Nucleon-transfer reactions with light exotic nuclei

Opportunities and questions

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Our challenge: connect theory to experiment

- An experiment measures a *cross section*:
  - Plenty of challenges already here – absolute numbers, resolution, correct energy, etc. Isolation of final states
- Cross section → *interpretation in context of a reaction theory (e.g. DWBA)* → something to compare to theory (relative or absolute SF, ANC).
  - The results always include some uncertainty from reaction theory.

What can we learn from light nuclei

- The structure of light nuclei can be calculated with first-principles approaches such as the Quantum Monte Carlo (QMC) and No-Core Shell Model (NCSM) (*form factors for DWBA*).
- Shell-model interactions should be well understood here.
- *Proximity to the neutron threshold: confront issues of reaction and structure theory for loosely bound systems*
- Experimentally accessible at the energies thought to be appropriate for single-nucleon transfer reactions.

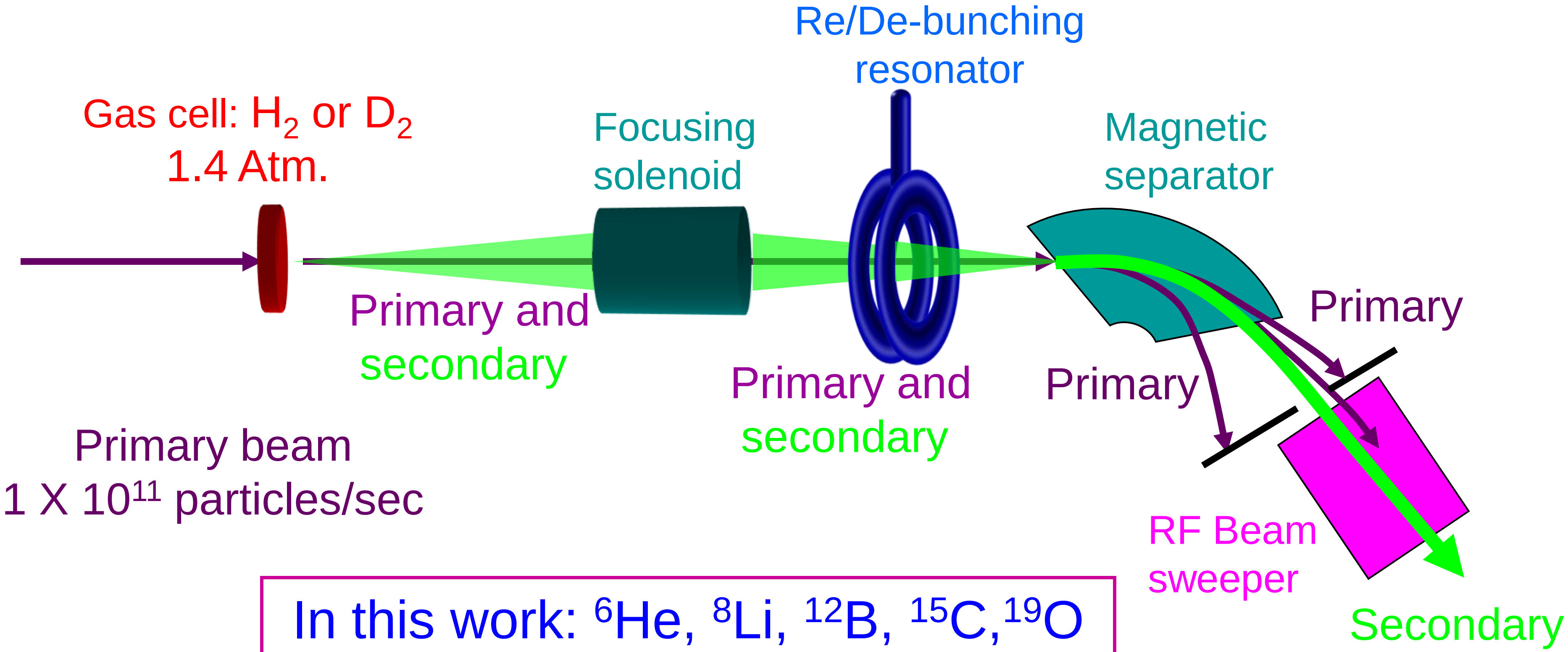
Two regimes

- *p*-shell: stripping and pickup reactions to both bound and unbound states, compare results to QMC
- *sd*-shell: Stripping reactions with a new technique that yields better resolution than previously achievable – compare to SM calculations
- What *can* these data tell us? What can they *not* tell us?

Experimental approach

1. Make some exotic beams
2. Detect products with “conventional detectors,” or -
3. Detect products with HELIOS

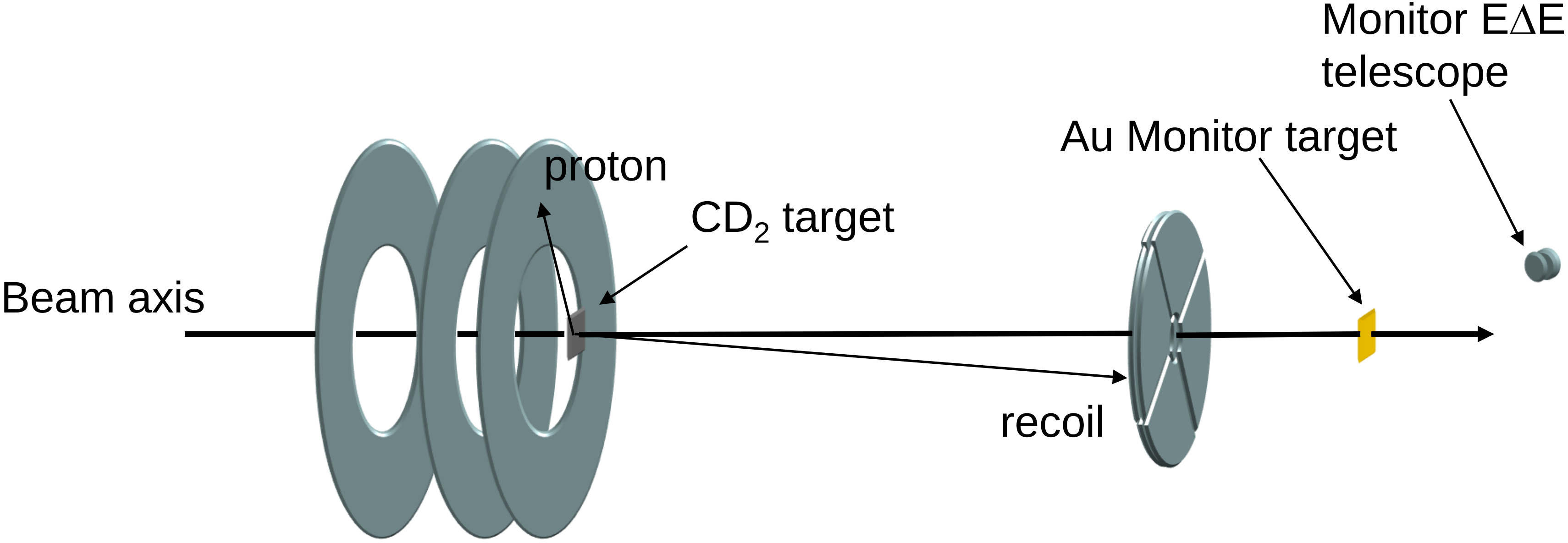
Producing light unstable beams
"In-flight" production at ANL*



In this work: ^{6}He, ^{8}Li, ^{12}B, ^{15}C,^{19}O
Intensities range from 5X10^{3} to 1.5X10^{6} particles/sec

*B. Harss, K. E. Rehm *et al*.,
Rev. Sci. Instrum. **71**, 380 (2000)

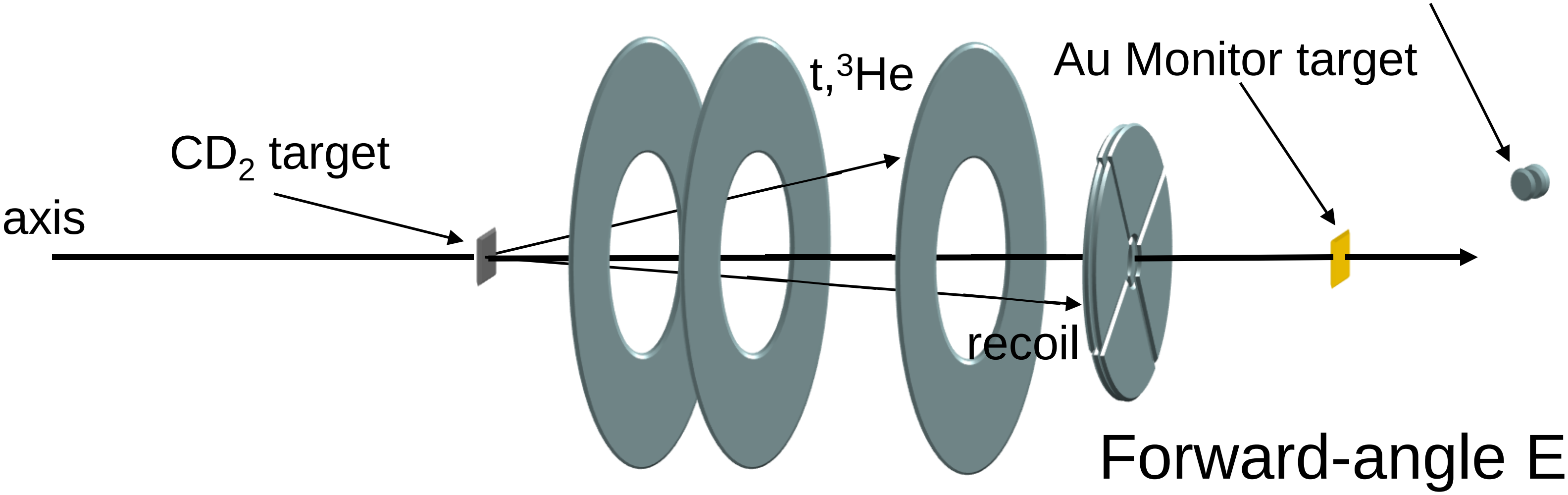
"Conventional" (*d,p*) Experimental setup



Annular silicon detectors
$\Omega_{lab} \sim 3.5$ sr
$\theta_{lab}=109^o$-159^o

Forward-angle EΔE detectors
$\theta_{lab}=1^o$-7^o

“Conventional” (*d*,*t*) (*d*,^{3}He) Experimental setup



Monitor EΔE telescope

Au Monitor target

t,^{3}He

CD$_2$ target

Beam axis

recoil

Forward-angle EΔE detectors

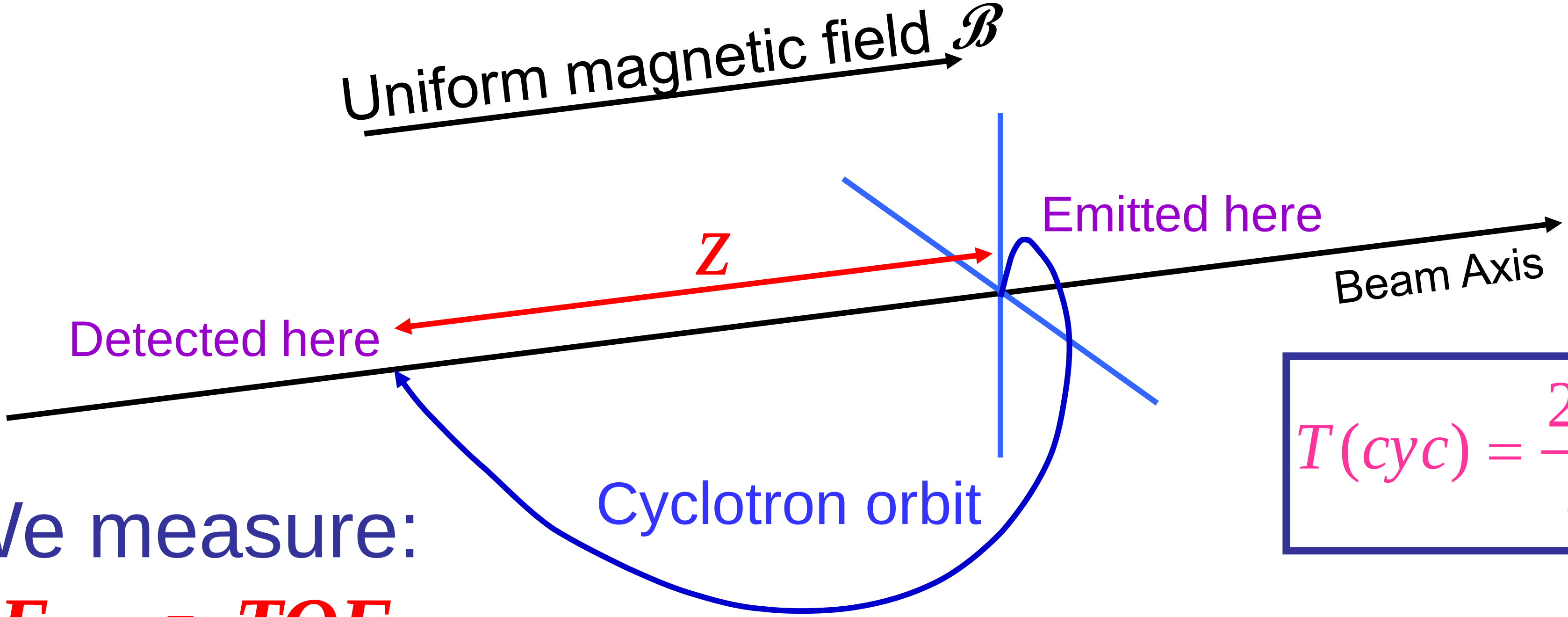
θ_{lab}=1°-7°

Annular silicon detectors

$\Omega_{lab} \sim 2.2$ sr

θ_{lab}=9°-50°

In a magnetic field with HELIOS



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

We measure:

