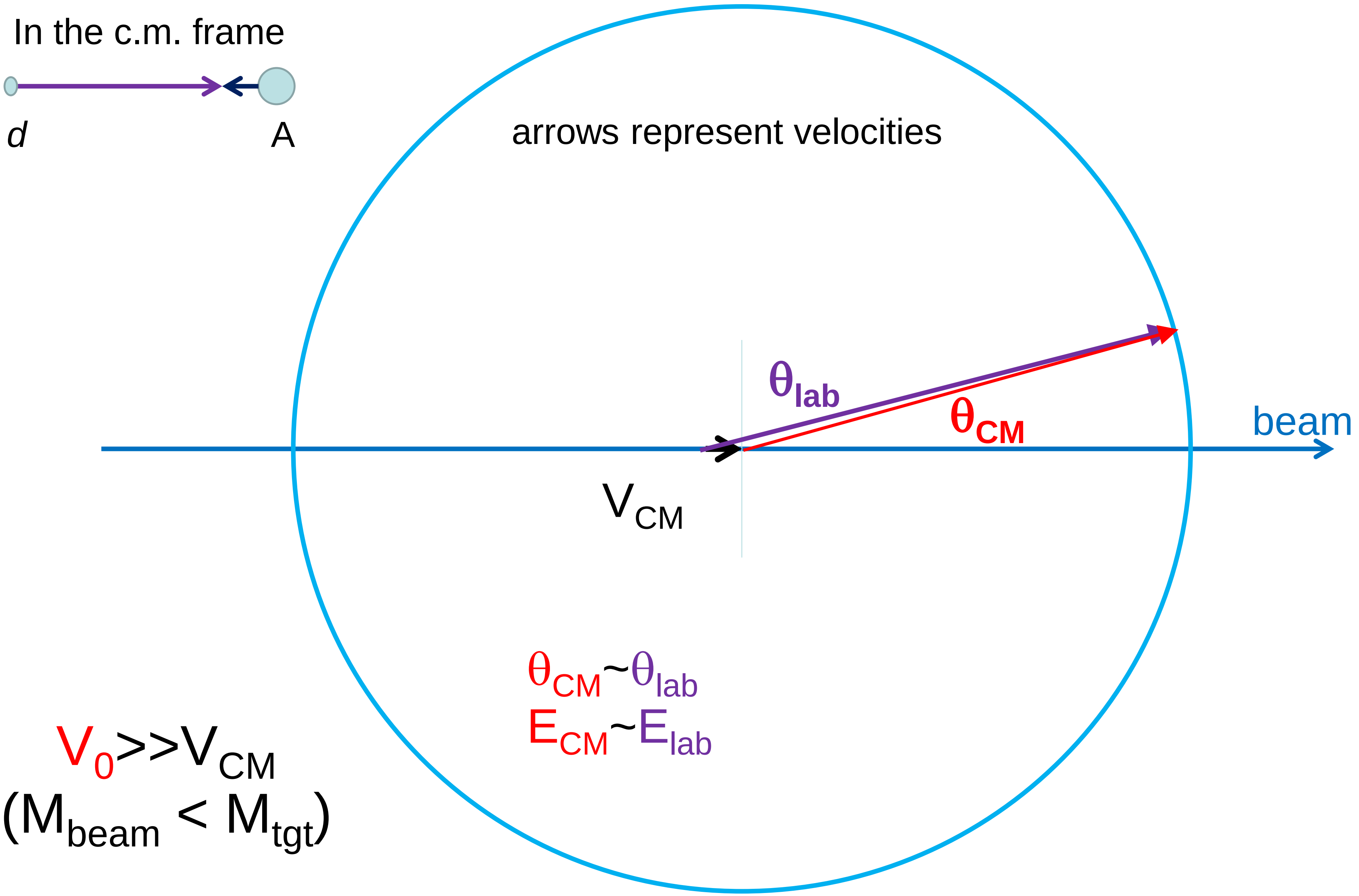
Nuclear reactions

Lecture 3

Modern concrete examples, and some techniques

How we can actually learn things

“Normal kinematics”



