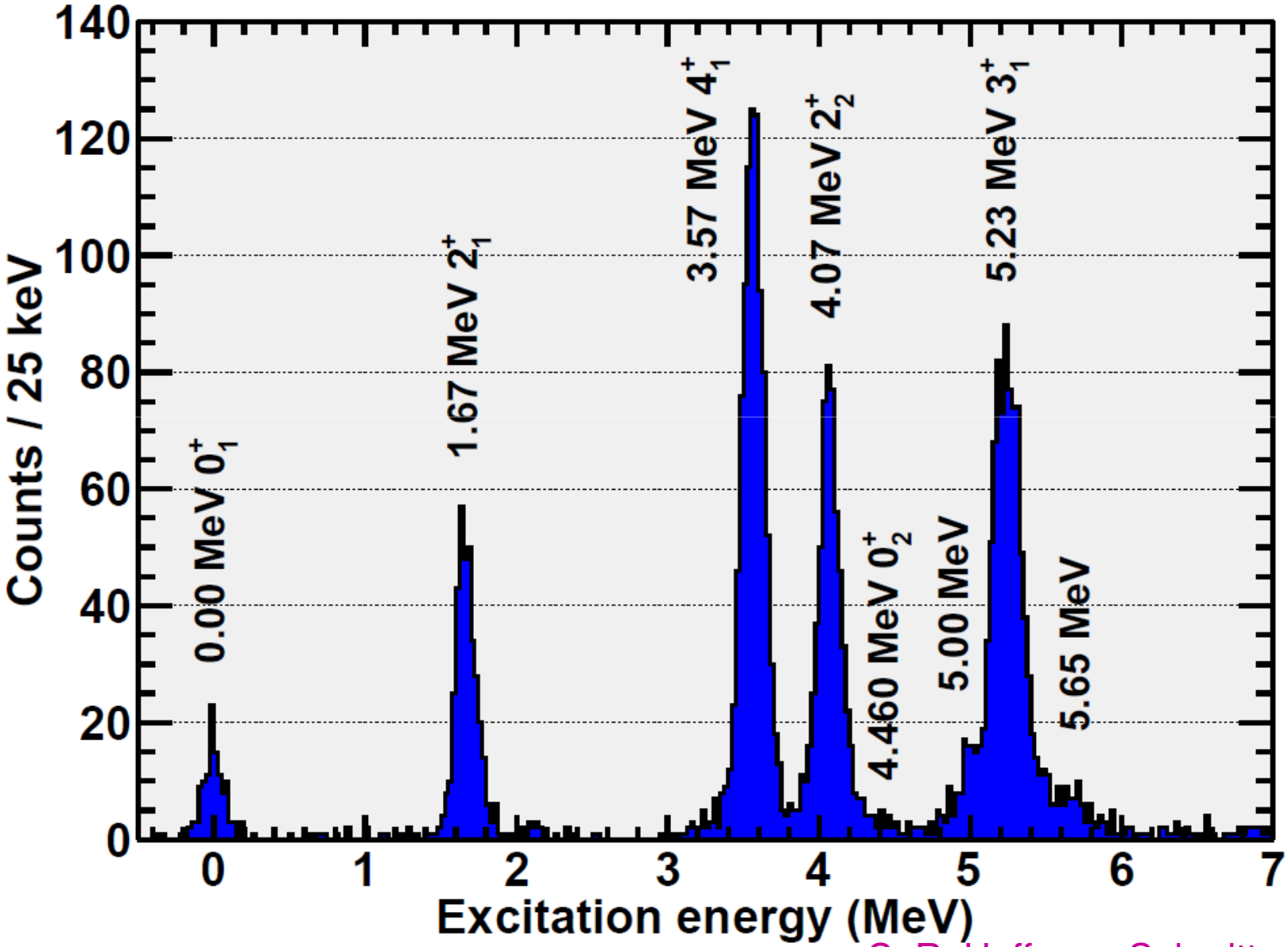
B. P. Kay et al, PRC *in press*

$^{19}O(d,p)^{20}O$: Further into the *sd* shell



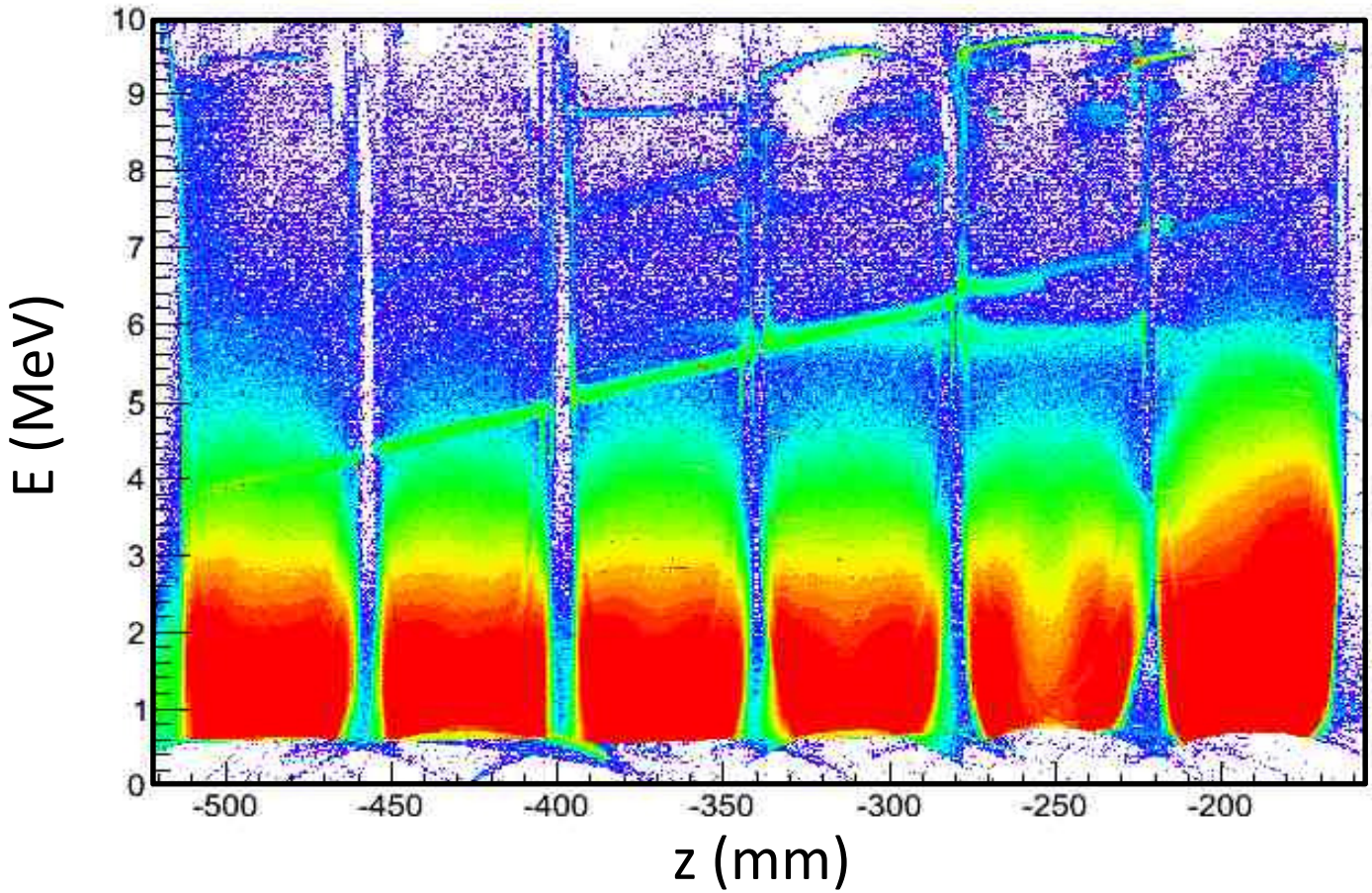
C. R. Hoffman, Submitted to PRC

$\nu(sd)+\nu(d_{5/2})^3{}_{5/2+}$ states in ^{20}O