E_{lab}, z, TOF

We deduce:

E_{CM}, θ_{CM}

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

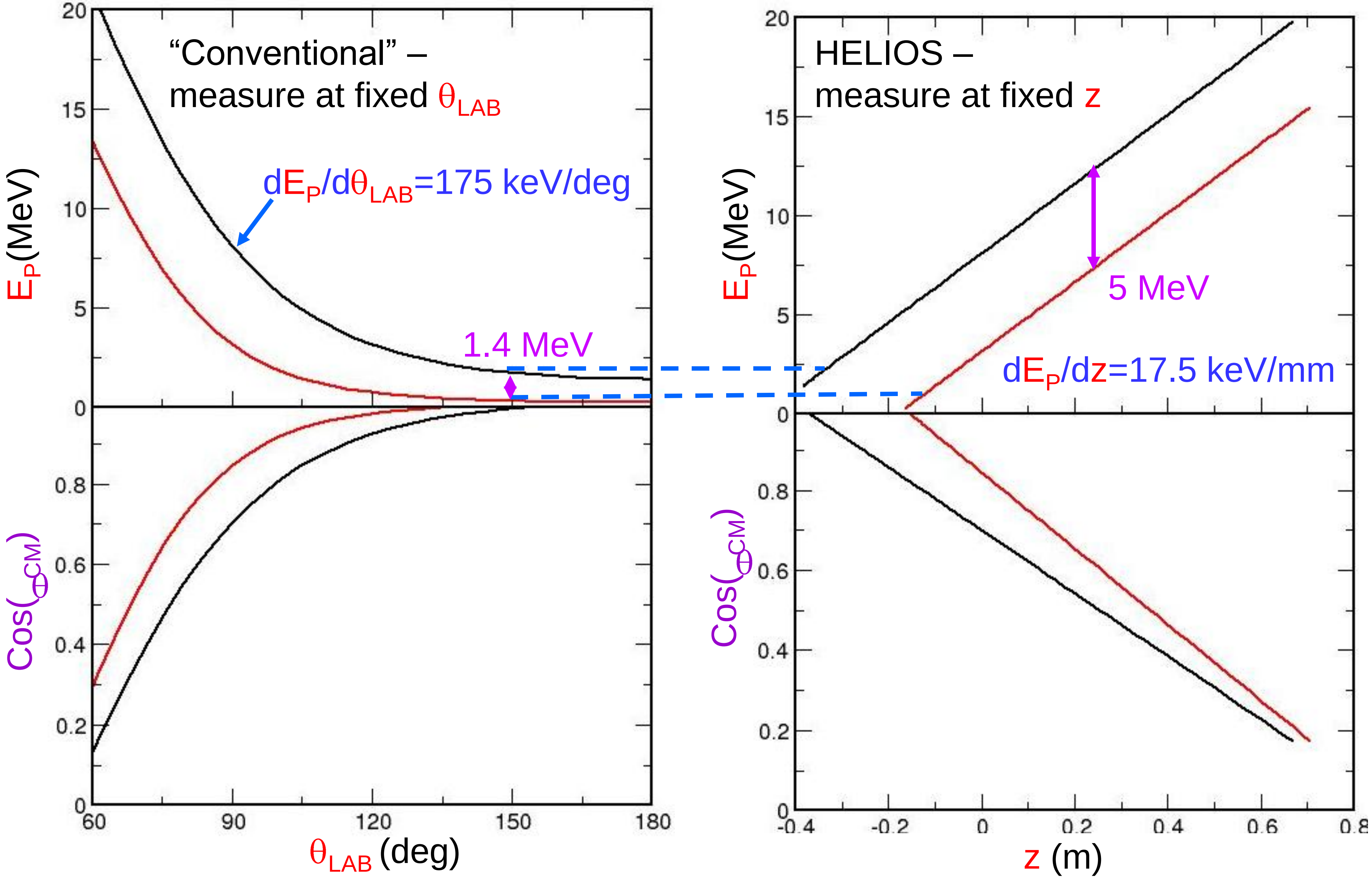
$$E_{lab} = E_{CM} - A + Bz$$

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

For a given state

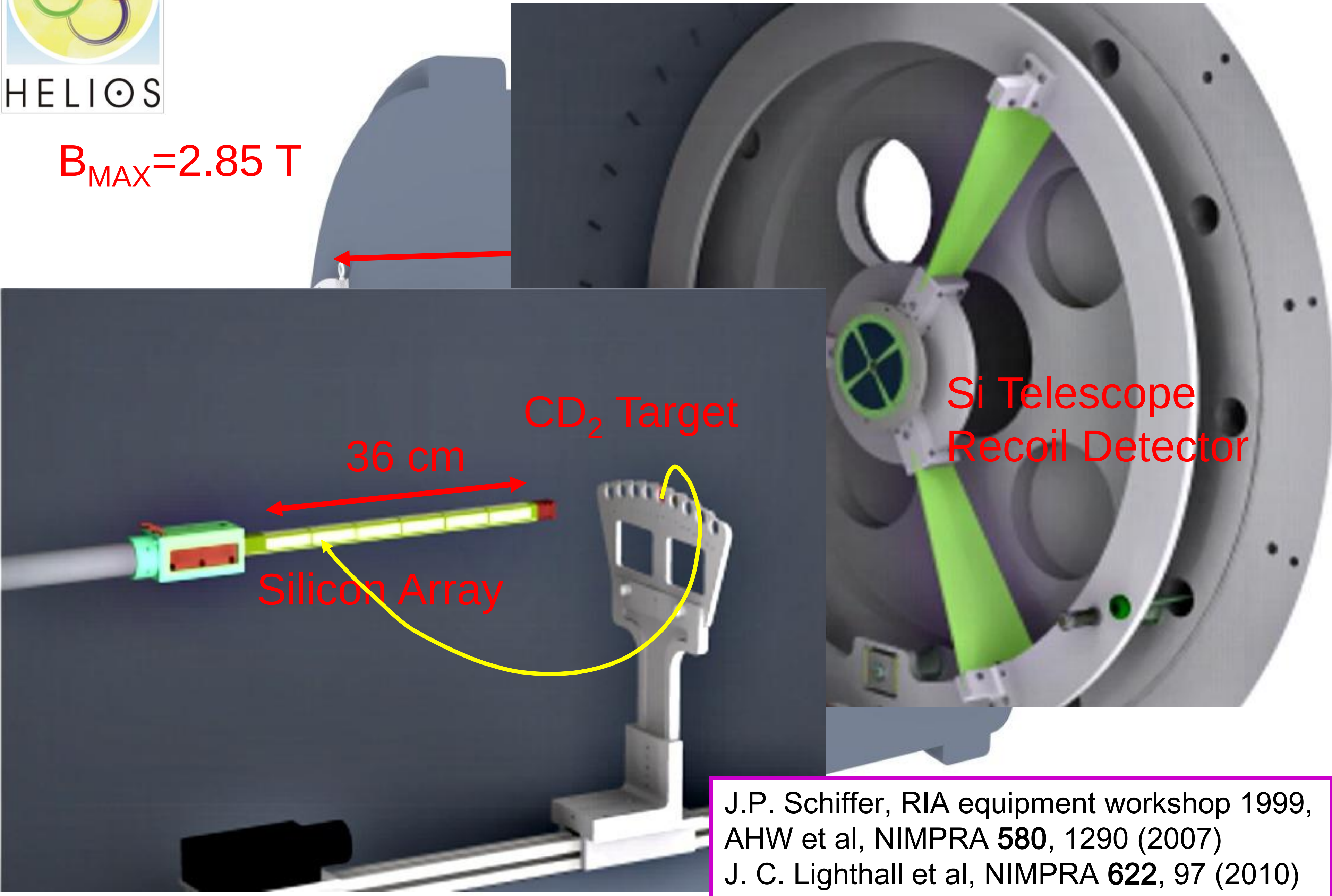
For two states at fixed z

Advantages to the HELIOS approach



HELIcal Orbit Spectrometer -HELIOS

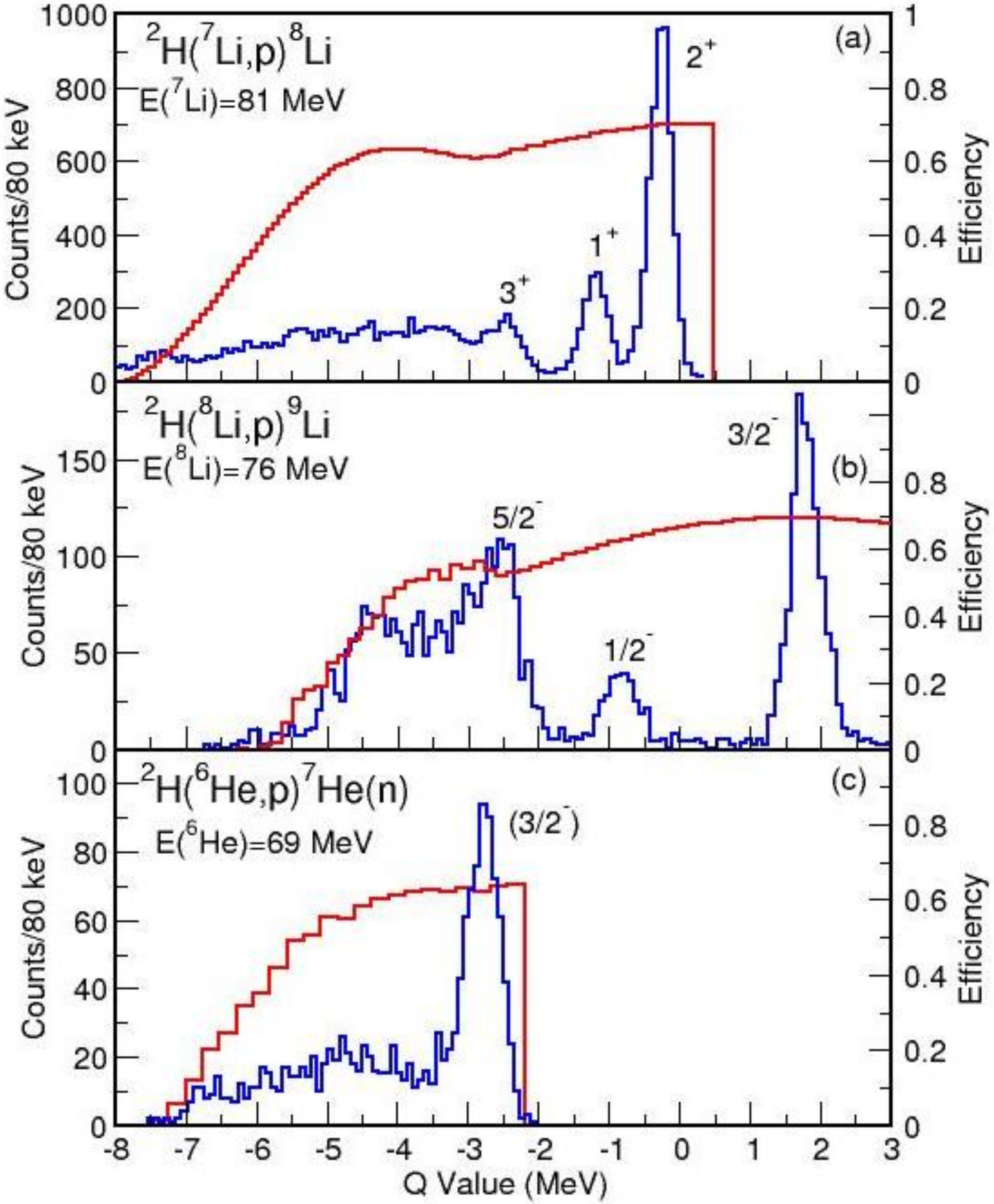
B_{MAX}=2.85 T



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

Spectrometer completed in August 2008

Q-value spectra from $^{7,8}Li(d,p)^{8,9}Li$ $^{6}He(d,p)^{7}He$

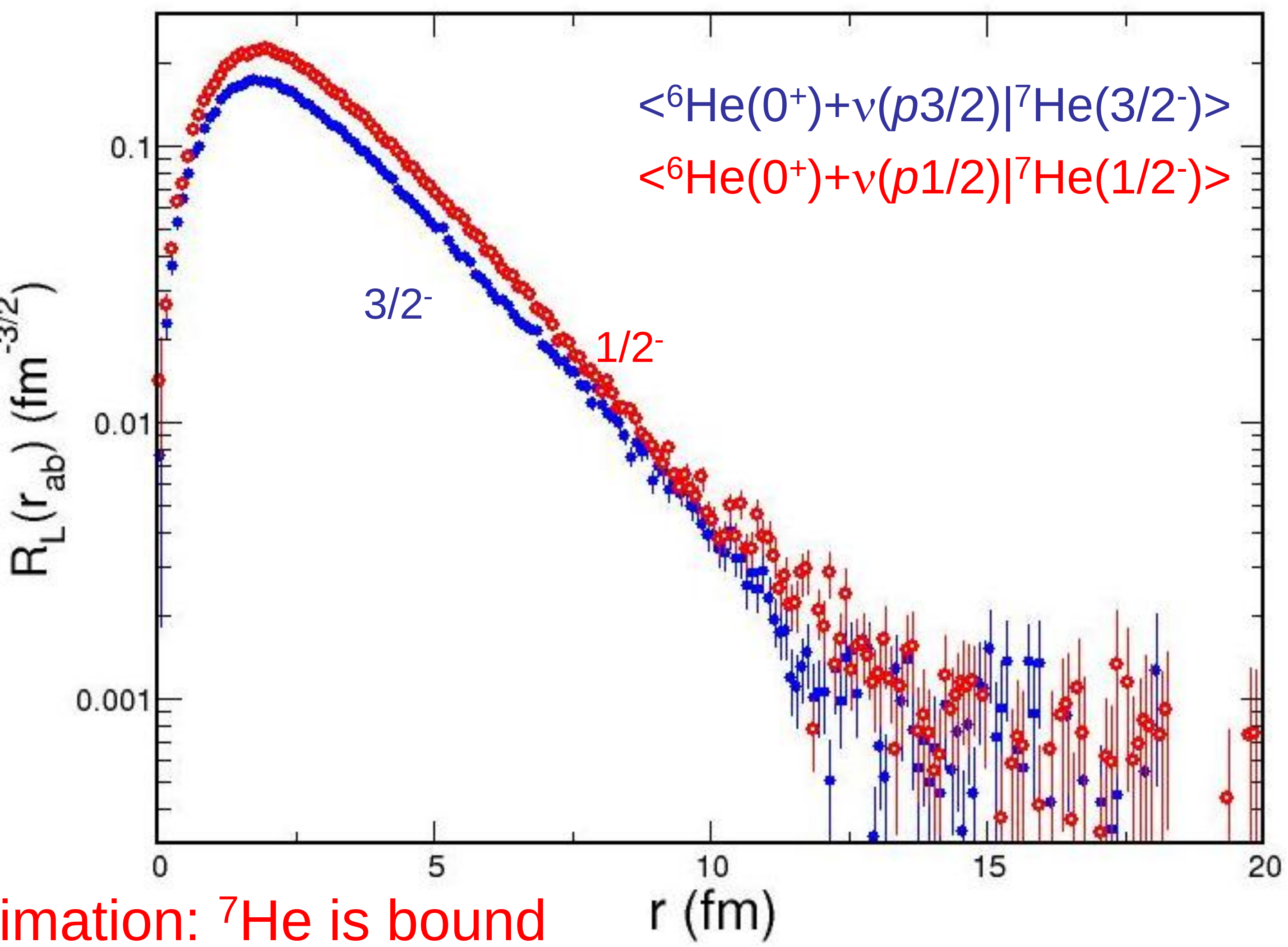


p-Li or *p*-^{6}He coincidences