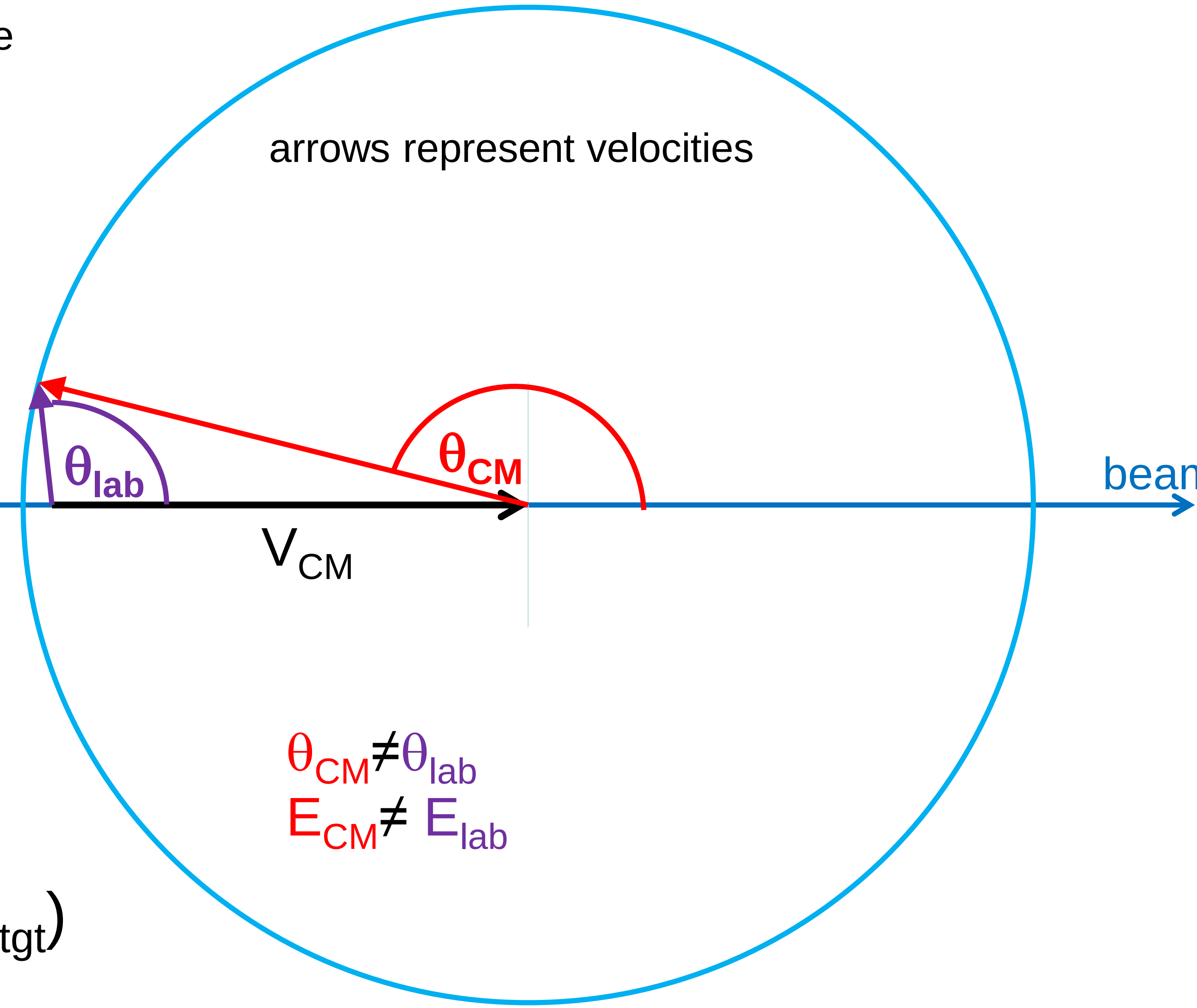
$V_0 >> V_{CM}$

$(M_{beam} < M_{tgt})$

“Inverse kinematics” I

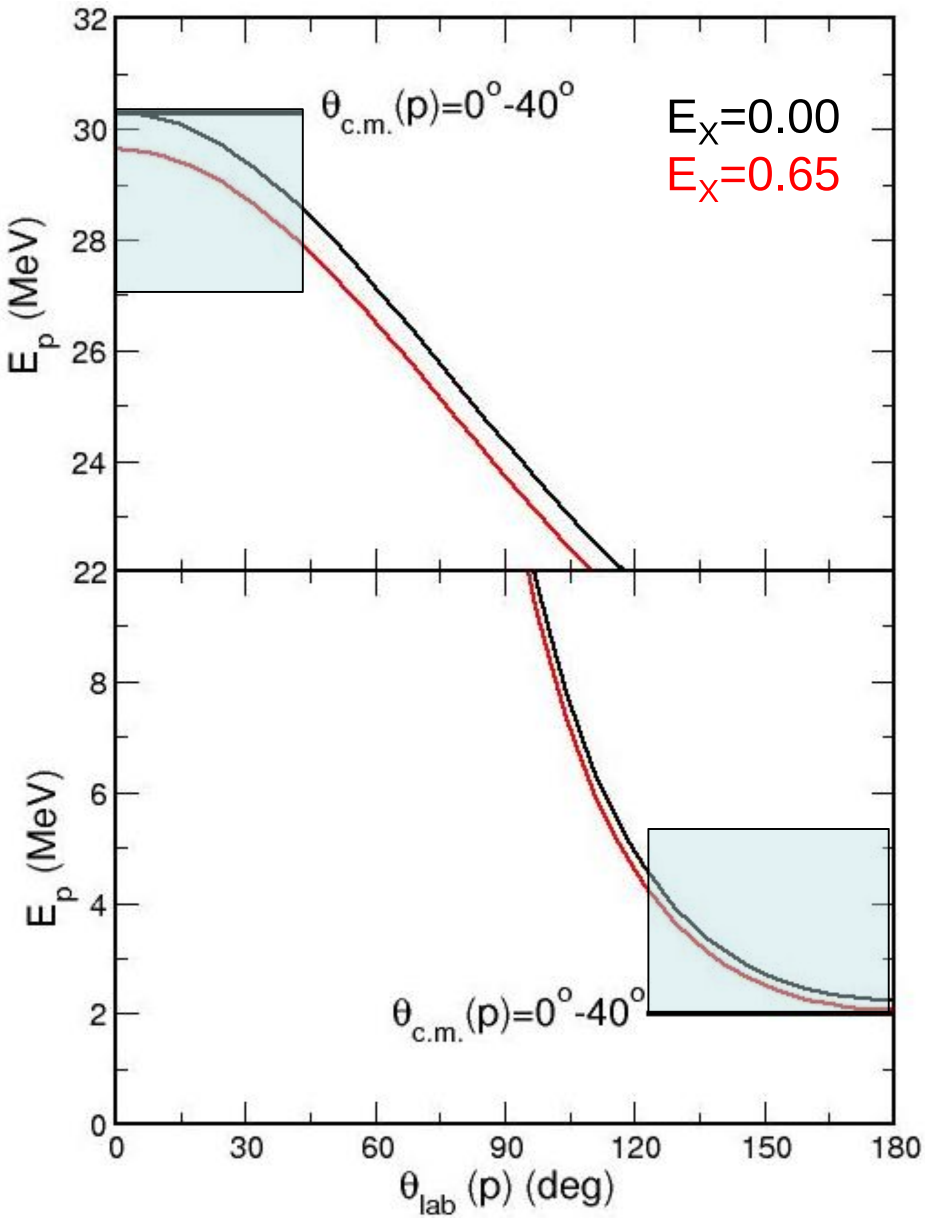
In the c.m. frame

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



$V_0 > V_{CM}$
$(M_{beam} > M_{tgt})$

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



Normal Kinematics
(^{2}H beam+^{13}B target)

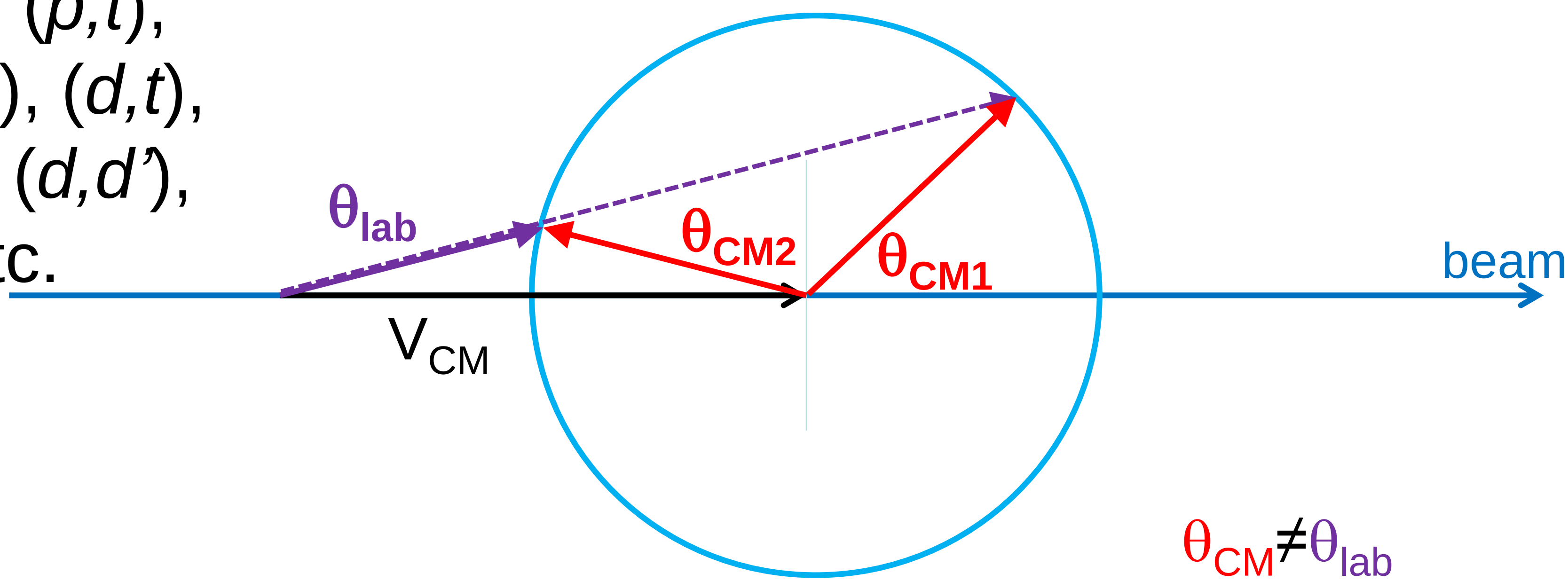
Inverse Kinematics
(^{13}B beam+^{2}H target)

"Inverse kinematics" II

In the c.m. frame

arrows represent velocities

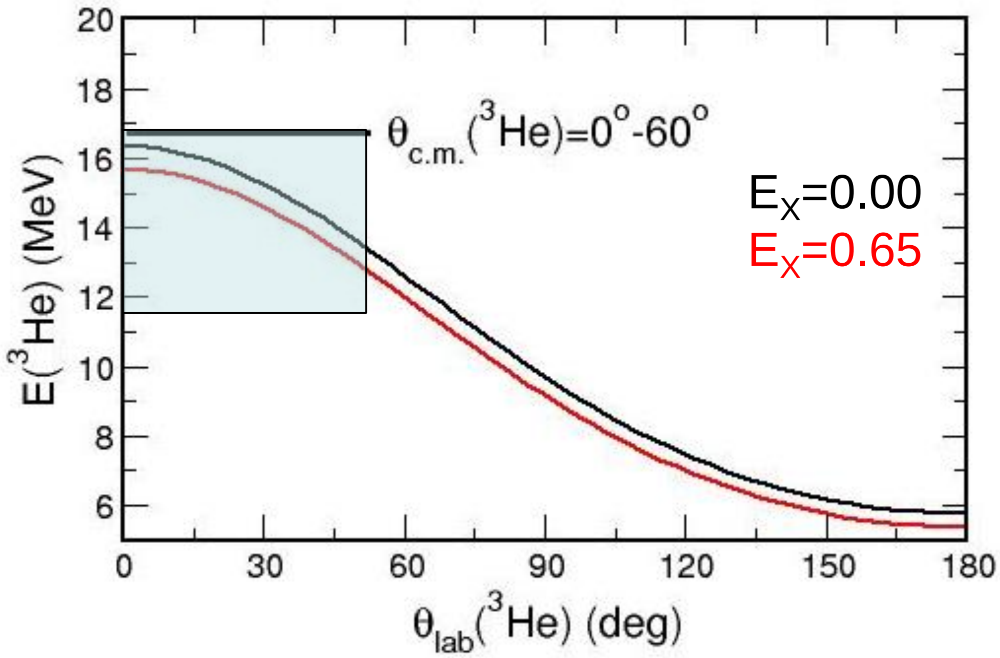
(p,d), (p,t), (d,^{3}He), (d,t), (p,p'), (d,d'), etc.