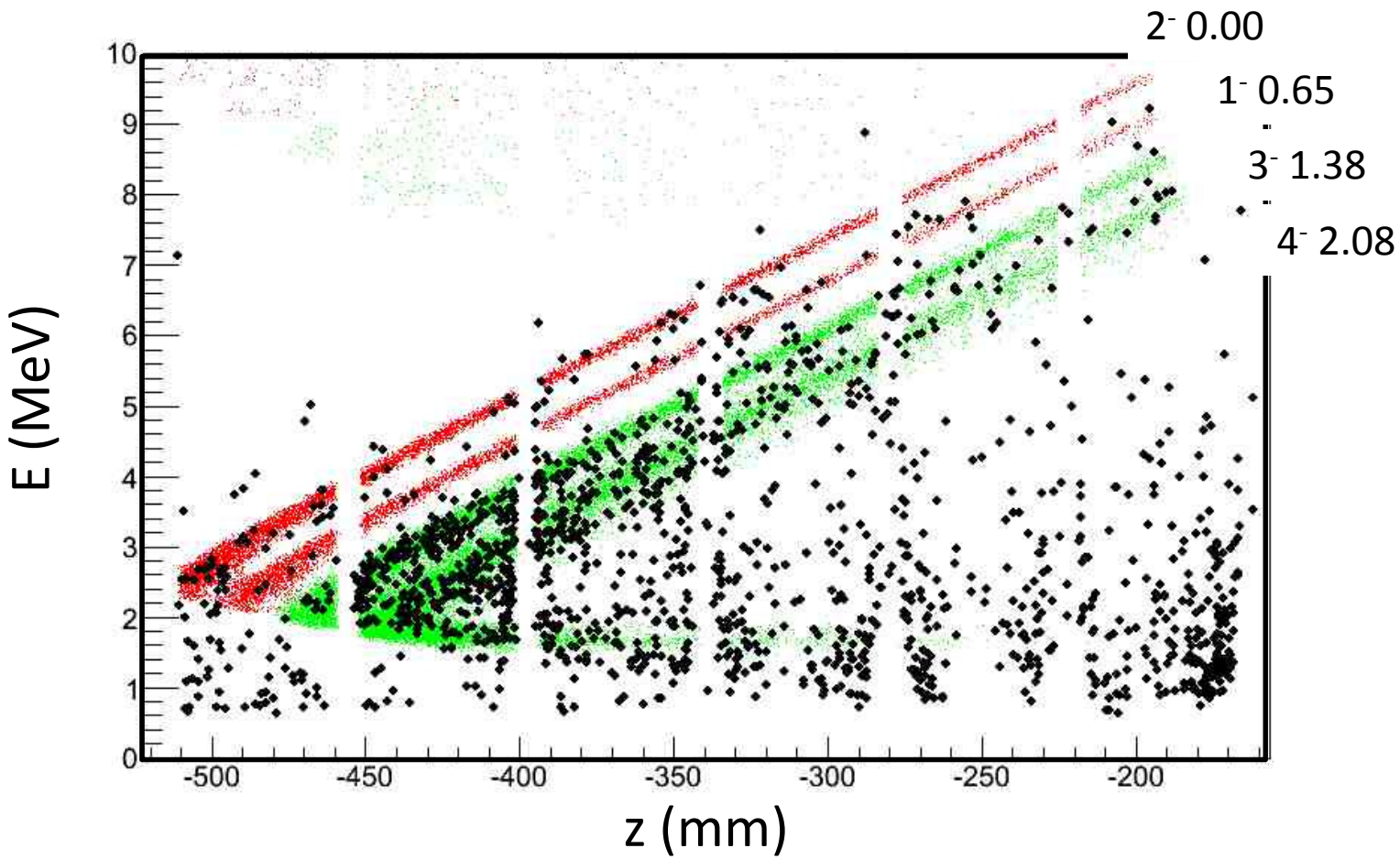


C. R. Hoffman, Submitted to PRC

Proton beam impurity: p-d elastics



E vs Z, data and Monte-Carlo



Red: n bound, p+^{14}B

Green: n-unbound p+^{13}B

^{13}B(d,p)^{14}B in HELIOS

PHYSICAL REVIEW C **81**, 021301(R) (2010)