Efficiency from Monte Carlo simulations

PRL **94**, 082502 (2005),
PRC **72**, 061301(R) (2005)

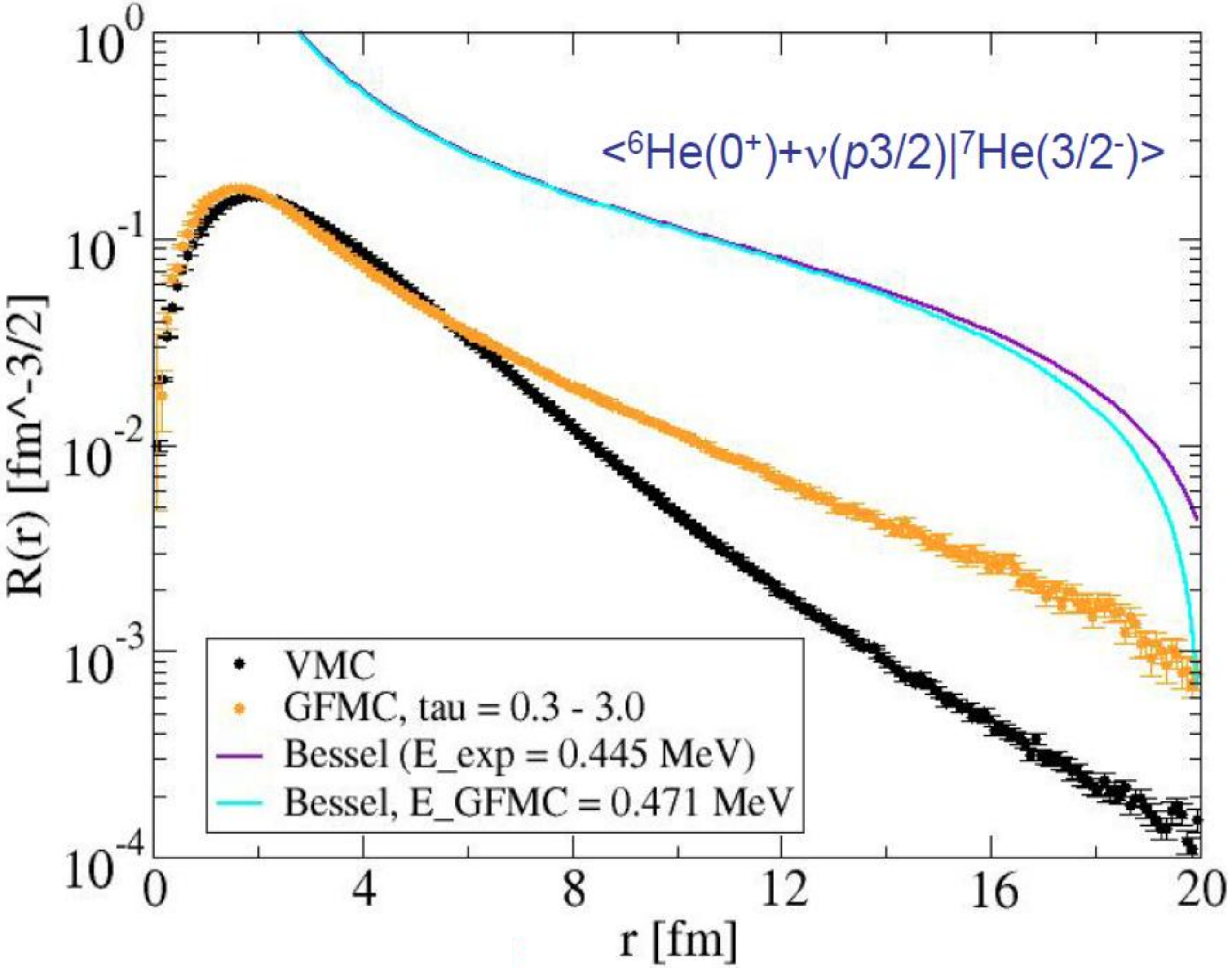
Overlaps and (*d,p*) Spectroscopic factors from VMC



Approximation: ^{7}He is bound (just barely)

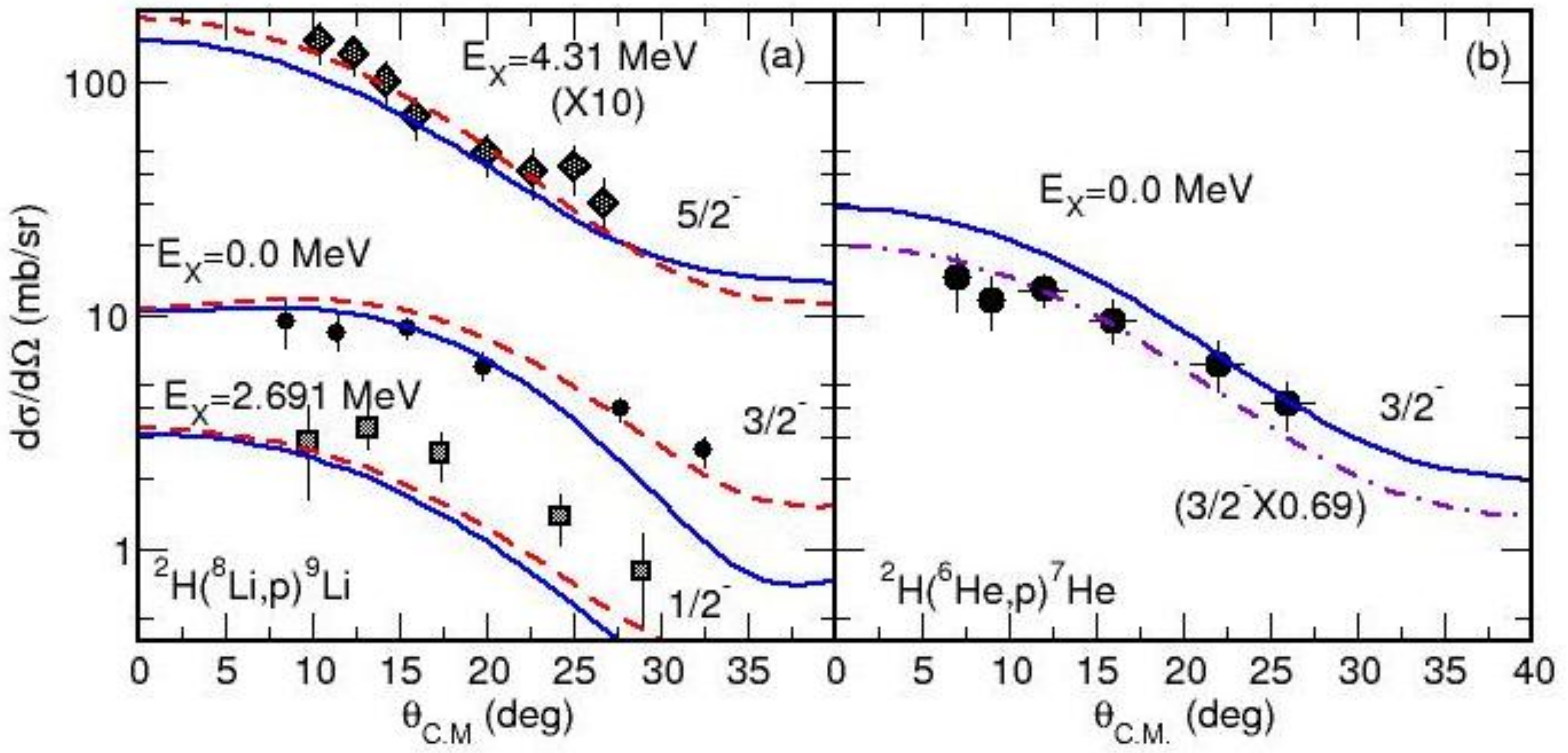
R. Wiringa, priv. comm.

Overlaps from GFMC



I. Brida, priv. comm.

(*d*,*p*) Angular Distributions - narrow states



^{2}H(^{8}Li,*p*)^{9}Li DWBA calculations: **Red**, **blue** curves: VMC form factor with different OMP, no extra normalization

^{2}H(^{6}He,*p*)^{7}He$_{g.s.}$ DWBA calculations + VMC form factor. **Blue**: no normalization **violet**- VMC X 0.69.