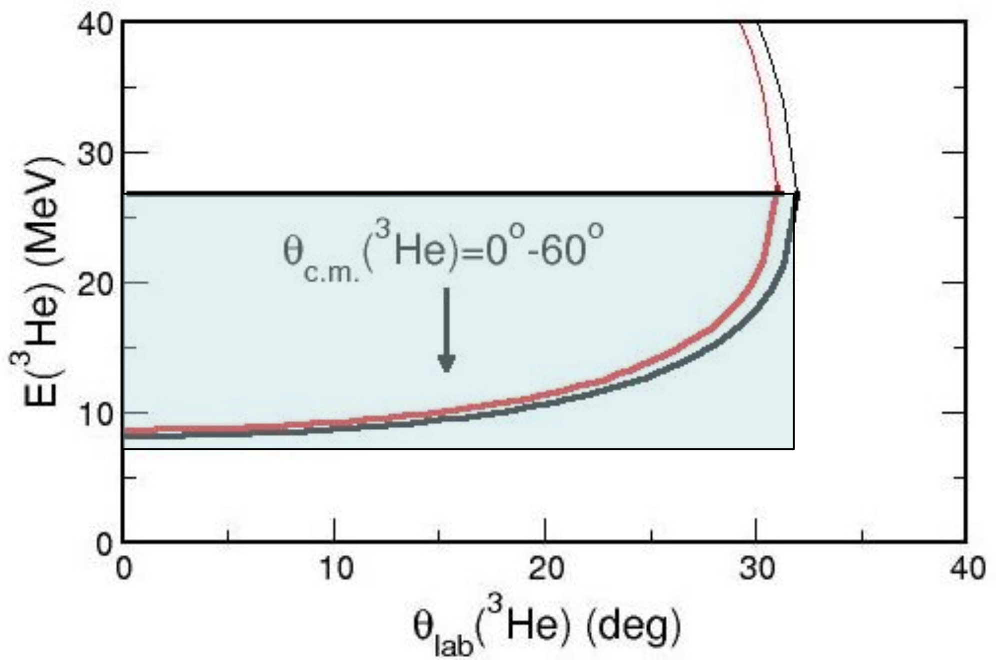
$V_0 < V_{CM}$
$(M_{beam} > M_{tgt})$

$\theta_{CM} \neq \theta_{lab}$
$E_{CM} \neq E_{lab}$
Two solutions

$^{15}C(d,{}^{3}He)^{14}B$ Kinematics

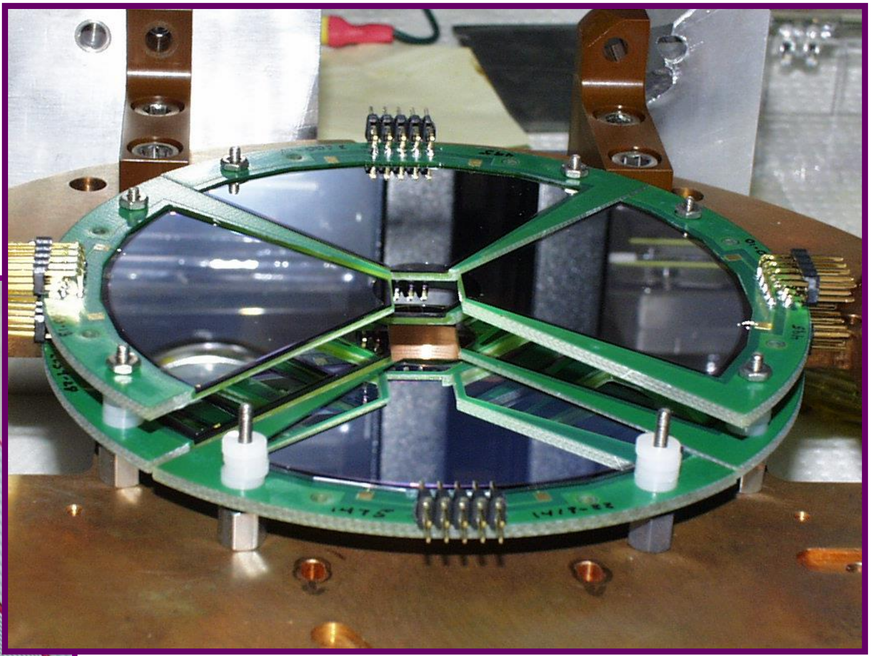


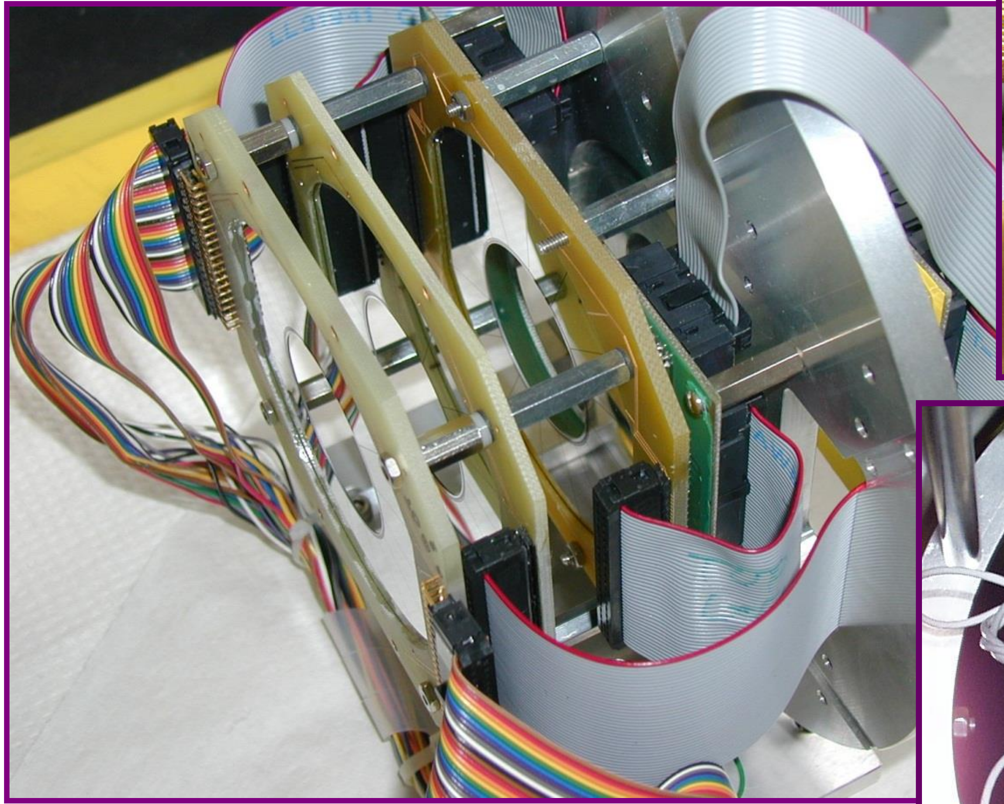
Normal Kinematics
(^{2}H beam+^{15}C target)

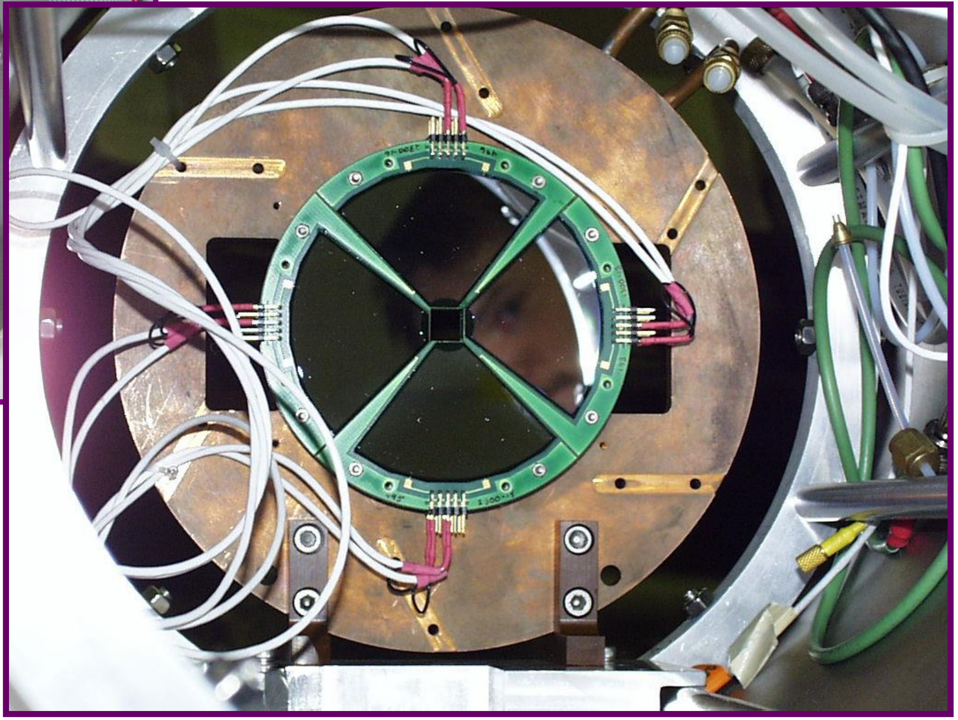


Inverse Kinematics
(^{15}C beam+^{2}H target)