Ab initio nuclear structure simulations: The speculative ^{14}F nucleus

P. Maris,[1] A. M. Shirokov,[1,2,*] and J. P. Vary[1]

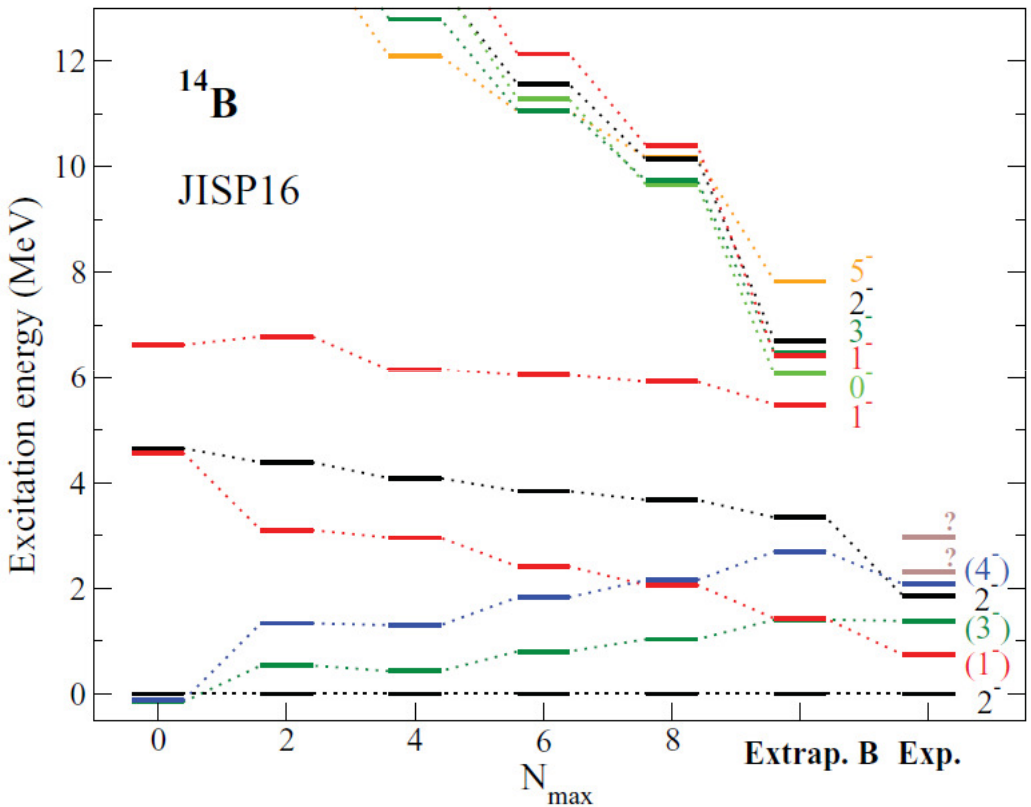
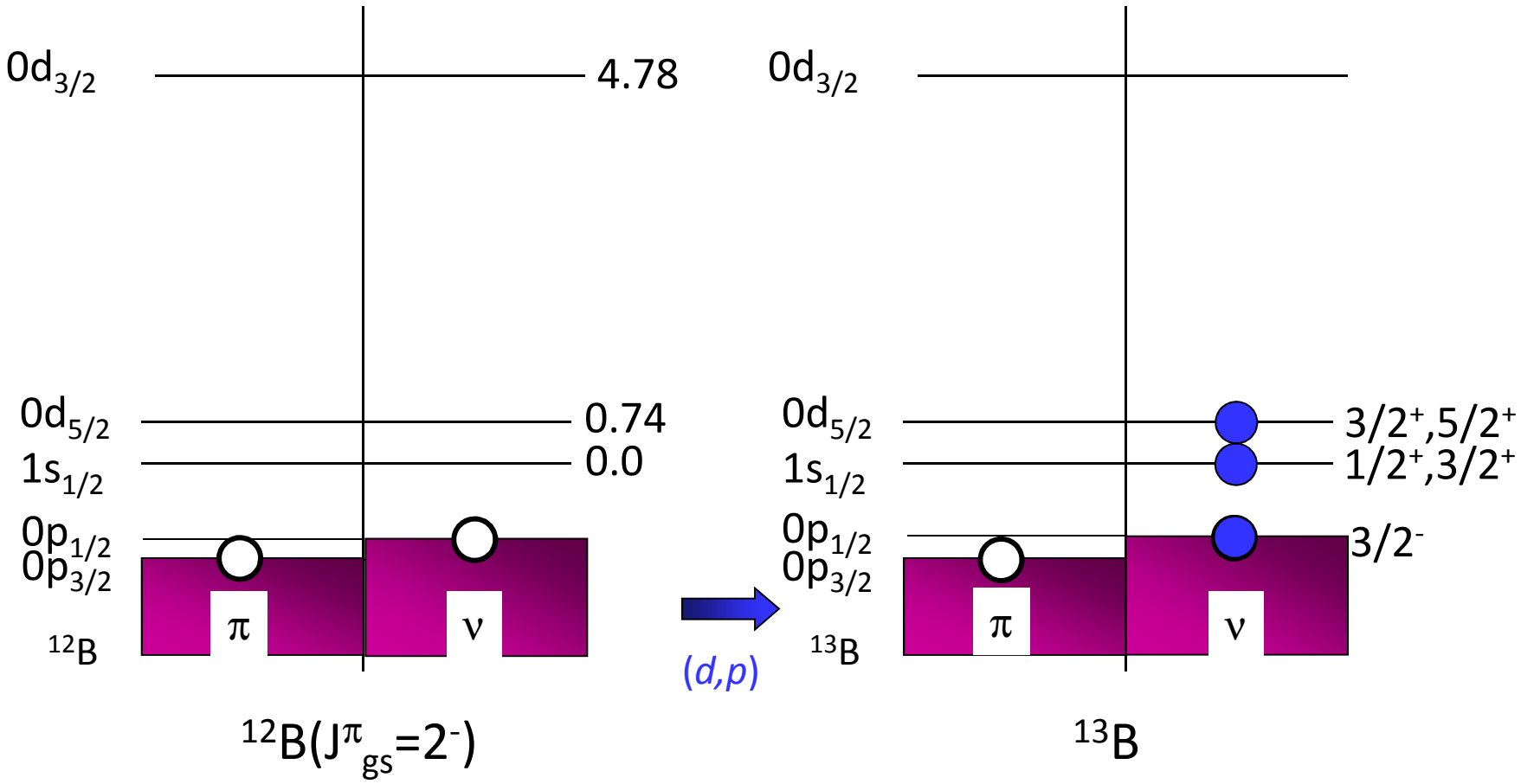


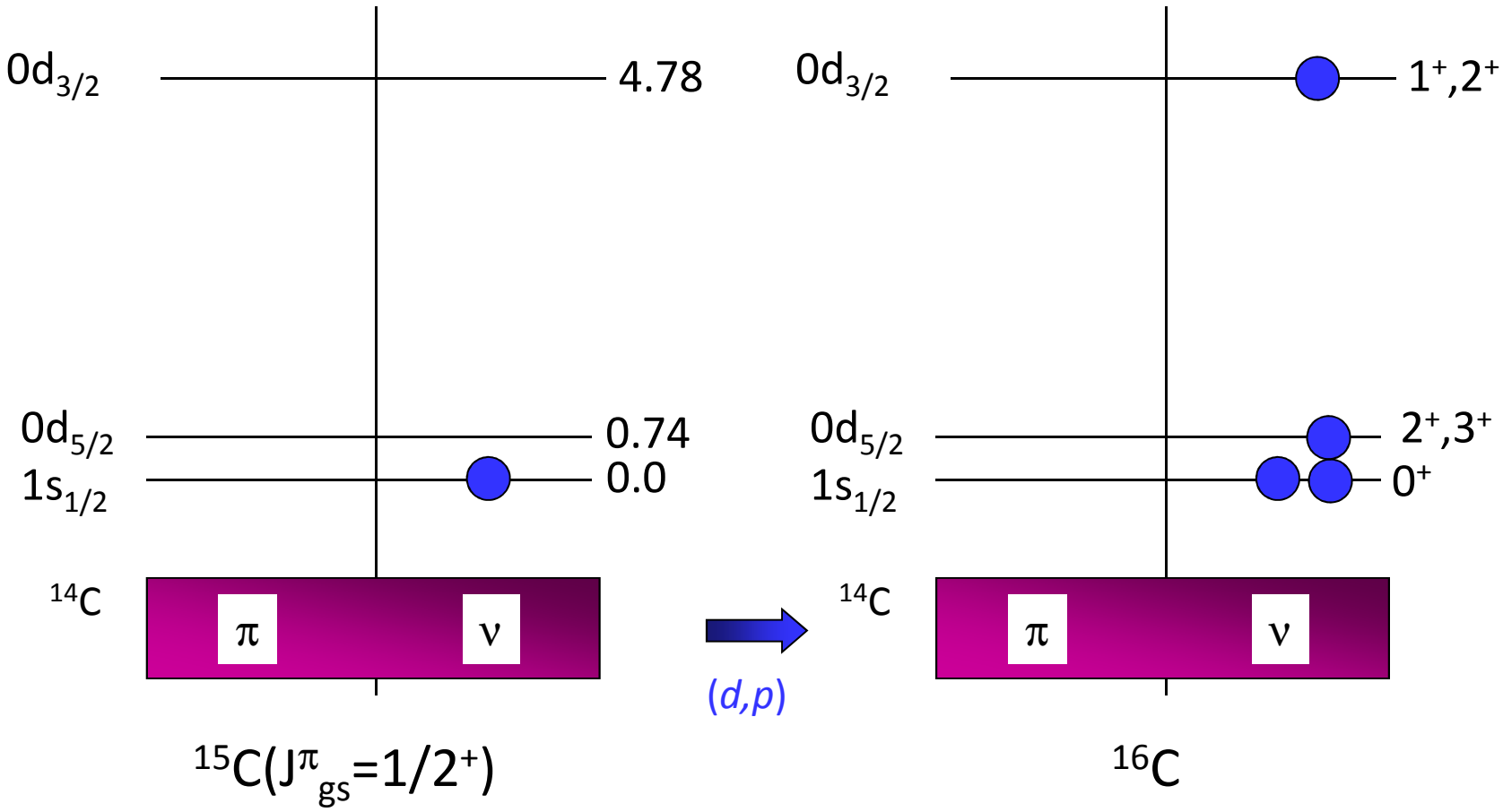
FIG. 3. (Color online) Negative-parity ^{14}B spectrum obtained with JISP16 at fixed $\hbar\Omega = 25$ MeV in successive basis spaces and extrapolated to infinite basis space using extrapolation B. Experimental (exp.) data are taken from Ref. [13].