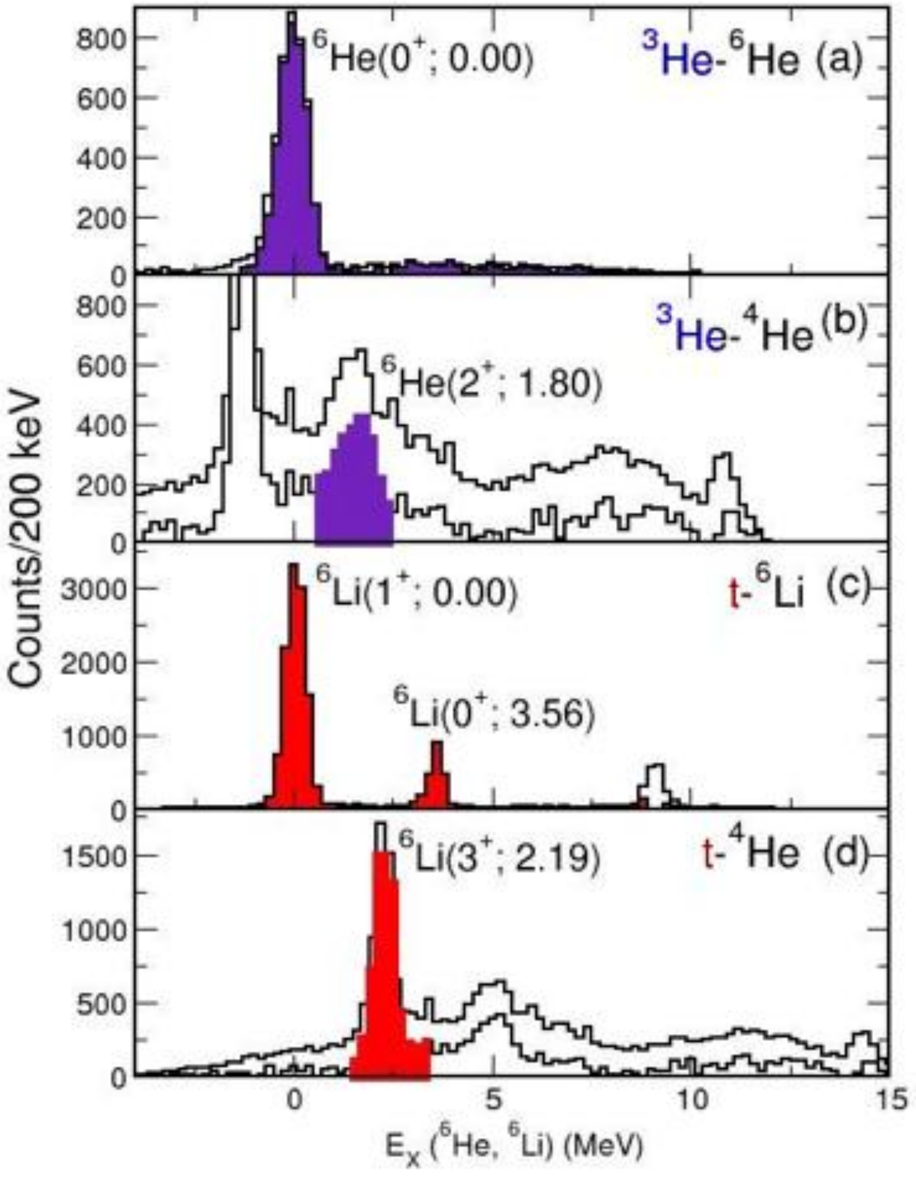
Optical-model parameters from Schiffer et al, PRC **164**

Observations for ^{8}Li(*d*,*p*)^{9}Li, ^{6}He(*d*,*p*)^{7}He

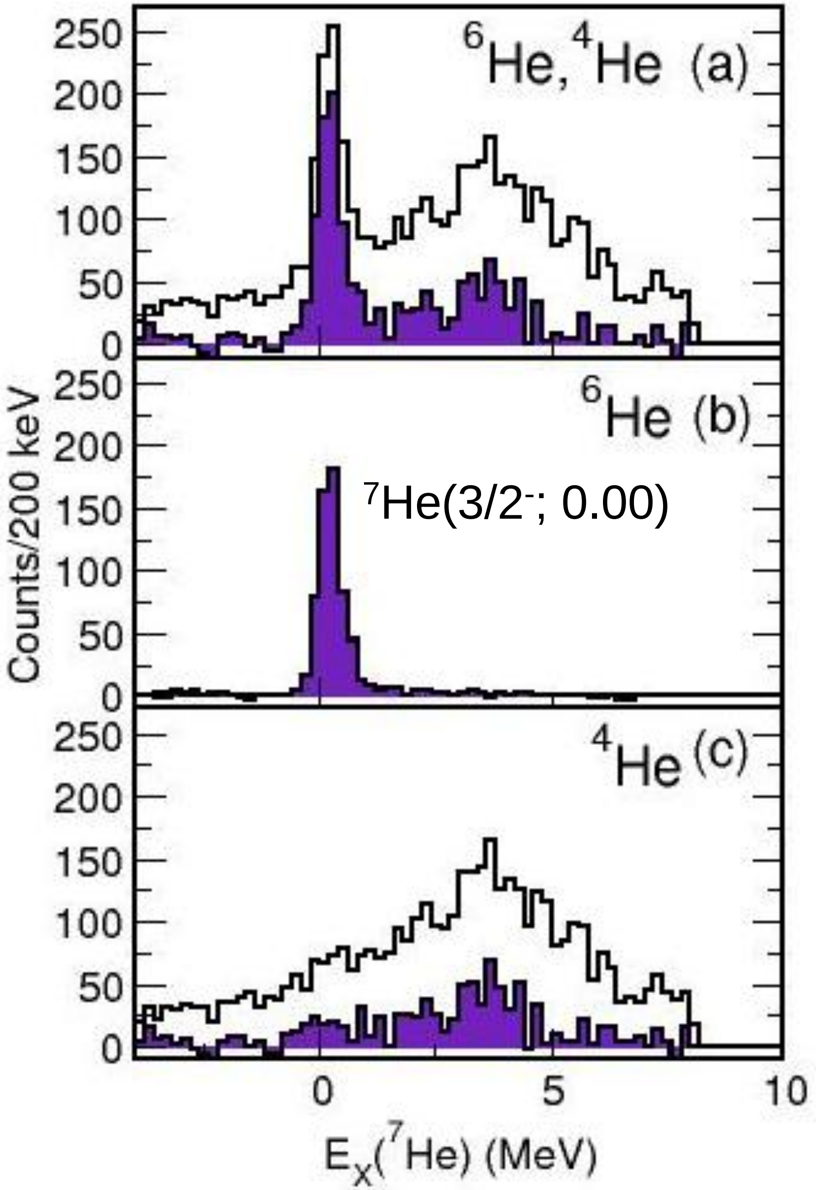
- ^{9}Li: QMC is reproduced (absolutely) to 20%.
- An old OMP set from nearby - ^{6,7}Li(*d*,*p*) - seems sufficient.
- ^{6}He(*d*,*p*)^{7}He$_{\text{g.s.}}$ absolute agreement is not quite as good, using same OMP as for ^{6,7,8}Li(*d*,*p*)
- Not obvious whether to blame the potentials, or the form factor, or both?!

(*d*,*t*), (*d*,^{3}He) reactions with ^{7,8}Li

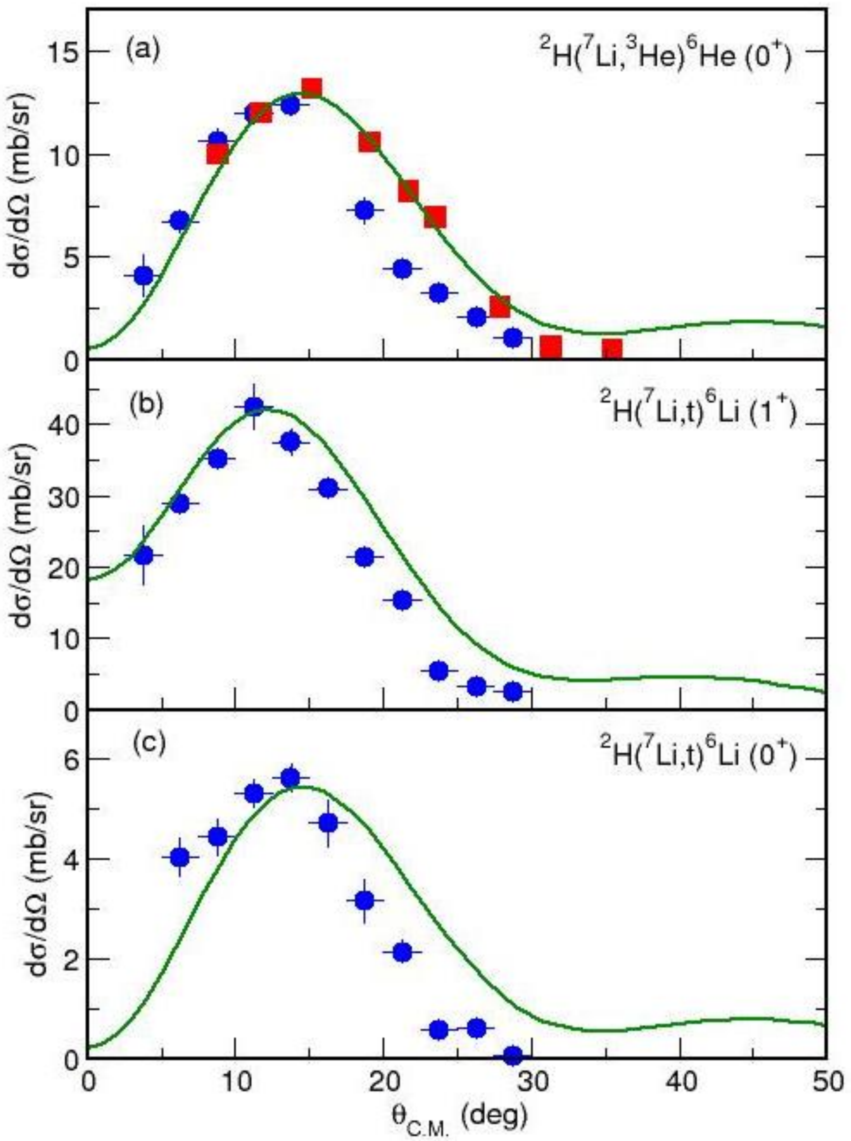
^{7}Li(*d*,*t*)^{6}Li, ^{7}Li(*d*,^{3}He)^{6}He

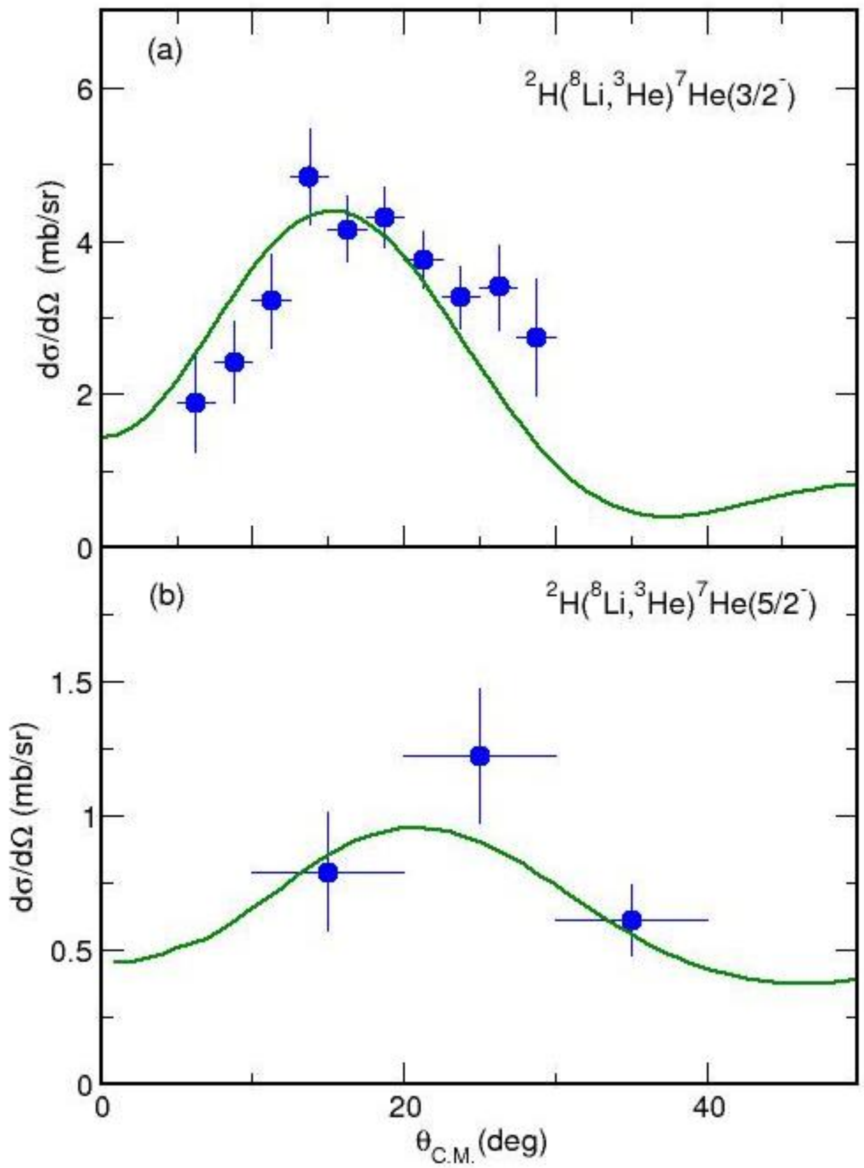


^{8}Li(*d*,^{3}He)^{7}He



n and p Pickup angular distributions





Angular distributions normalized to data

Experimental, theoretical SF for pickup reactions

Reaction	σ(Exp) (mb/sr)	C^2S (Exp)*	C^2S (VMC)
^{7}Li(d,^{3}He)^{6}He(0^+)	12.3(2.0)	0.44(6)	0.42
^{7}Li(d,t)^{6}Li(1^+)	41.2(6.0)	0.74(11)	0.68
^{7}Li(d,t)^{6}Li(0^+)	5.6(0.9)	0.19(3)	0.21
^{8}Li(d,^{3}He)^{7}He($3/2^-$)	4.5(0.9)	0.36(7)	0.58
^{8}Li(d,^{3}He)^{7}He($5/2^-$)	1.0(0.5)	0.29(0.15)	0.17