Detectors



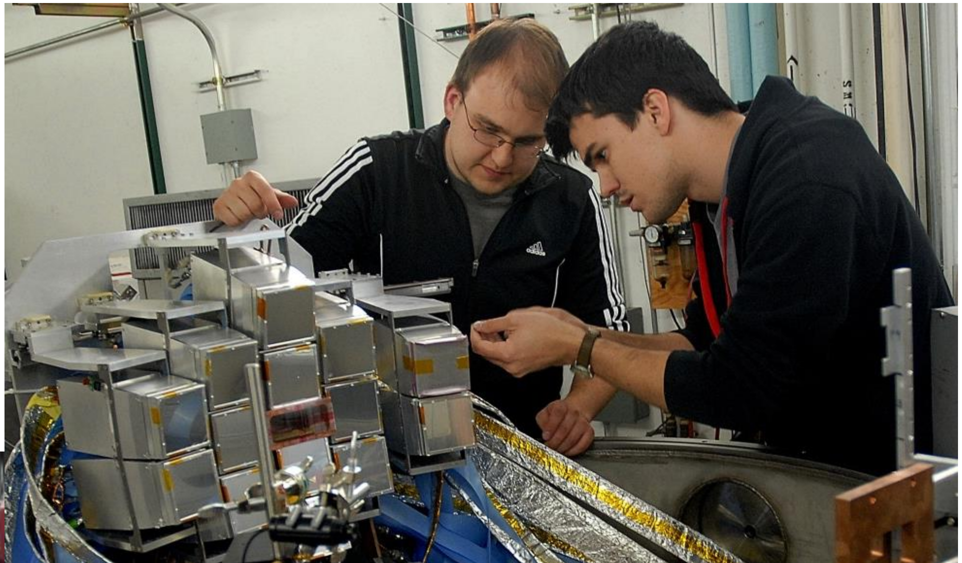




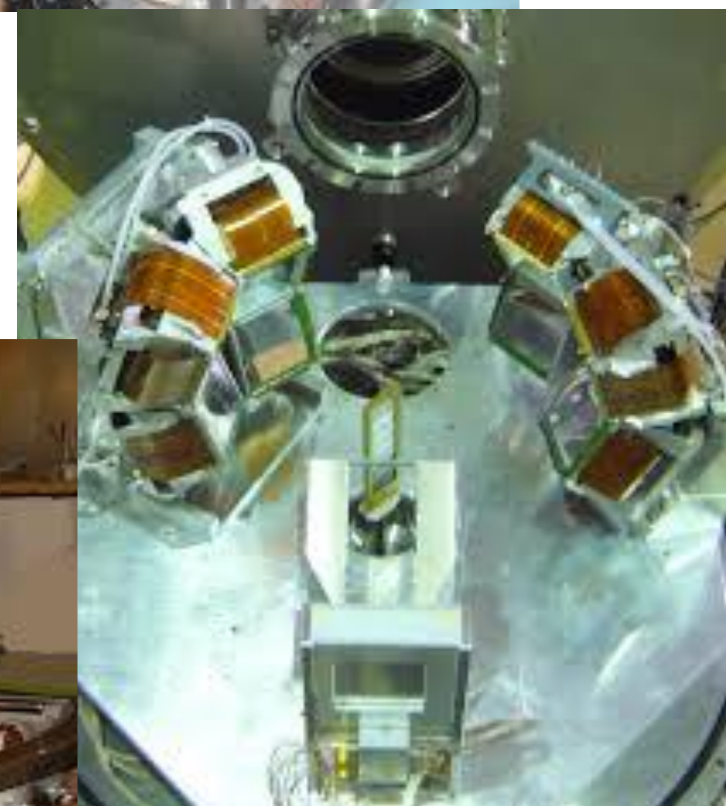
Segmented proton detectors

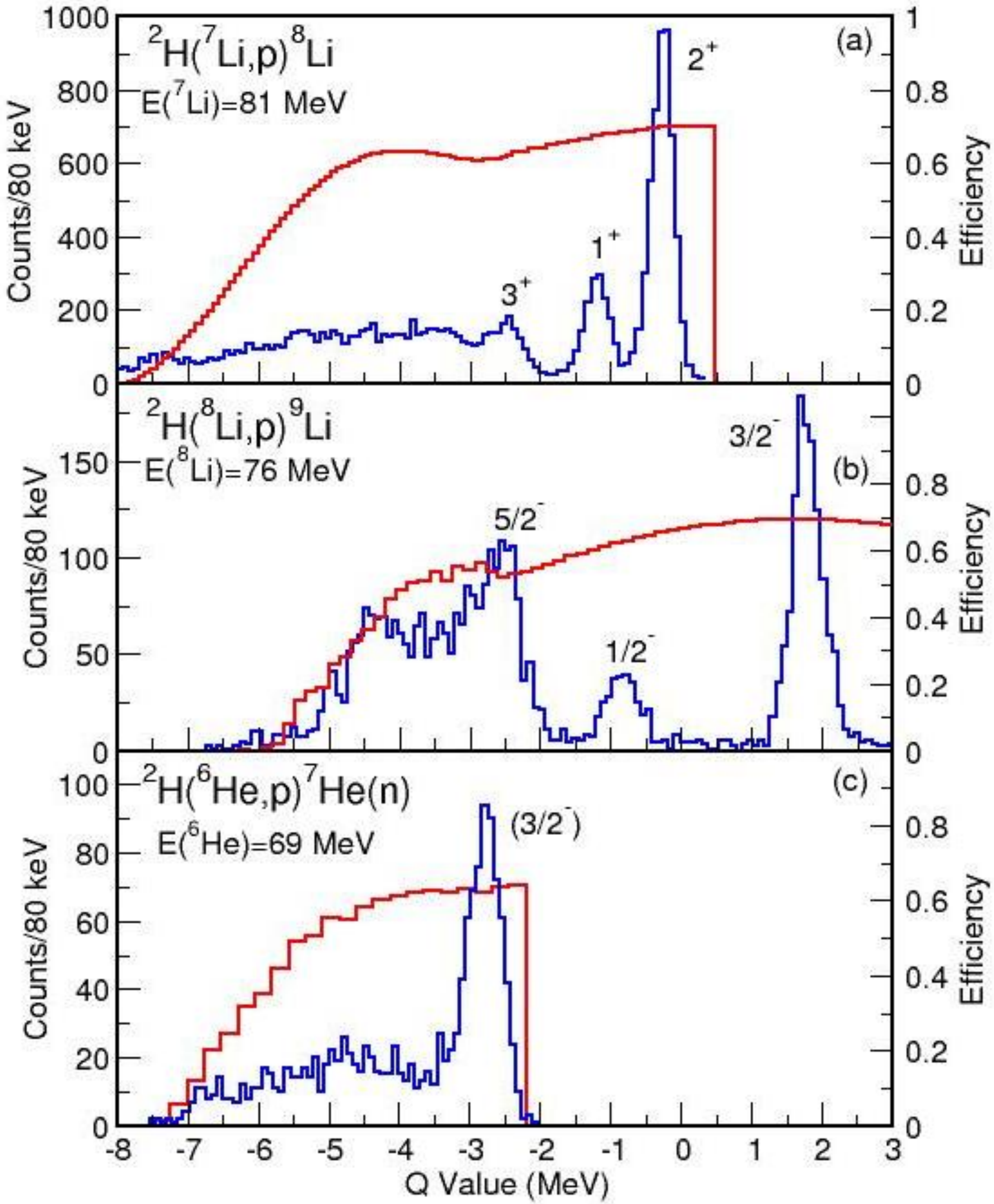
500μm/1000μm silicon EΔE telescope

Can be far more complicated…



Many, many detectors and channels…





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

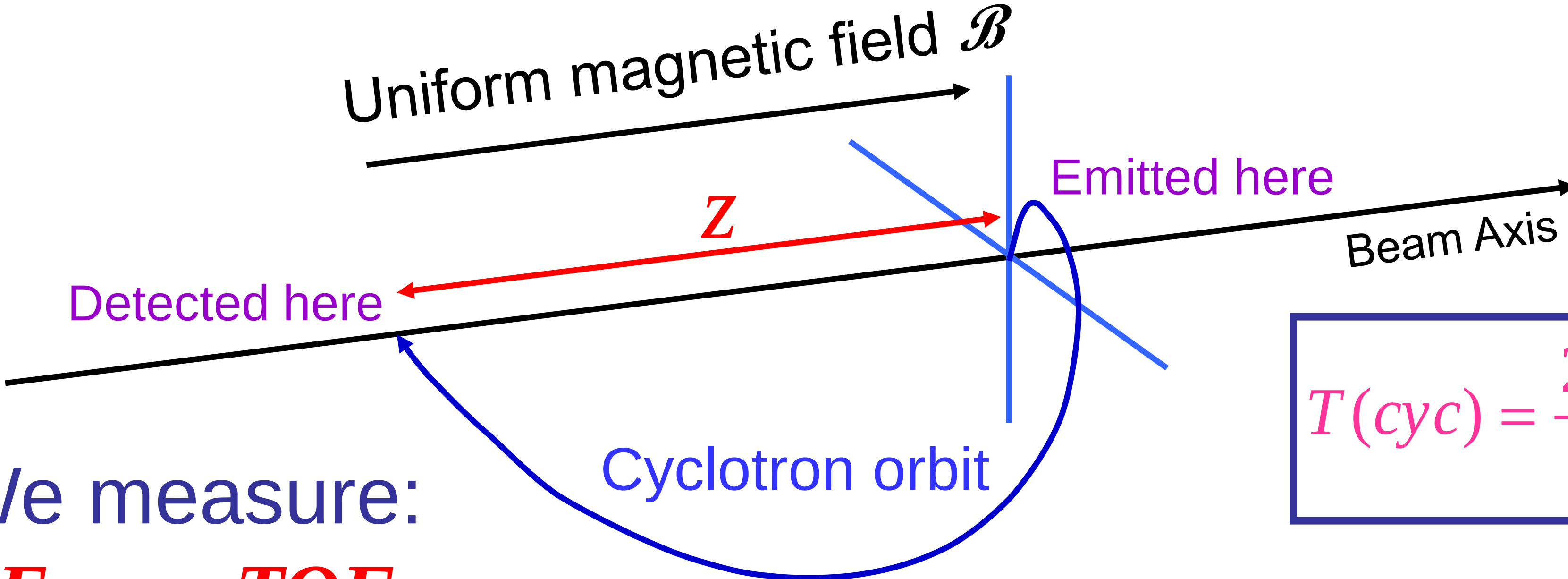
p-Li or p-^{6}He coincidences

Efficiency from Monte Carlo simulations

Resolution is 400-600 keV FWHM

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

The solenoid approach to inverse kinematics



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

We measure:

E_{lab}, z, TOF

We deduce:

E_{CM}, θ_{CM}

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

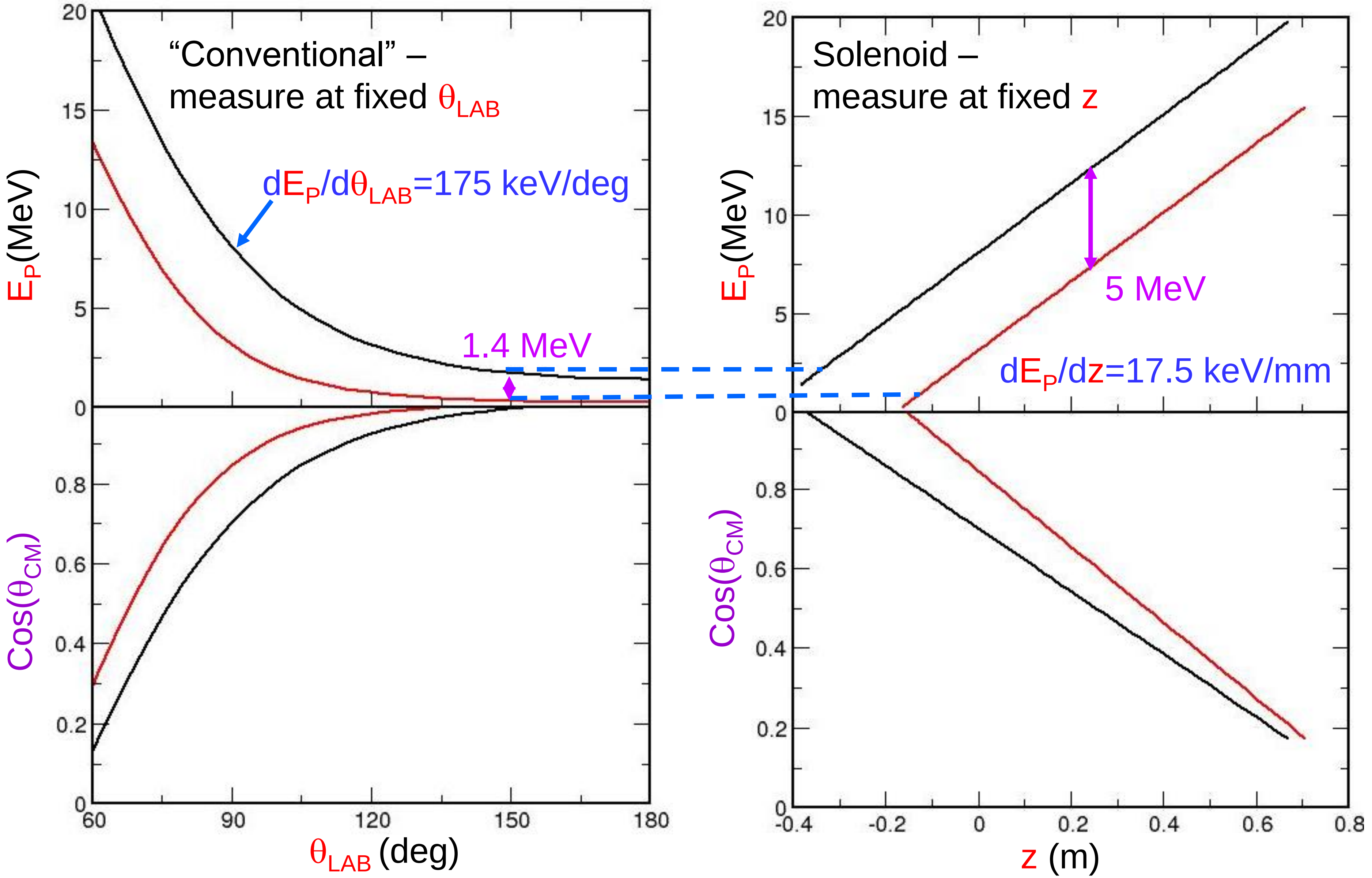
$$E_{lab} = E_{CM} - A + Bz$$

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

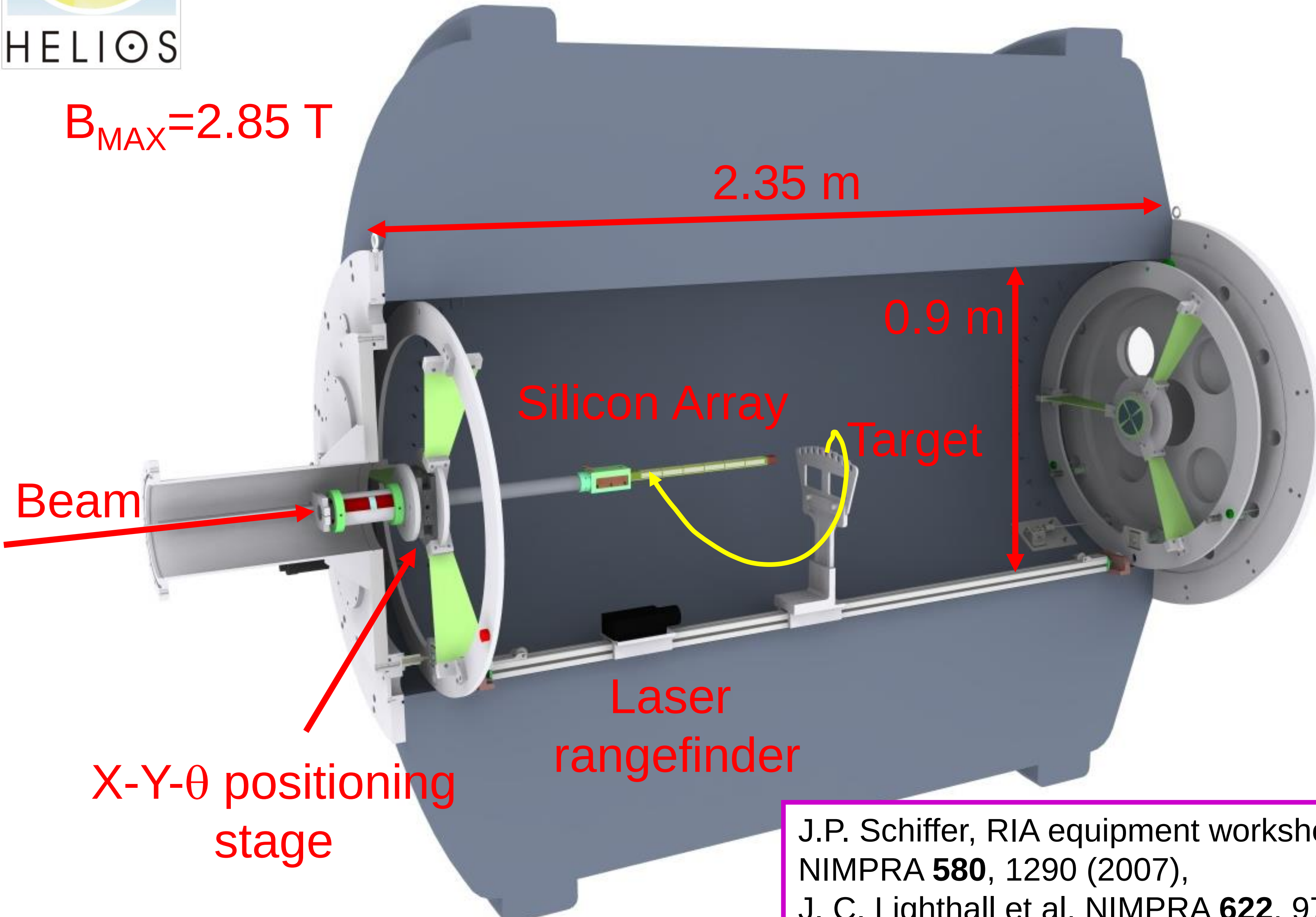
For a given state

For two states at fixed z

"Solenoid kinematics" for (*d*,*p*)