Simple considerations for $^{12}B(d,p)^{13}B$



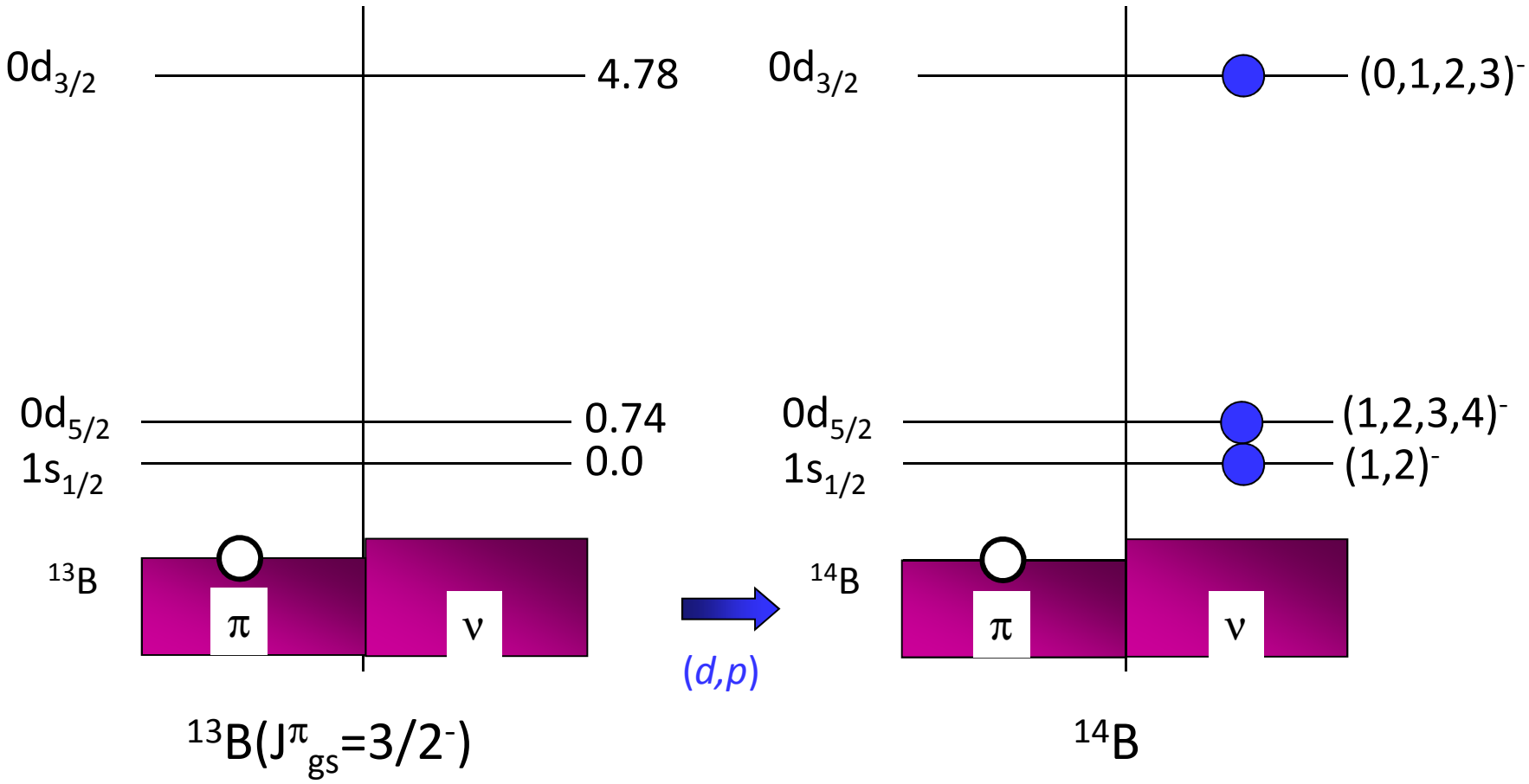
+ parity states are p-h excitations out of the *p* shell