*$C^2S(\mathrm{Exp})=(\sigma_{max}/\sigma_{DWBA})$ X 0.32

Large dependence on OMP make absolute comparisons *unreliable!*

Observations for $(d,{}^{3}\mathrm{He})$,(d,t) on ^{7,8}Li

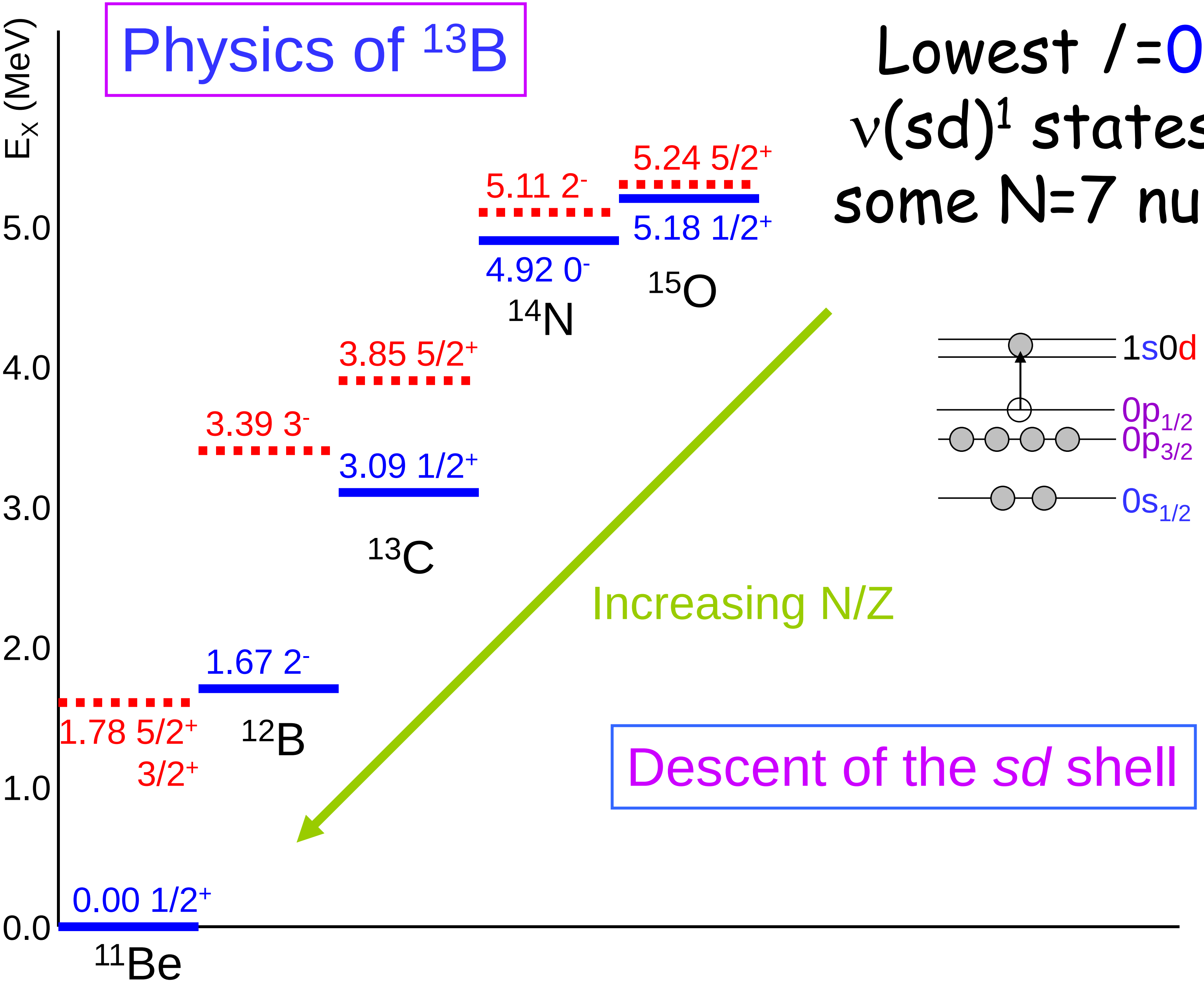
- Sensitivity to optical-model parameters (for the exit channel).
- *Absolute* cross-section comparisons to theory are no longer reliable.
- BUT: *Relative* SF results for ^{7,8}Li(d,^{3}He)^{6,7}He and ^{7}Li(d,t)^{6}Li are in good agreement with VMC predictions.

(*d*,*p*) reactions producing ^{13}B, ^{16}C, and ^{20}O

- ^{13}B, ^{16}C and ^{20}O are beyond the reach of VMC/GFMC, but we can test shell-model calculations
- New technique to obtain high-quality data for transfer reactions (HELIOS)
- What works? What doesn’t?

Physics of ^{13}B

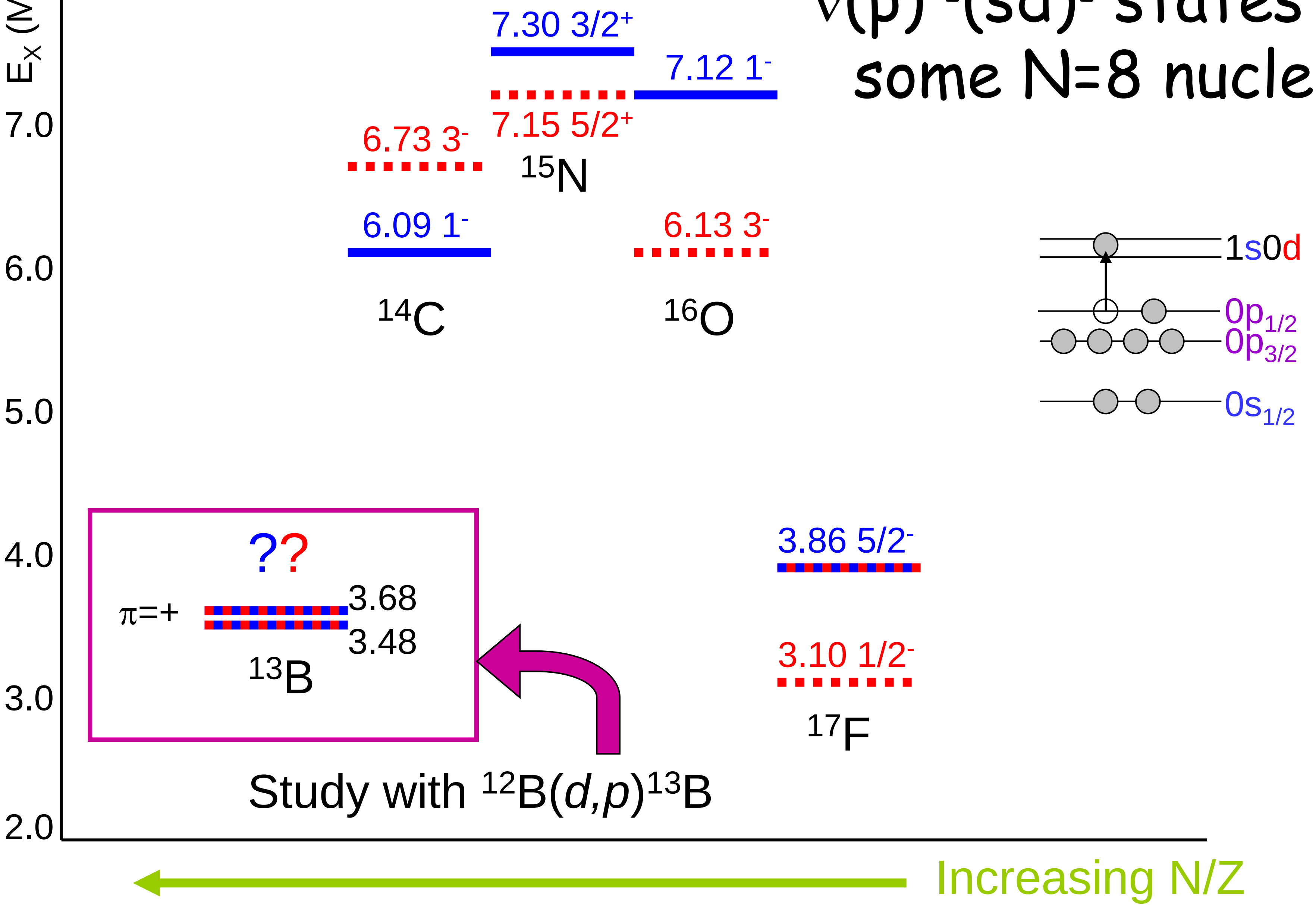
Lowest l=0,2 $\nu(sd)^1$ states in some N=7 nuclei



Descent of the *sd* shell

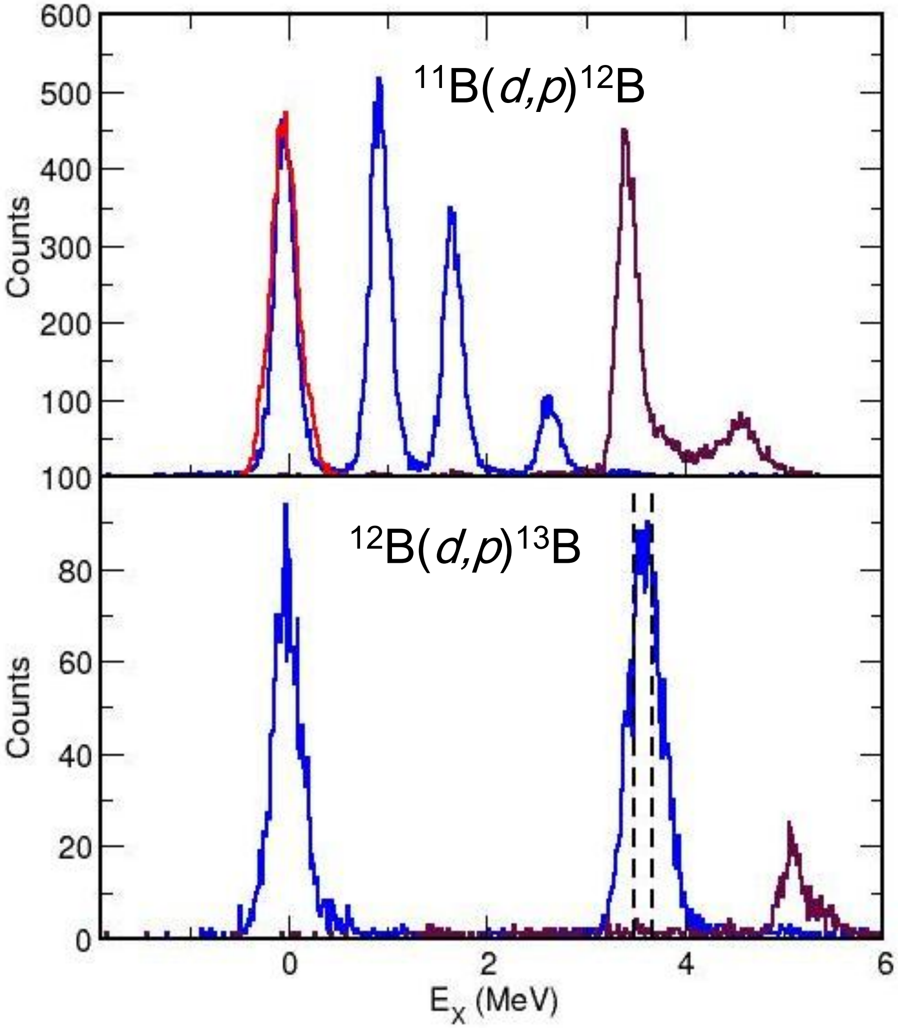
Physics of ^{13}B

Lowest l=0,2 $\nu(p)^{-1}(sd)^1$ states in some N=8 nuclei

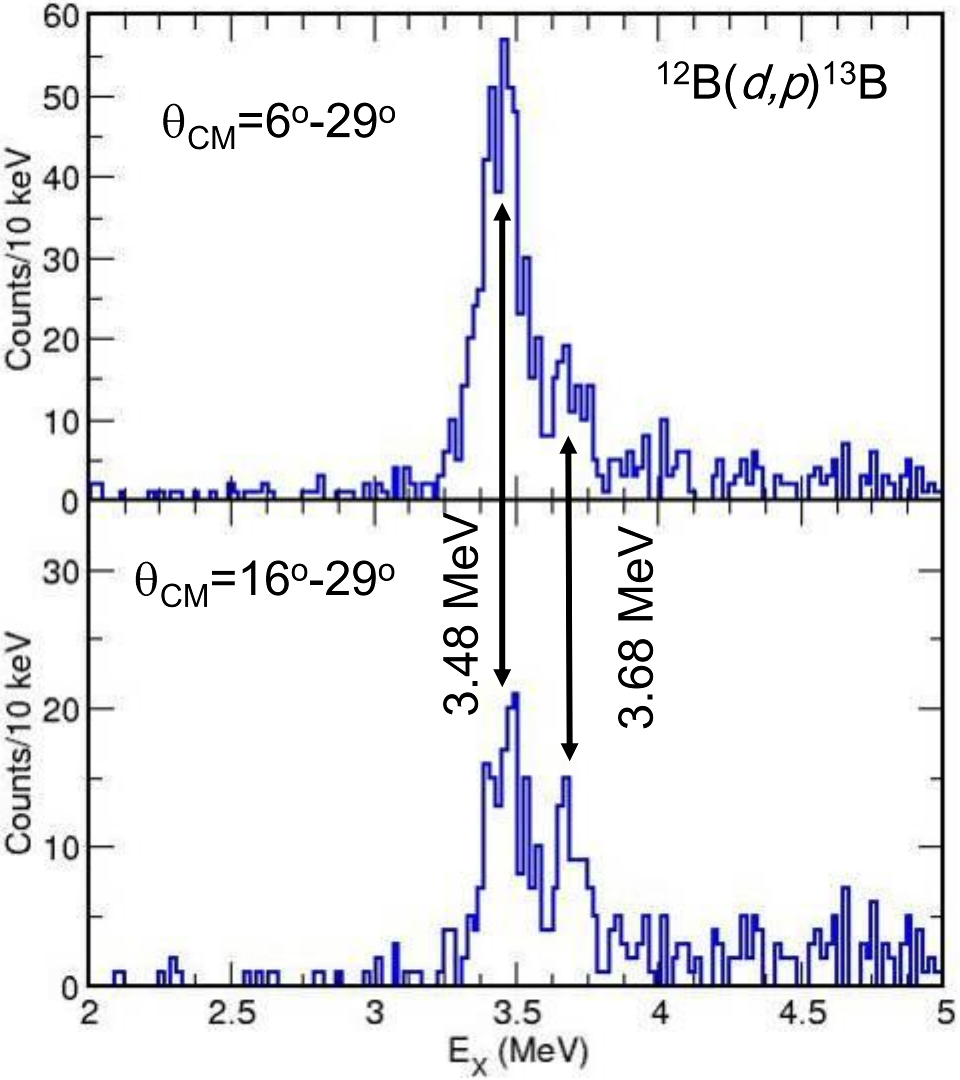


Study with ^{12}B(d,p)^{13}B

Improved resolution for $^{11,12}B(d,p)^{12,13}B$



“Conventional”