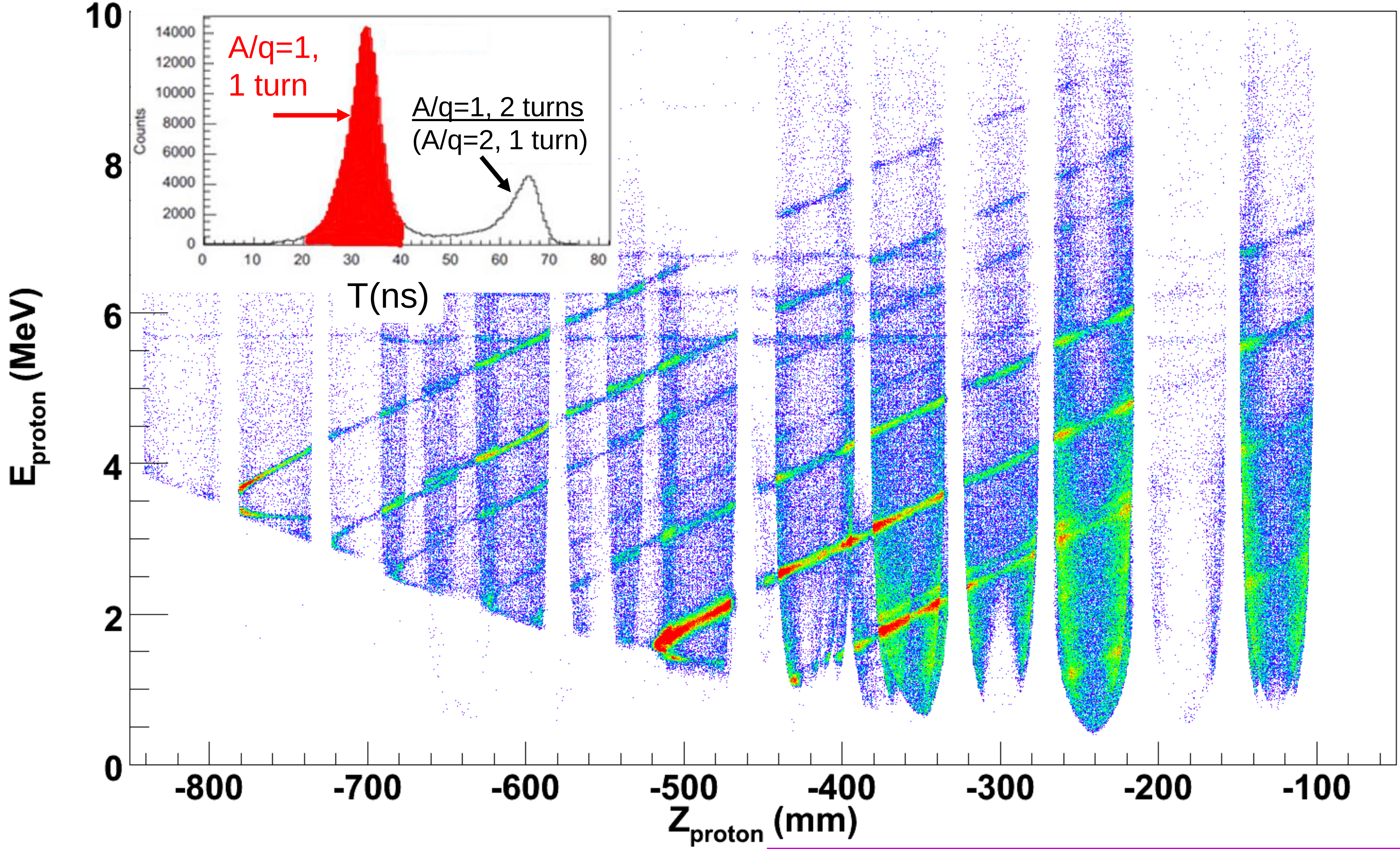


HELIcal Orbit Spectrometer -HELIOS



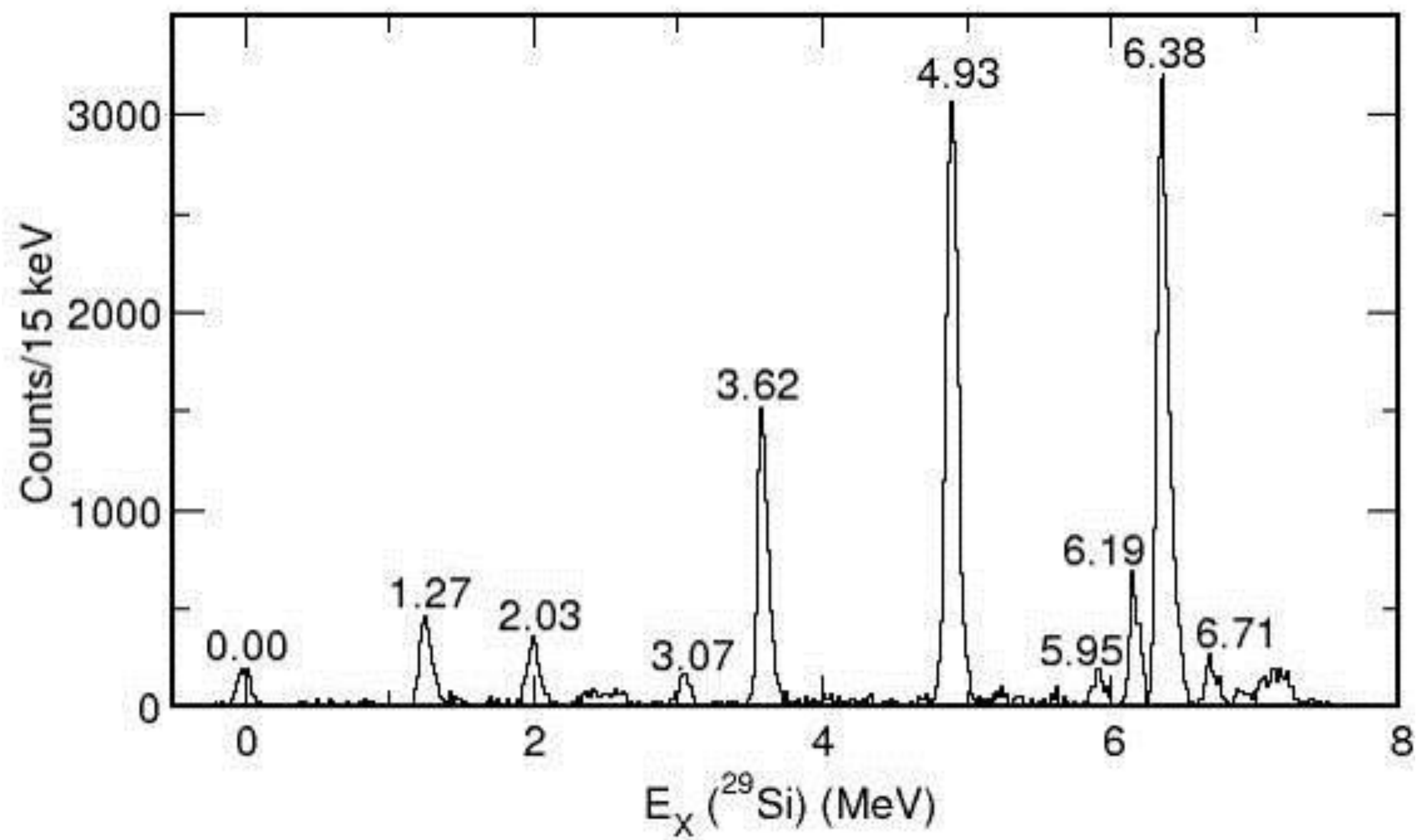
J.P. Schiffer, RIA equipment workshop 1999,
NIMPRA **580**, 1290 (2007),
J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

Stable beam, no recoil: $^{28}Si(d,p)^{29}Si$



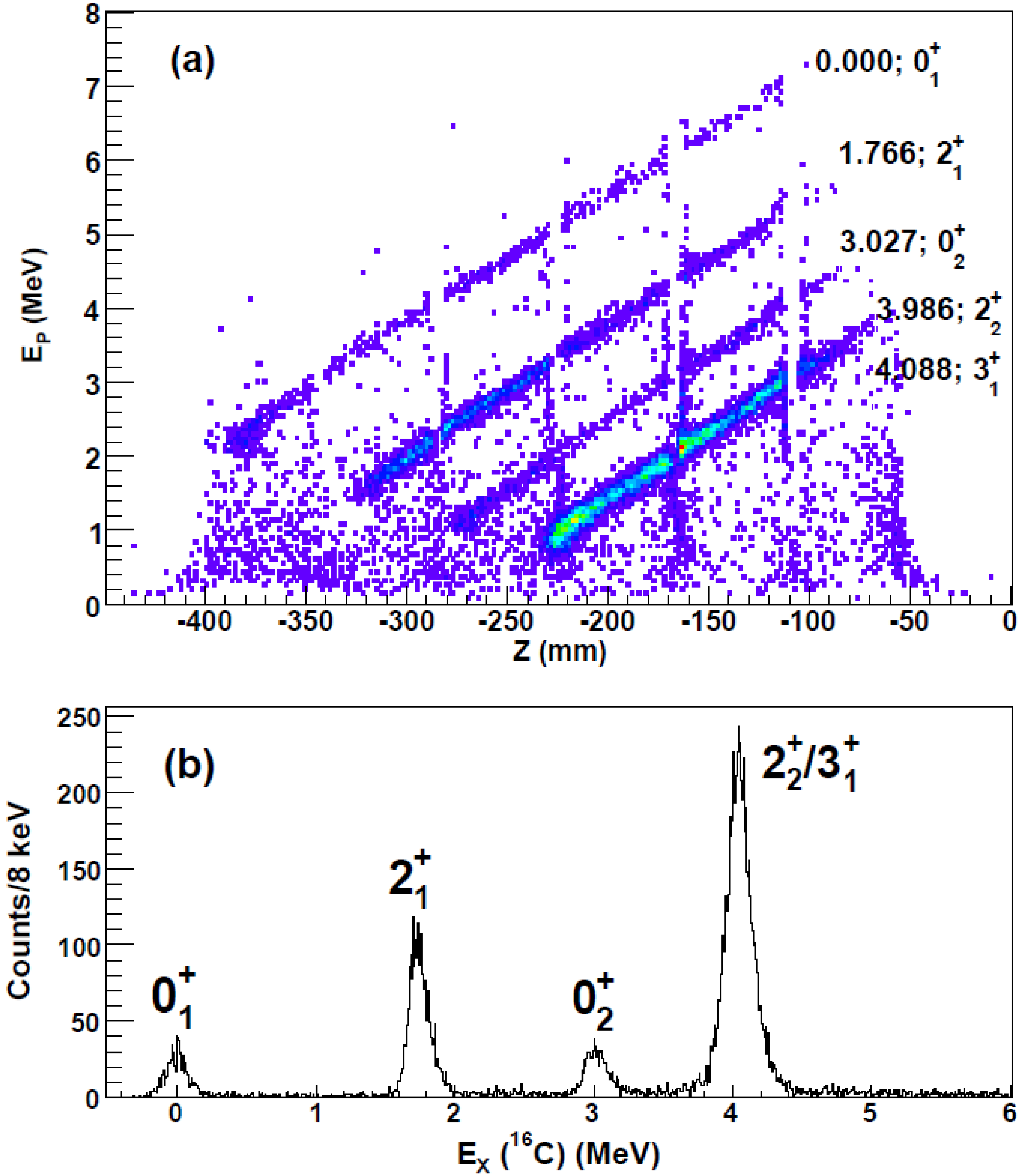
J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