Simple considerations for $^{15}C(d,p)^{16}C$



(*d,p*) samples $\nu(1s_{1/2})$ content of states in ^{16}C

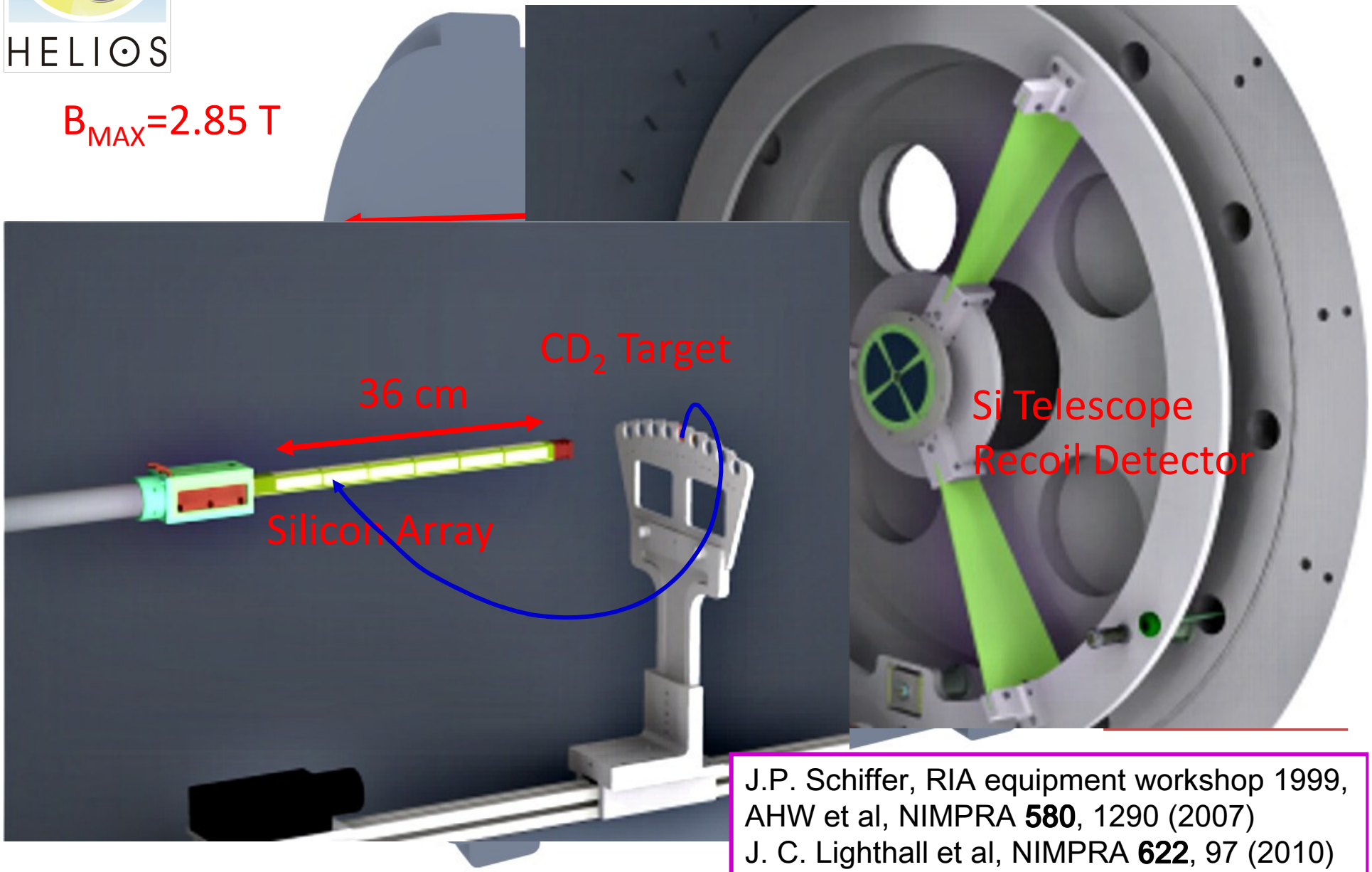
Simple considerations for $^{13}B(d,p)^{14}B$