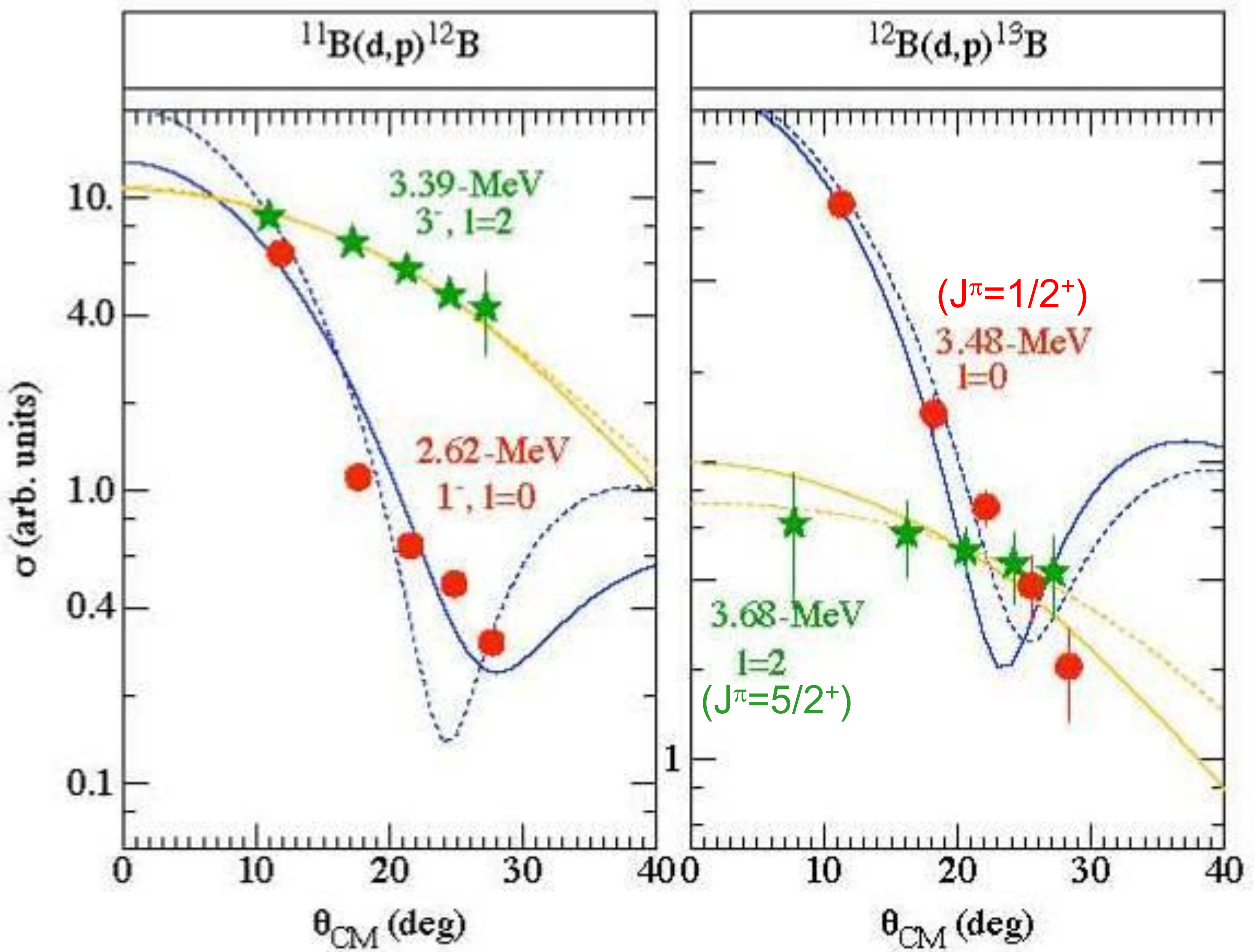


HELIOS

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

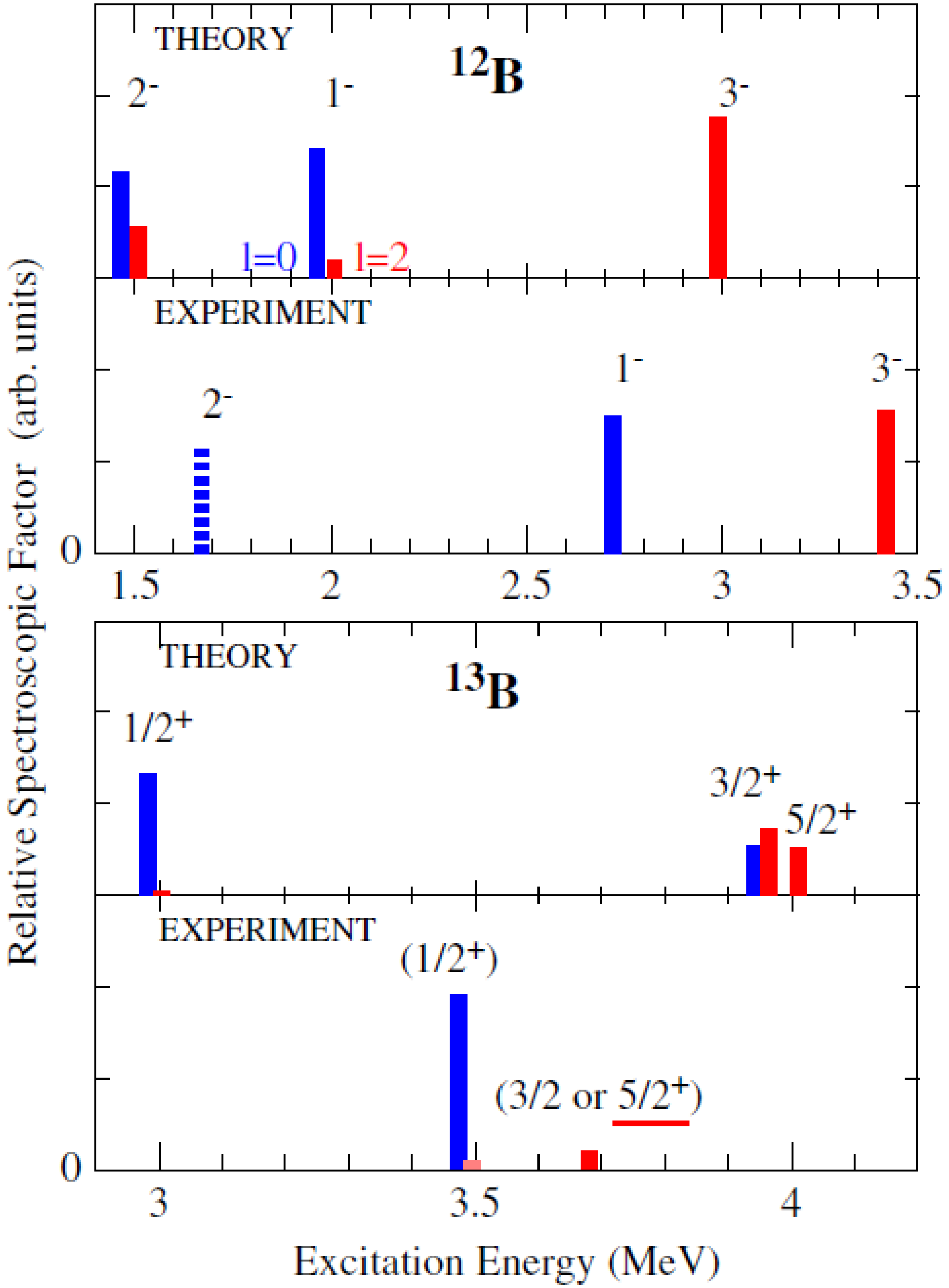
B. B. Back et al., PRL **104**, 132501 (2010)

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



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

Theory versus experiment for ^{13}B



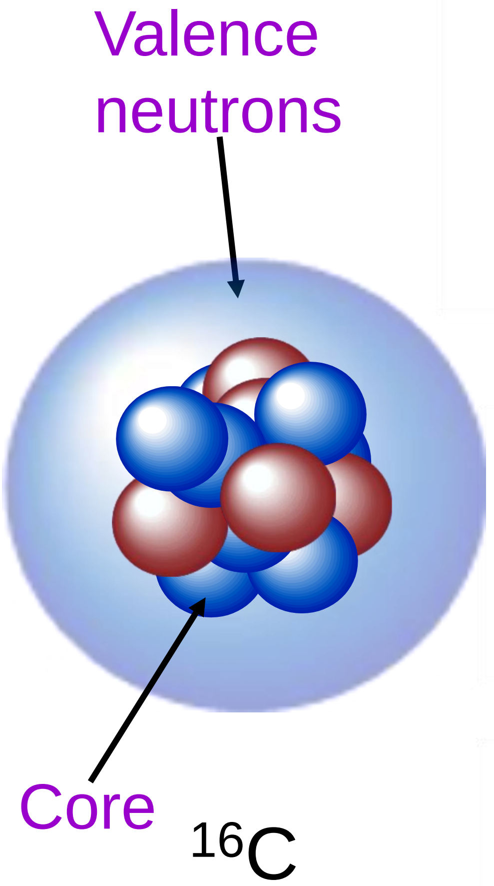
Excitation energies and *relative* spectroscopic factors from the shell model (WBP interaction)

Agreement is reasonable for ^{12}B (simple),
poor for ^{13}B (complex)

Blue: L=0
Red: L=2

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

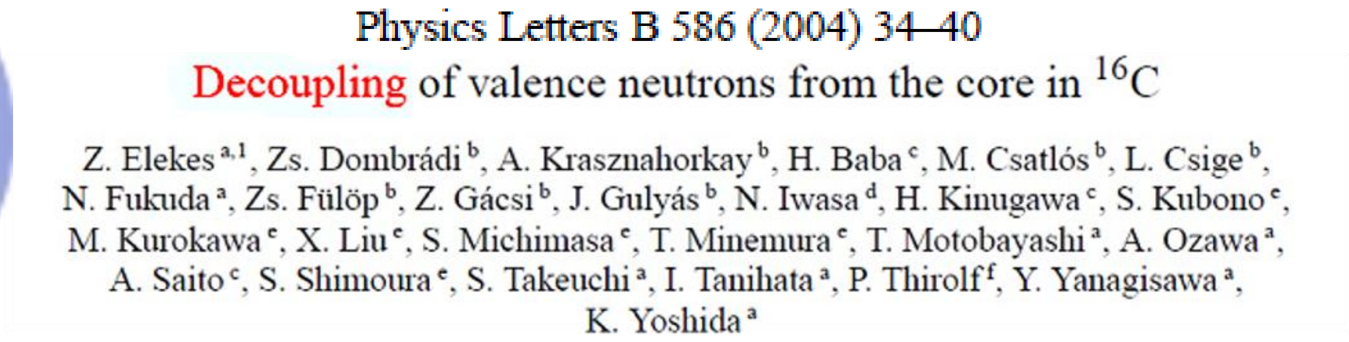
Exotic behavior in ^{16}C?