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



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

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



Unstable beam $^{15}C(d,p)^{16}C$

Proton energy-position correlation with recoil

^{16}C Excitation-energy spectrum

Resolution is ~150 keV FWHM

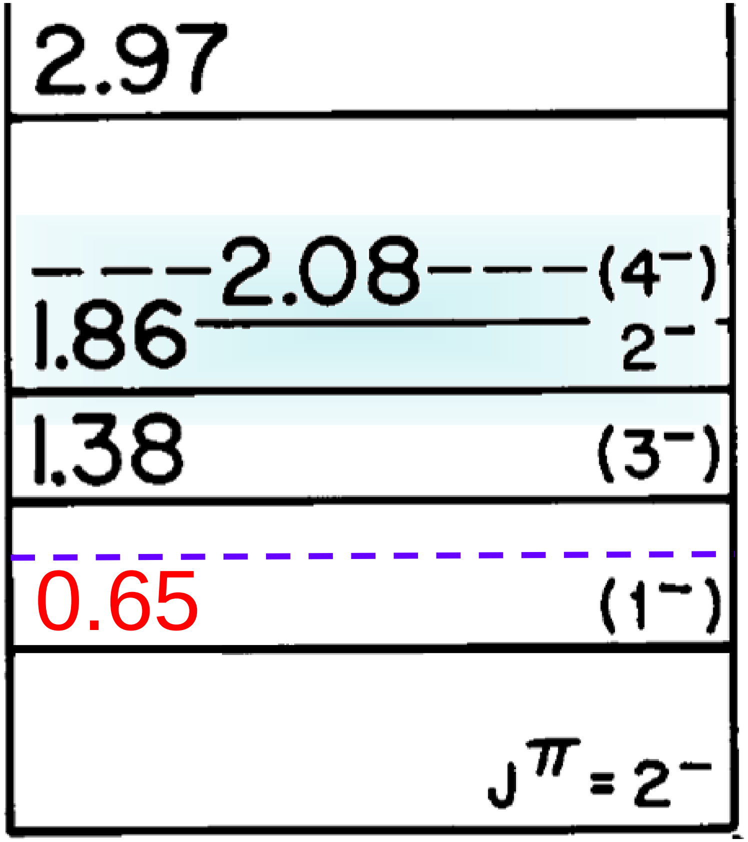
$I(^{15}C) \sim 10^6$ pps

PRL **105**, 132501 (2010)

^{14}B – as far as you can go with N=9 (and still be stable)

- We expect ^{14}B to have a neutron structure similar to ^{15}C with one neutron in $1s_{1/2}$ orbital
- But: Complications due to $p_{3/2}$ proton hole lead to multiplets of states, configuration mixing.
- Identification of the $L=0$ and 2 strength can pin down the single-particle energies

States in ^{14}B



^{14}B

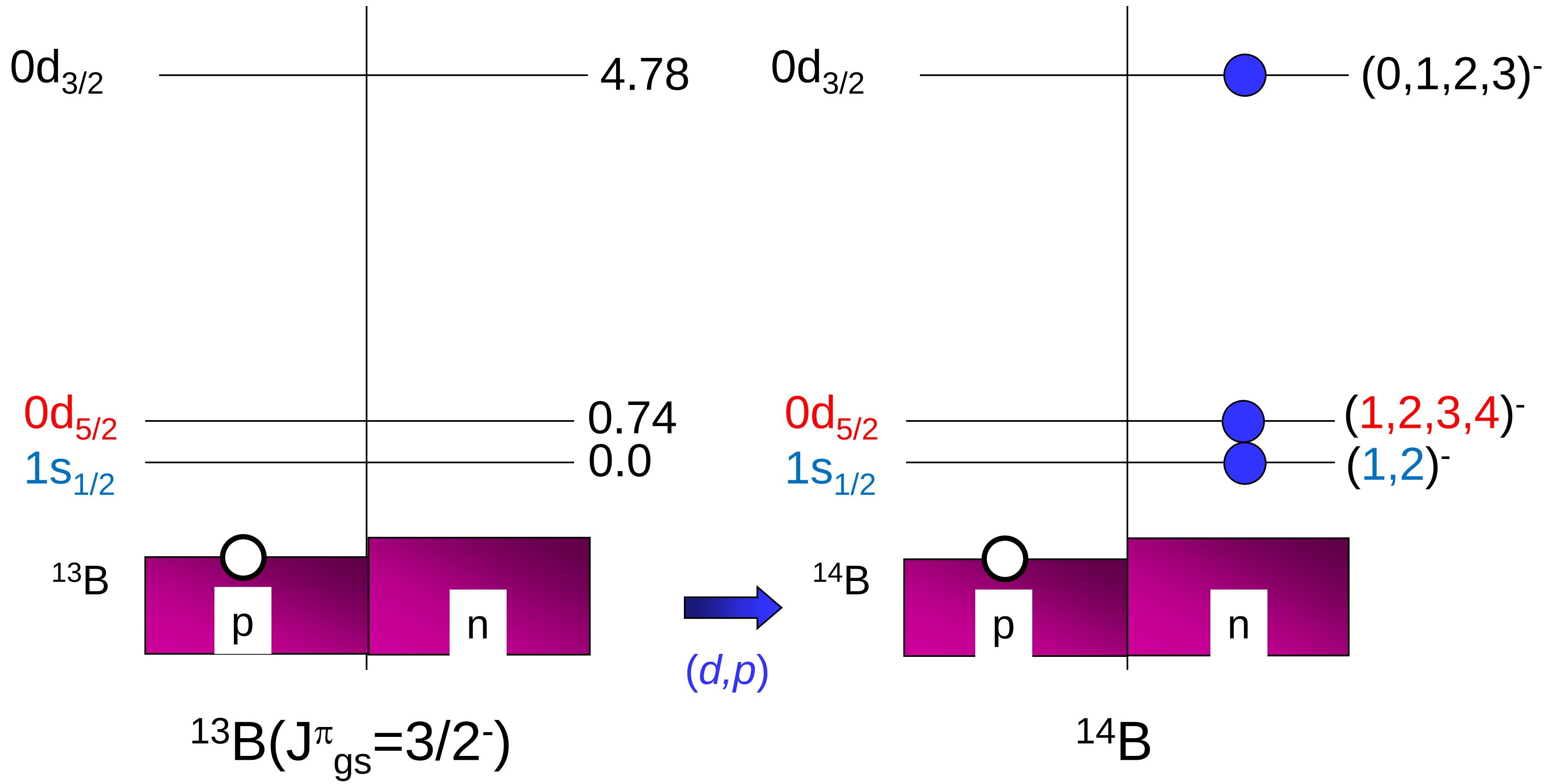
From most recent TUNL A=14 compilation (1991)

2^-_2 state is broad (Γ~1 MeV)