(*d,p*) populates single-neutron states in ^{14}B

HELIcal Orbit Spectrometer -HELIOS

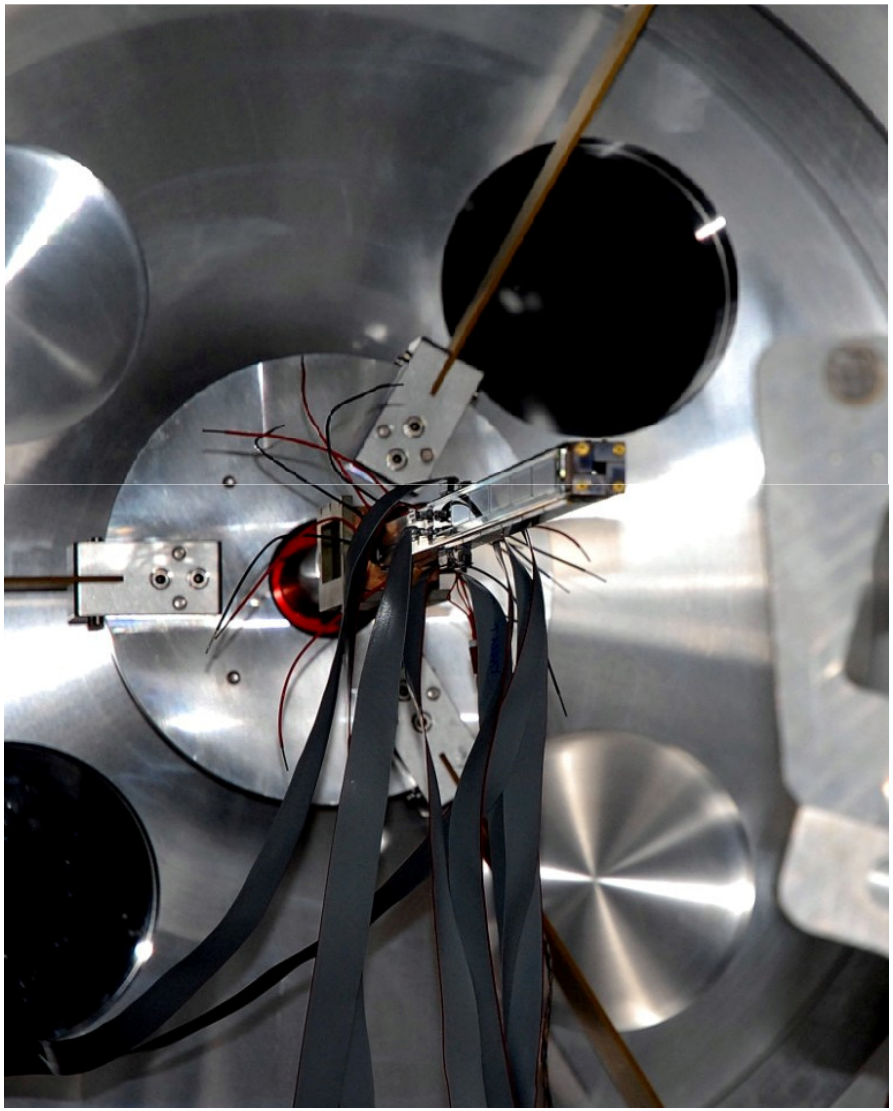
B_{MAX}=2.85 T

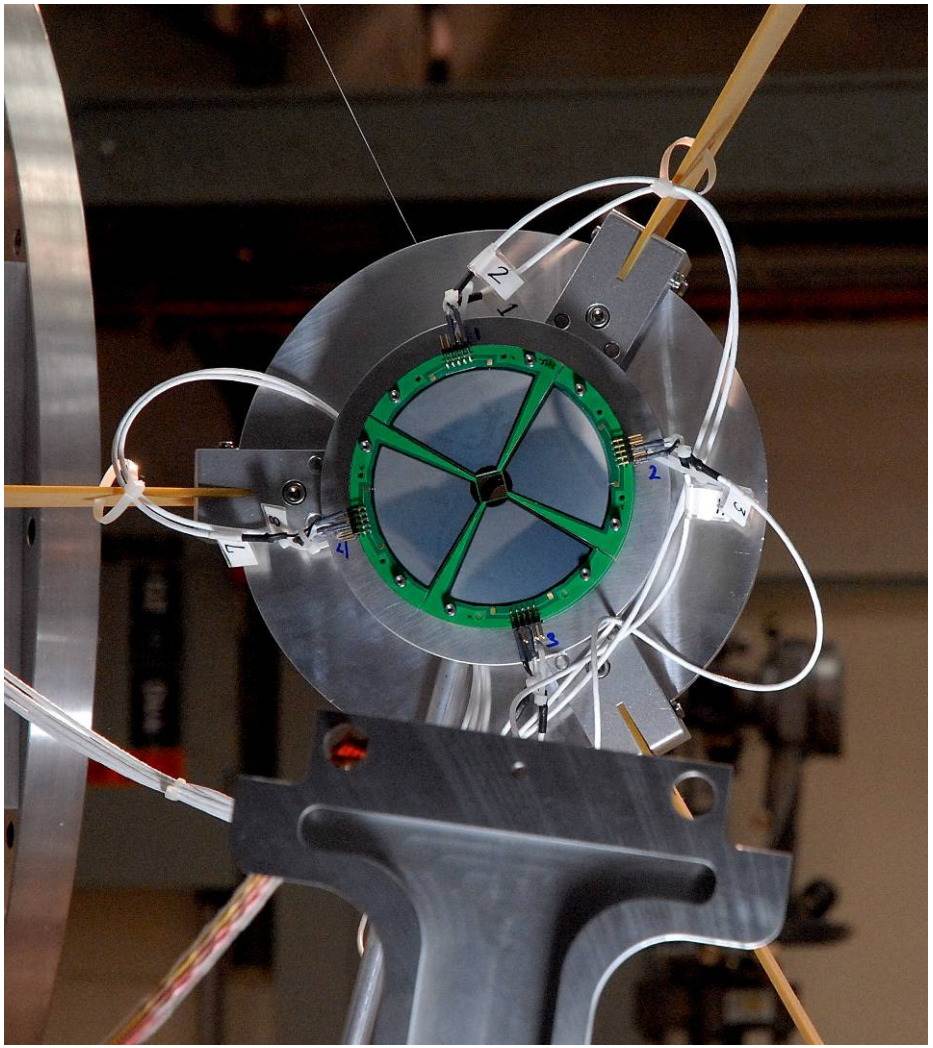


J.P. Schiffer, RIA equipment workshop 1999,
AHW et al, NIMPRA **580**, 1290 (2007)
J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

This you have seen...

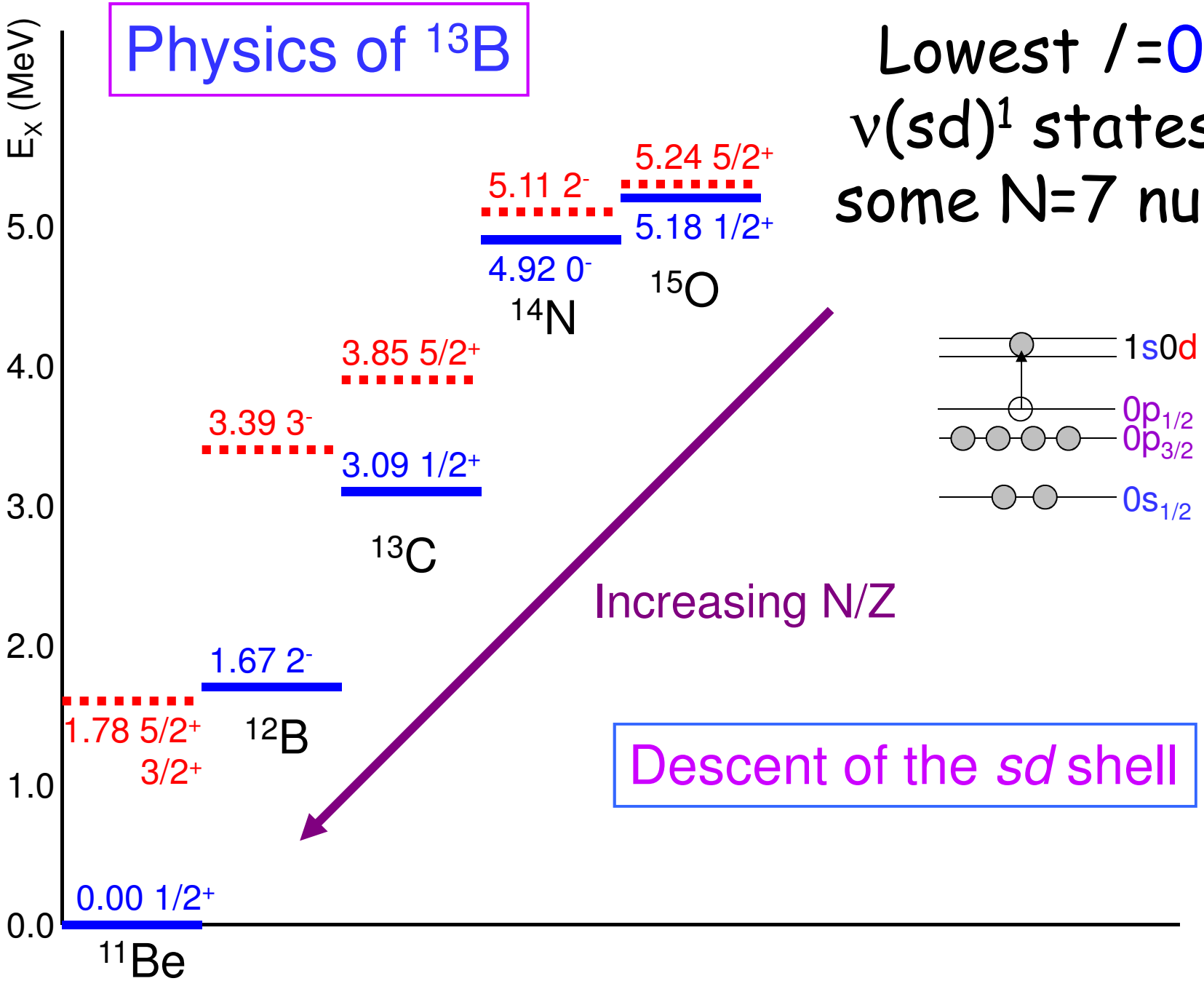
But maybe not this...