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

Anomalously Hindered $E2$ Strength $B(E2; 2_1^+ \to 0^+)$ 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[e],
M. Kurokawa[c], X. Liu[e], S. Michimasa[c], T. Minemura[c], T. Motobayashi[a], A. Ozawa[a],
A. Saito[c], S. Shimoura[e], 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

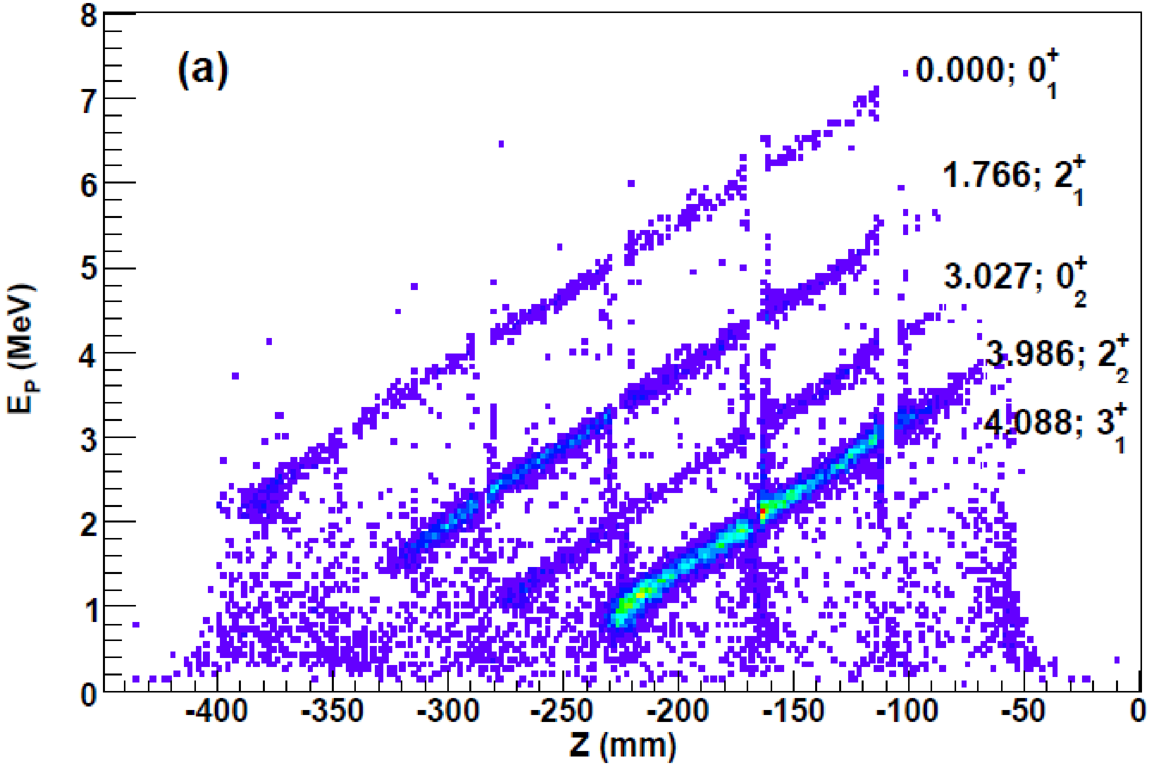
M. Wiedeking, P. Fallon, A. O. Macchiavelli, J. Gibelin, M. S. Basunia, R. M. Clark, M. Cromaz, M.-A. Deleplanque,
S. Gros, H. B. Jeppesen, P. T. Lake, I.-Y. Lee, L. G. Moretto, J. Pavan, L. Phair, and E. Rodriguez-Vietiez
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

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)

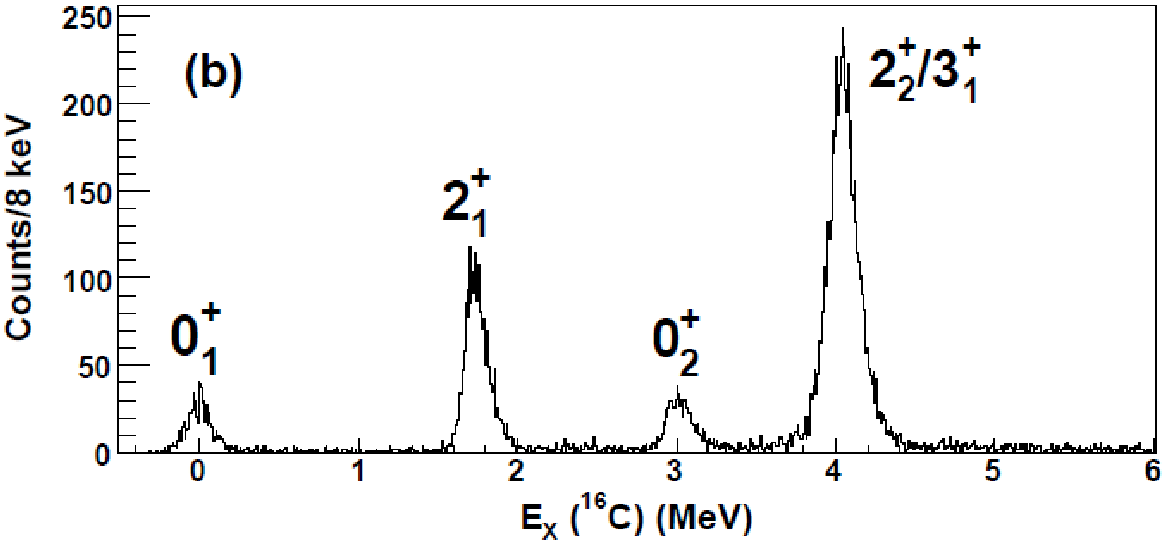
Study with ^{15}C(d,p)^{16}C

No hindrance, and
no exotic behavior.

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



Proton energy-position correlation

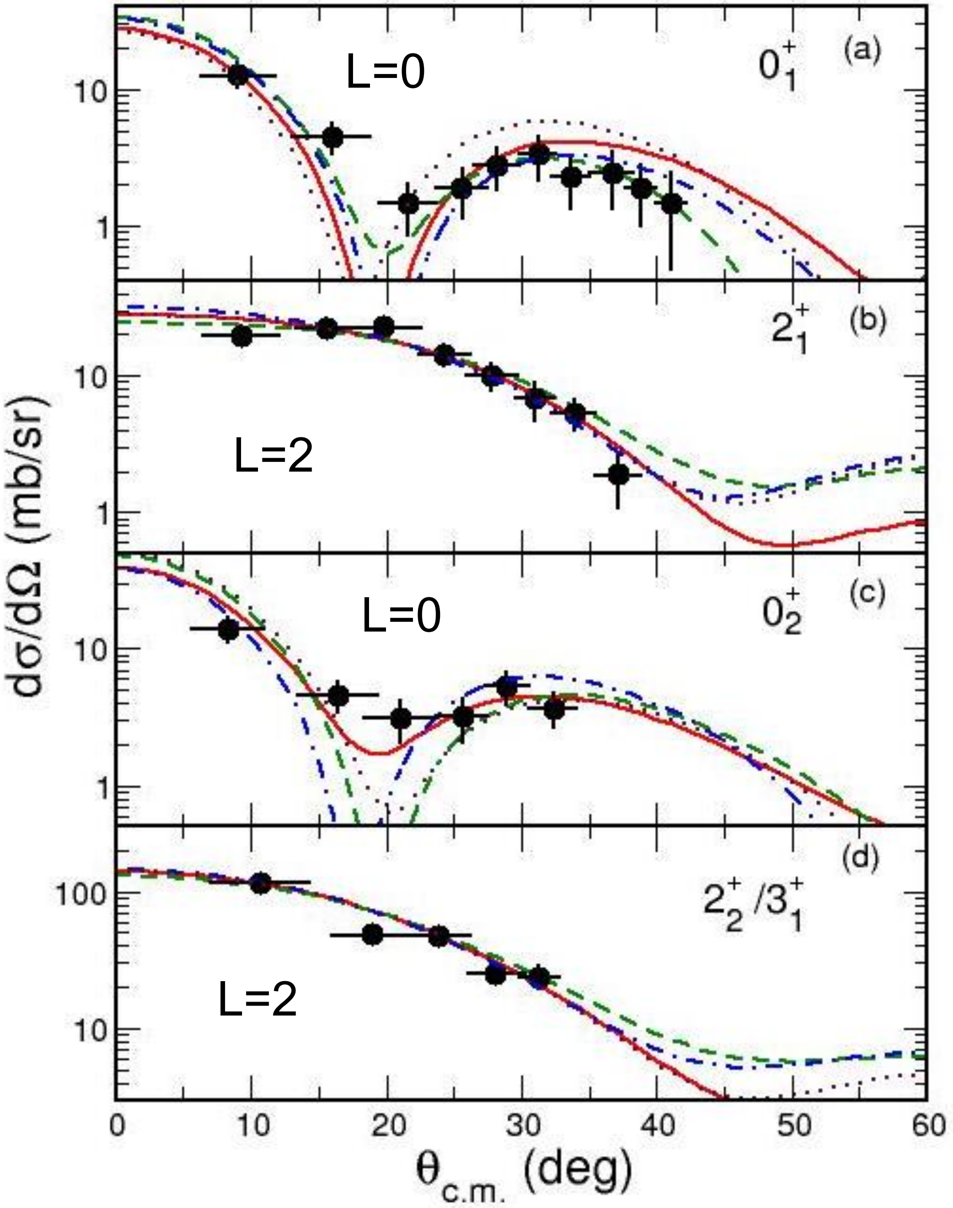


^{16}C Excitation-energy spectrum

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

PRL **105**, 132501 (2010)

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



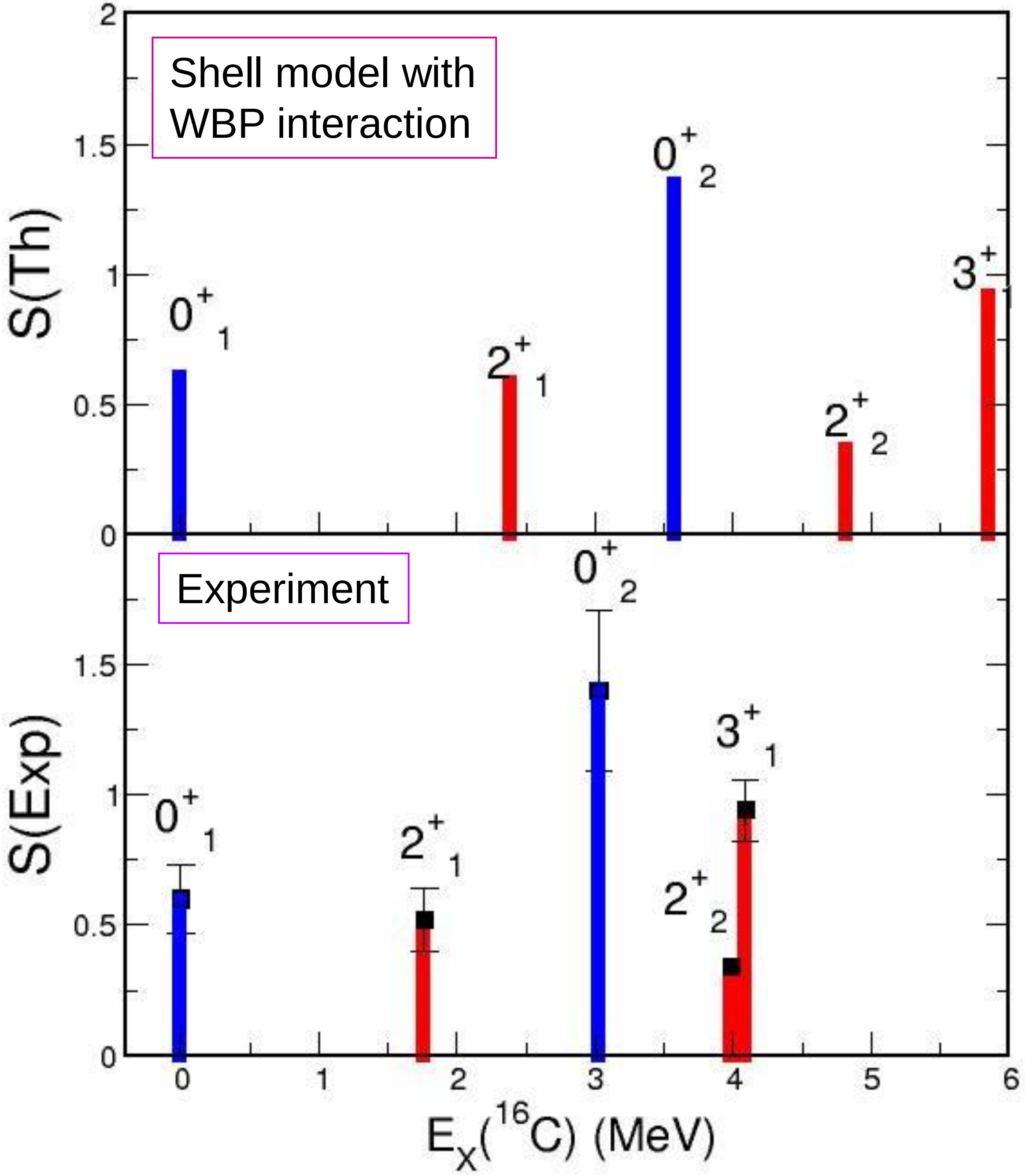
Curves are DWBA calculations with various optical-model potentials.