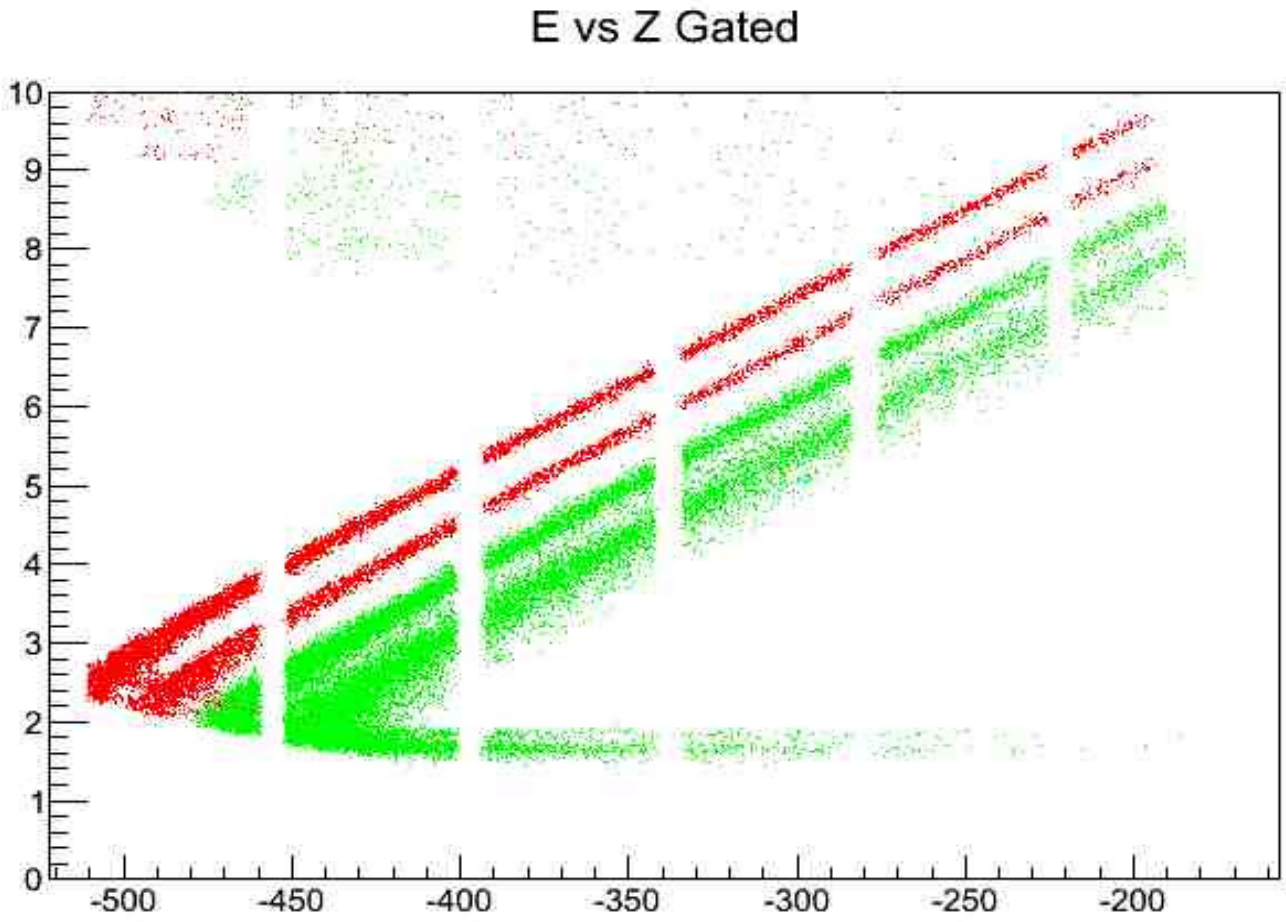


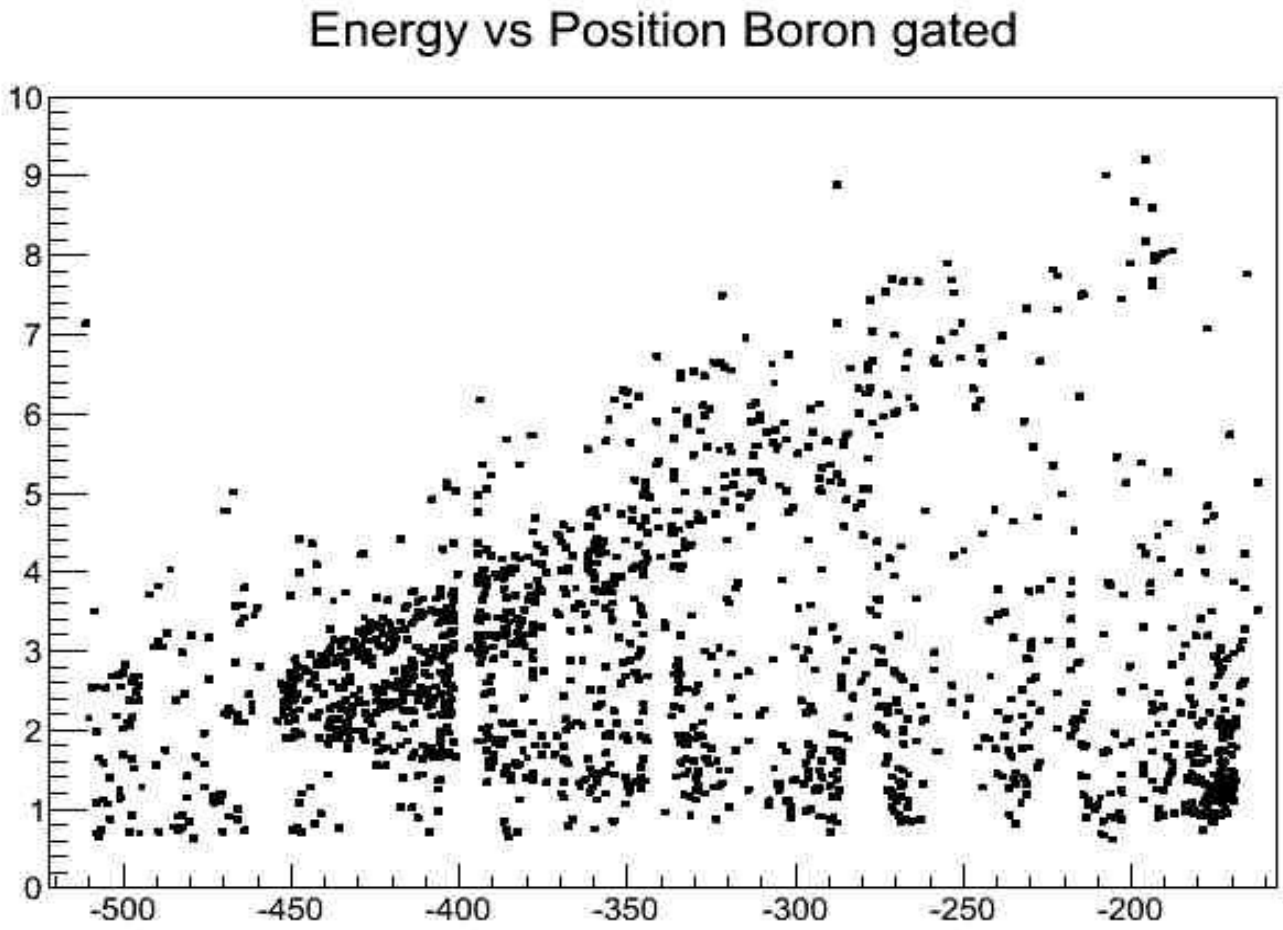
Physics of ^{13}B

Lowest l=0,2 $\nu(sd)^1$ states in some N=7 nuclei

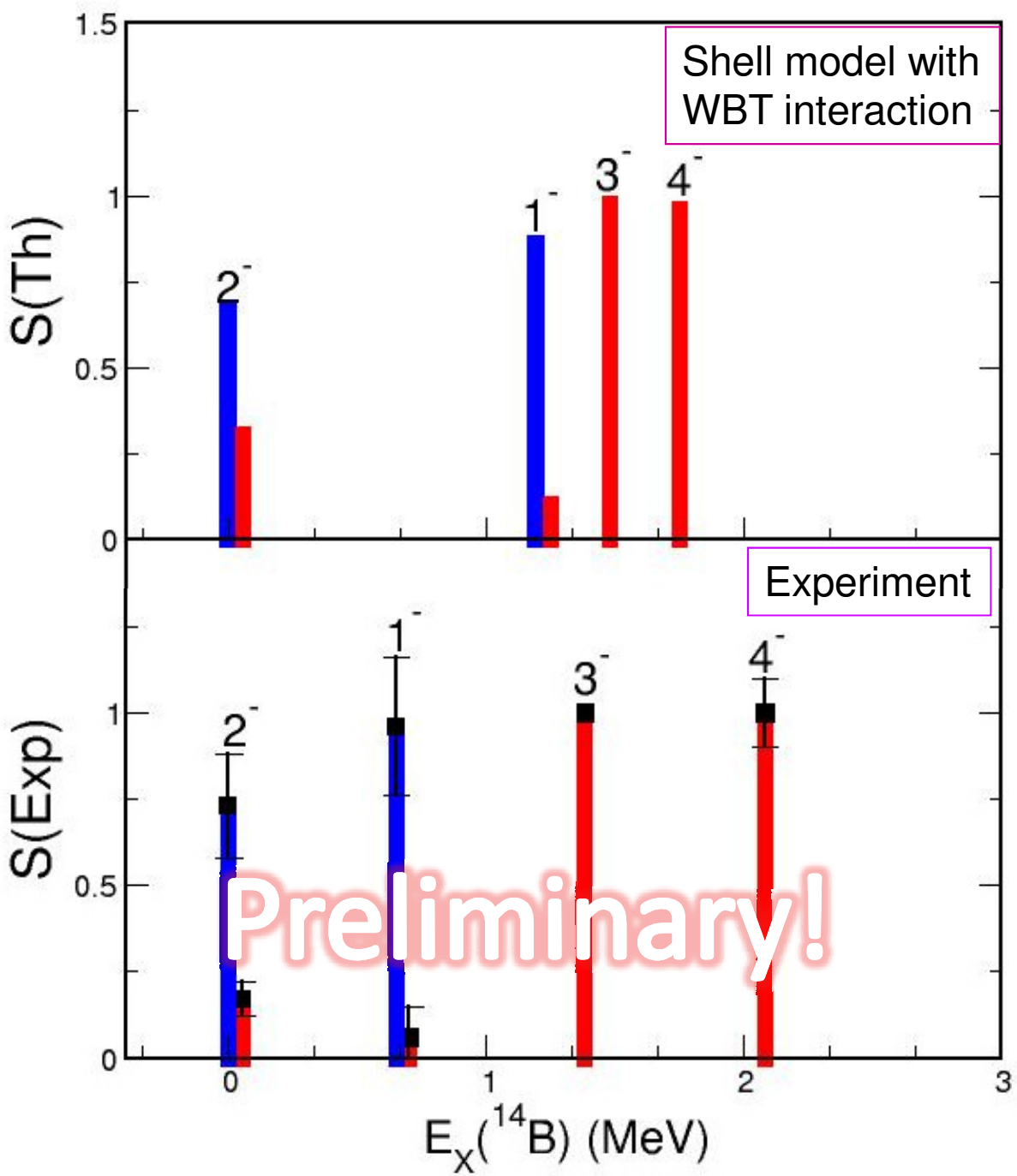


Descent of the *sd* shell


E vs Z Gated
10
9
8
7
6
5
4
3
2
1
0
-500
-450
-400
-350
-300
-250
-200


Energy vs Position Boron gated
10
9
8
7
6
5
4
3
2
1
0
-500
-450
-400
-350
-300
-250
-200

$^{13}B(d,p)^{14}B$ Spectroscopic factors

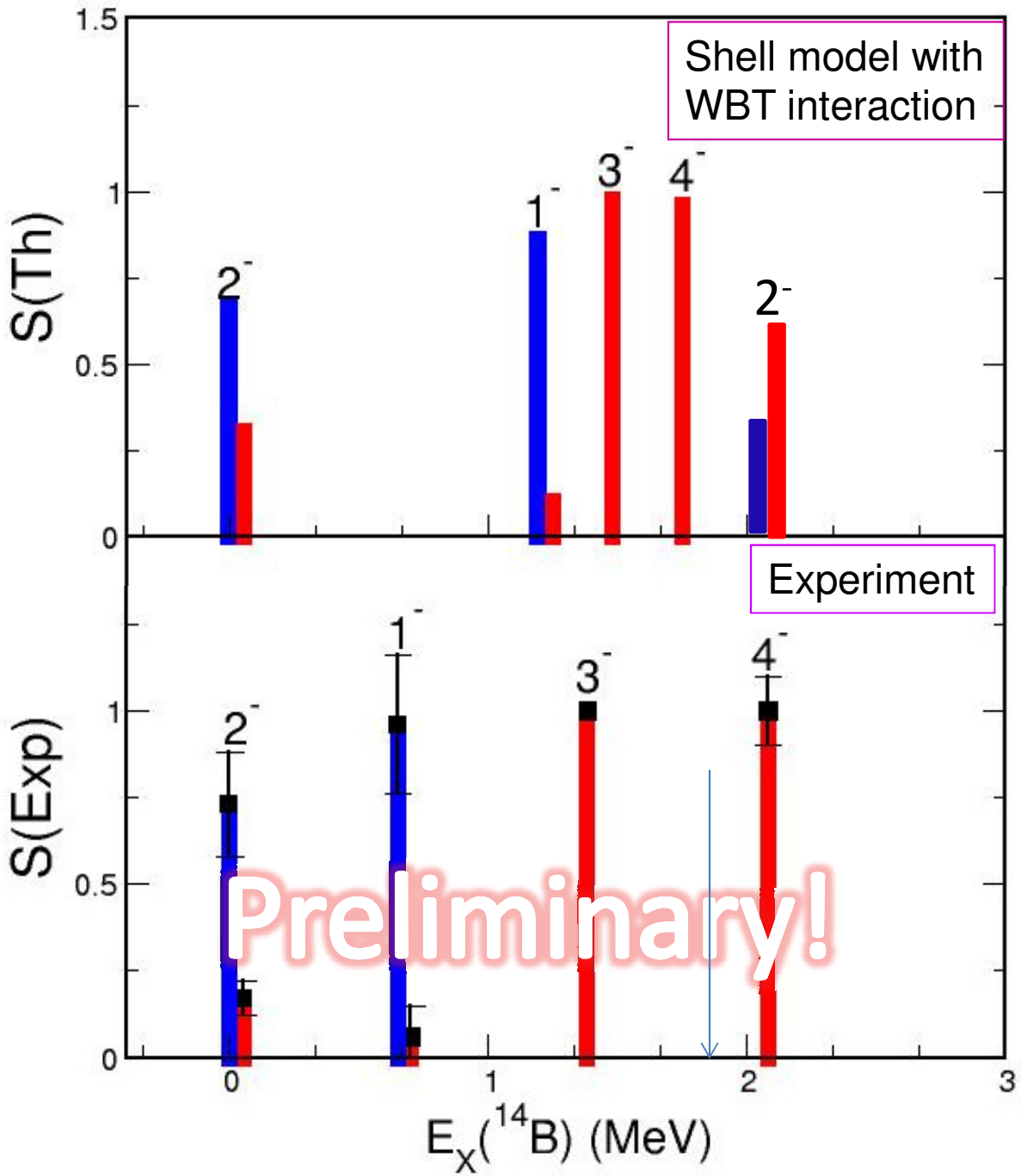


Excitation energies and relative spectroscopic factors from the shell model

Blue: L=0, $1s_{1/2}$

Red: L=2, $0d_{5/2}$

2^- mixed L=0+2,
1^- pure *L*=0
Reasonable agreement
But *caveat emptor*!



$^{13}B(d,p)^{14}B$ Spectroscopic factors

Excitation energies and relative spectroscopic factors from the shell model

Blue: L=0, $1s_{1/2}$

Red: L=2, $0d_{5/2}$

2^- mixed L=0+2,
1^- pure L=0
Reasonable agreement
But *caveat emptor*!

What's in *your* beam?