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



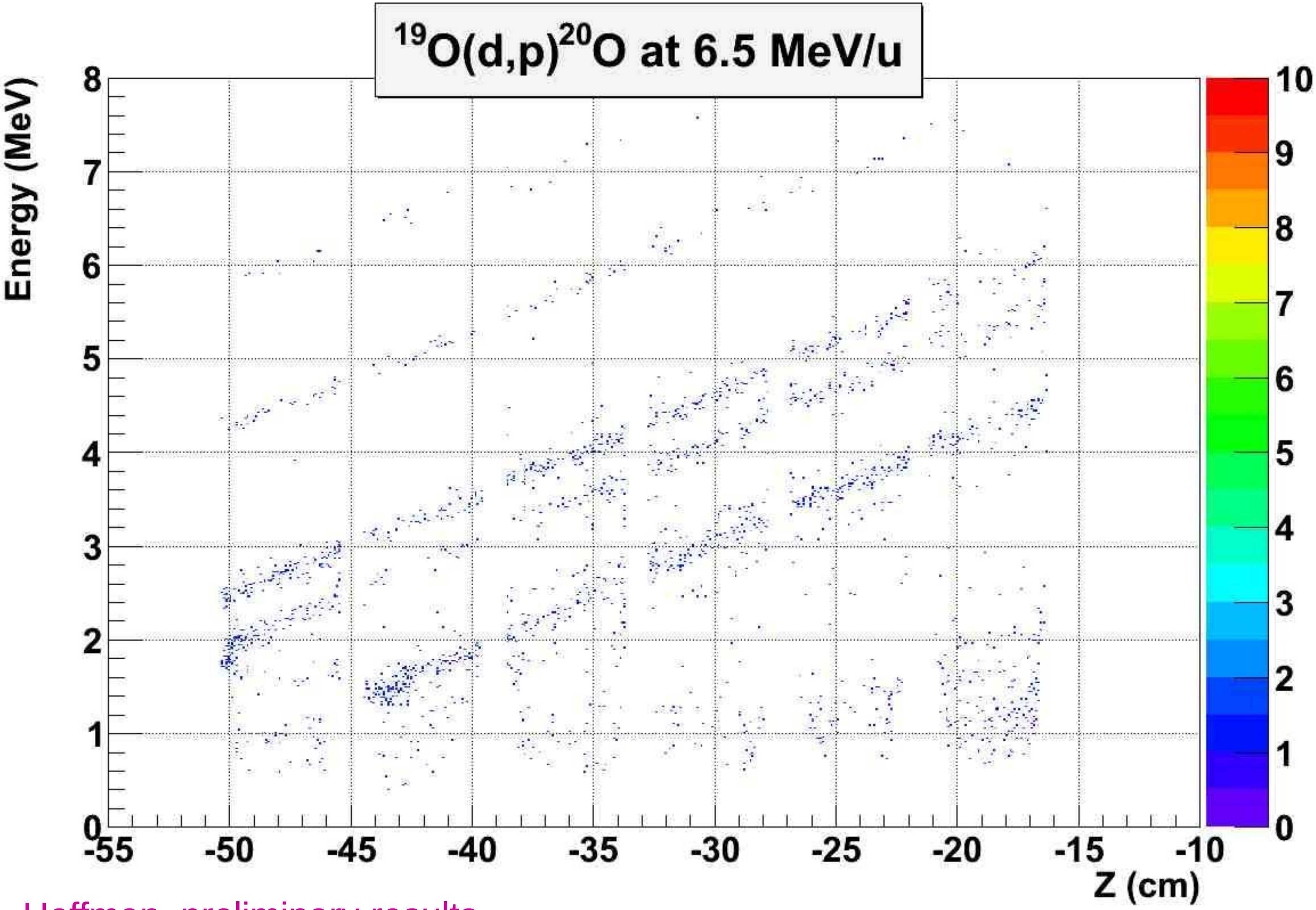
Excitation energies and relative spectroscopic factors from the shell model

Blue: L=0
Red: L=2

Agreement for SF is excellent!
No need for exotica

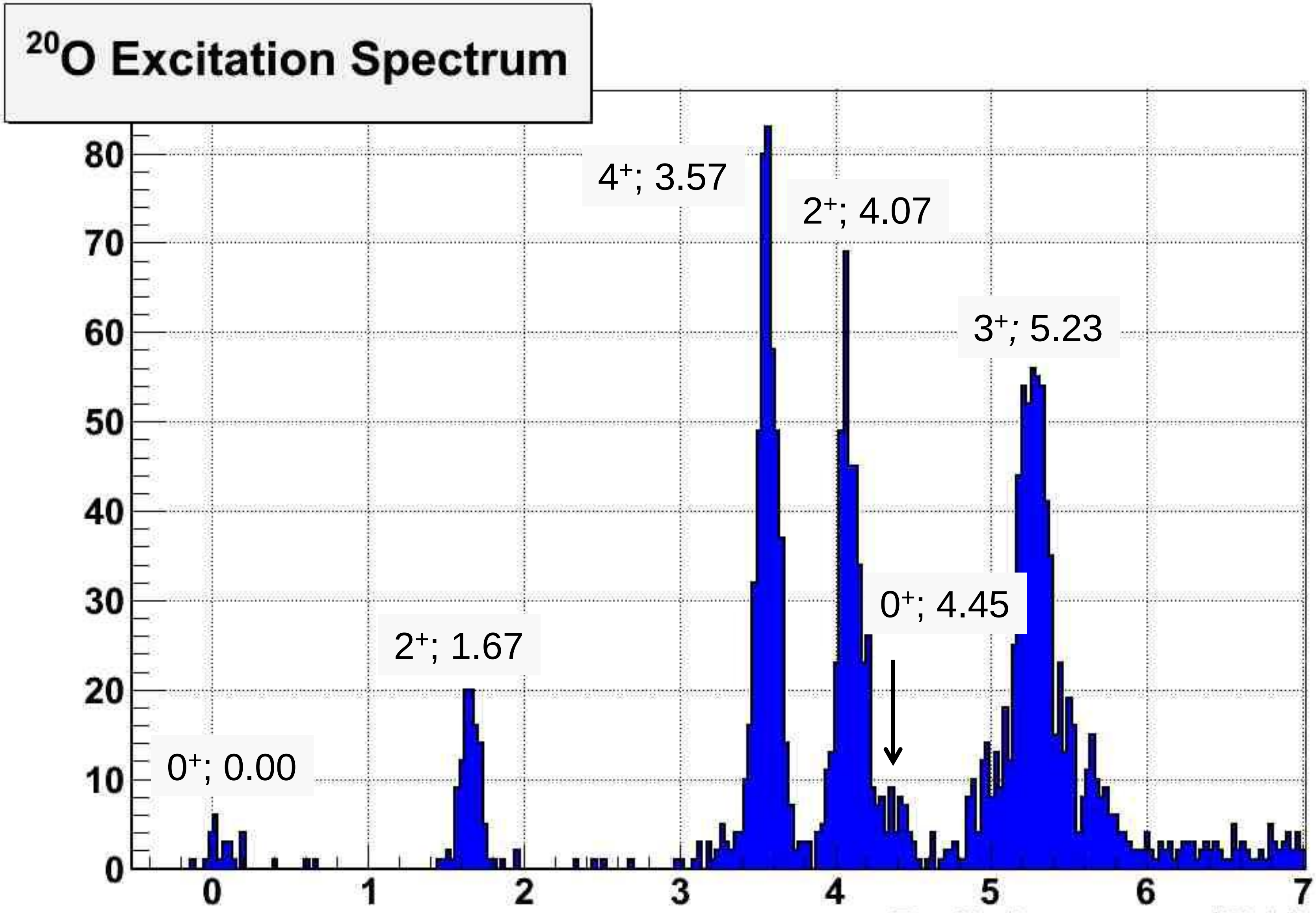
PRL **105**, 132501 (2010)

Further into the *sd* shell



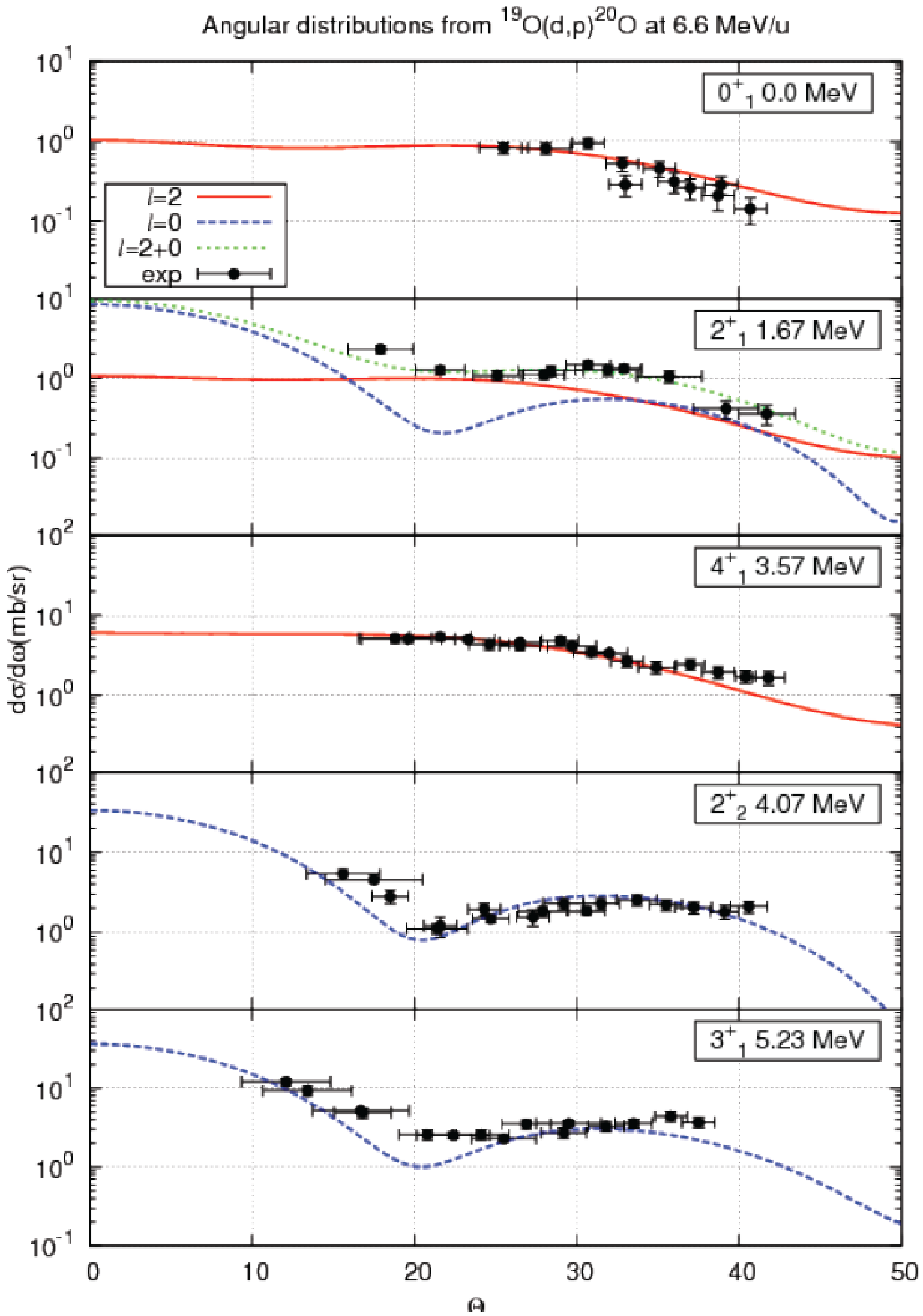
C. R. Hoffman, preliminary results

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



C. R. Hoffman, preliminary results

Angular distributions for $^{19}O(d,p)^{20}O$



Results will be analyzed to extract spectroscopic factors, configuration mixing.

C. R. Hoffman, preliminary results

Conclusions

- Despite concerns about the reliability of reaction theory, good absolute agreement with *ab-initio* form-factor calculations can be achieved at the 20-30% level for (*d,p*), even for unbound states.
- Other reactions are problematic: e.g. *absolute* (*d,t*) and ($d,{}^3He$) results show a strong dependence on optical-model parameters
- It seems that *relative* spectroscopic factors can be reproduced very well by *ab-initio* or SM calculations in most cases
- Interesting to extend studies further to unbound states to test structure calculations

Challenges/opportunities for reaction theory

- Need to understand OMP better for loosely-bound/unbound nuclei, and complex particles in the final state (e.g. ^{3}He, ^{3}H)
- DWBA is the workhorse, but is it sufficient? Lacks explicit treatment of 3-body effects (handled in, e.g., the Johnson-Soper approach) for (d,p).
  - No such animal is available for complex particles such as α, ^{3}H, ^{3}He, etc.

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S. C. Pieper
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S. Sinha
X. Tang
R. B. Wiringa

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L. Jisonna
R. E. Segel

KVI

R. H. Siemssen

Western Michigan University

J. Lighthall
S. Marley
N. Goodman
AHW

Hebrew University

M. Paul

CO School of Mines

N. Patel

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Office of Science
U.S. DEPARTMENT OF ENERGY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

And -

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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

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How HELIOS works

$$\vec{v}_{lab} = (v_{cm}\cos\theta_{cm} + V_{CM})\hat{z} + (v_{cm}\sin\theta_{cm})\hat{x}$$

$$v_{lab}^2 = v_{cm}^2 + V_{CM}^2 + 2V_{CM}v_{cm}\cos\theta_{cm}$$

$$but:$$

$$z = T_{cyc}(v_{cm}\cos\theta_{cm} + V_{CM})$$

$$v_{lab}^2 = v_{cm}^2 - V_{CM}^2 + \frac{2V_{CM}}{T_{CYC}}z$$

$$\therefore E_{lab} = E_{cm} - A + Bz$$