S_n=0.969 MeV

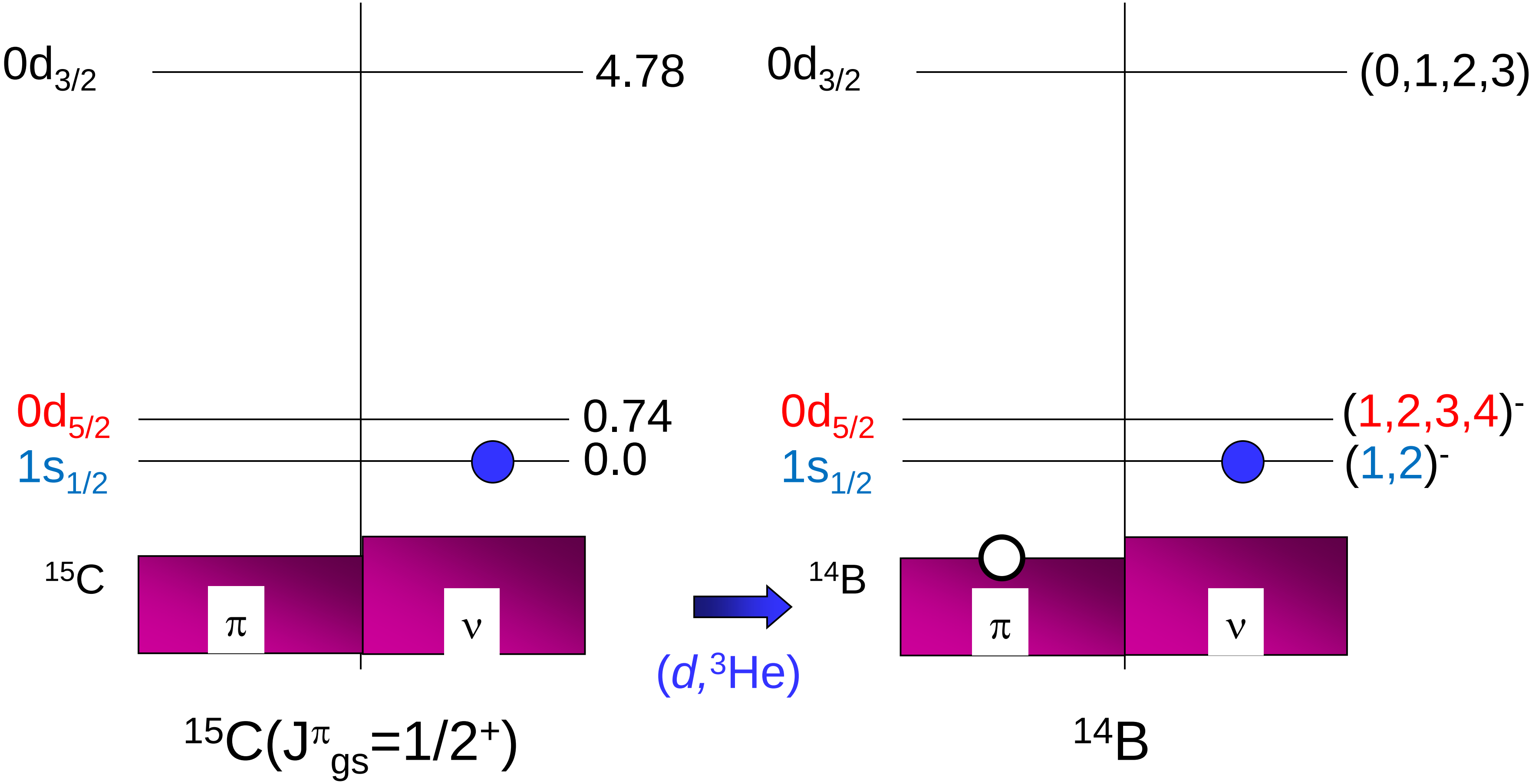
Most information is from ^{14}C(^{7}Li,^{7}Be)^{14}B and analogies to the ^{12}B spectrum.
More recent ^{14}Be β-decay work suggests positive-parity levels not shown here

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



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

Simple considerations for $^{15}C(d,^3He)^{14}B$



$(d,^3He)$ populates proton-hole states in ^{14}B

$\nu(sd)$ states in ^{14}B with (d,p)

$\psi(2_1^-) = \nu(1s_{1/2})\pi(0p_{3/2})^{-1}$

$\psi(2_2^-) = \nu(0d_{5/2})\pi(0p_{3/2})^{-1}$

2^-

$\psi(1_1^-) = \nu(1s_{1/2})\pi(0p_{3/2})^{-1}$

$\psi(1_2^-) = \nu(0d_{5/2})\pi(0p_{3/2})^{-1}$

1^-

$\psi(3_1^-) = \nu(0d_{5/2})\pi(0p_{3/2})^{-1}$

3^-

$\psi(4_1^-) = \nu(0d_{5/2})\pi(0p_{3/2})^{-1}$

4^-

Assuming that there is no mixing, states are pure

$\nu(sd)$ states in ^{14}B with (d,p)

$$\psi(2_1^-) = \alpha_2 \nu(1s_{1/2}) \pi(0p_{3/2})^{-1} + \beta_2 \nu(0d_{5/2}) \pi(0p_{3/2})^{-1}$$

$$\psi(2_2^-) = -\beta_2 \nu(1s_{1/2}) \pi(0p_{3/2})^{-1} + \alpha_2 \nu(0d_{5/2}) \pi(0p_{3/2})^{-1}$$

2^-

$$\psi(1_1^-) = \alpha_1 \nu(1s_{1/2}) \pi(0p_{3/2})^{-1} + \beta_1 \nu(0d_{5/2}) \pi(0p_{3/2})^{-1}$$

$$\psi(1_2^-) = -\beta_1 \nu(1s_{1/2}) \pi(0p_{3/2})^{-1} + \alpha_1 \nu(0d_{5/2}) \pi(0p_{3/2})^{-1}$$

1^-

$$\psi(3_1^-) = \alpha_3 \nu(0d_{5/2}) \pi(0p_{3/2})^{-1}$$

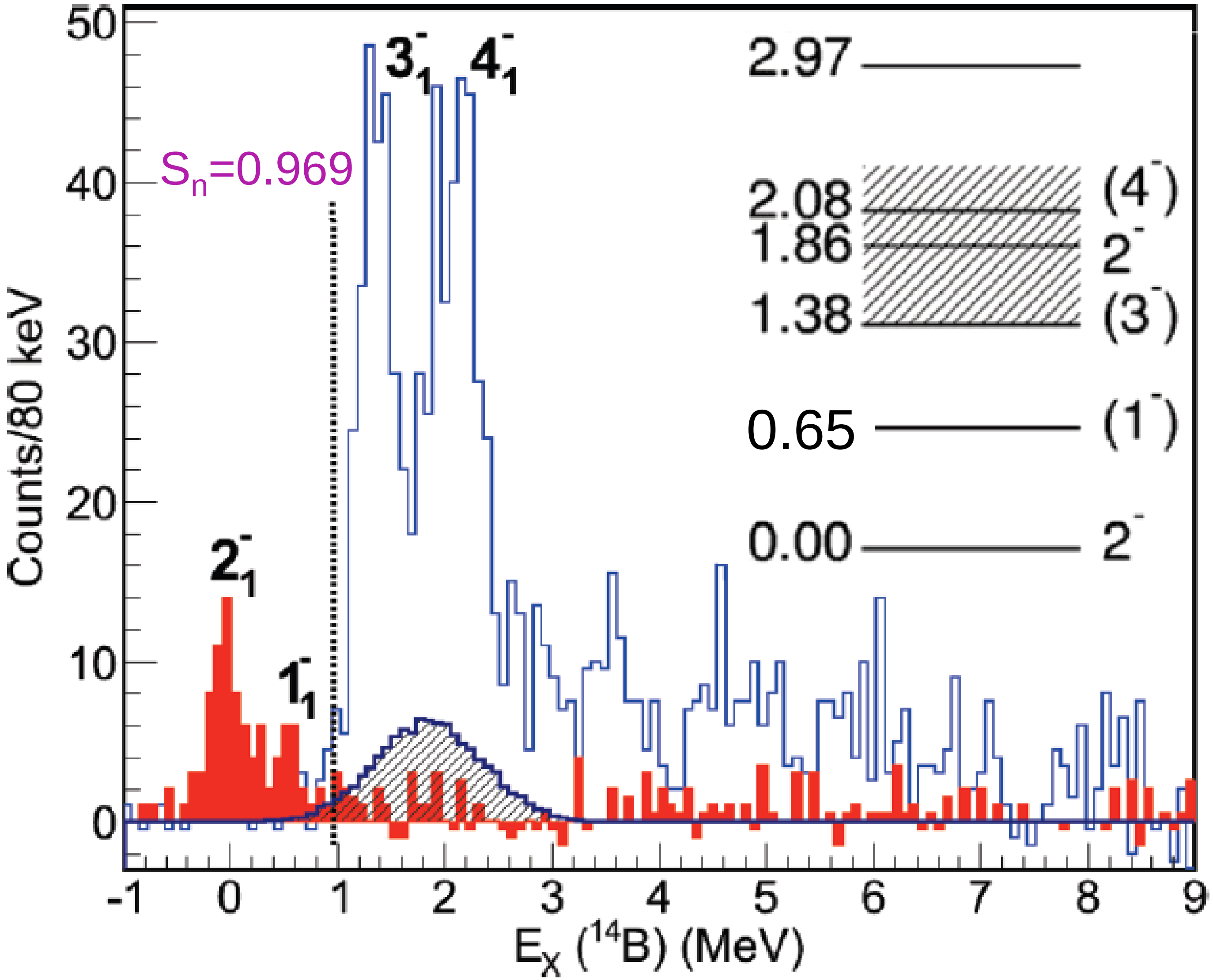
3^-

$$\psi(4_1^-) = \alpha_4 \nu(0d_{5/2}) \pi(0p_{3/2})^{-1}$$

4^-

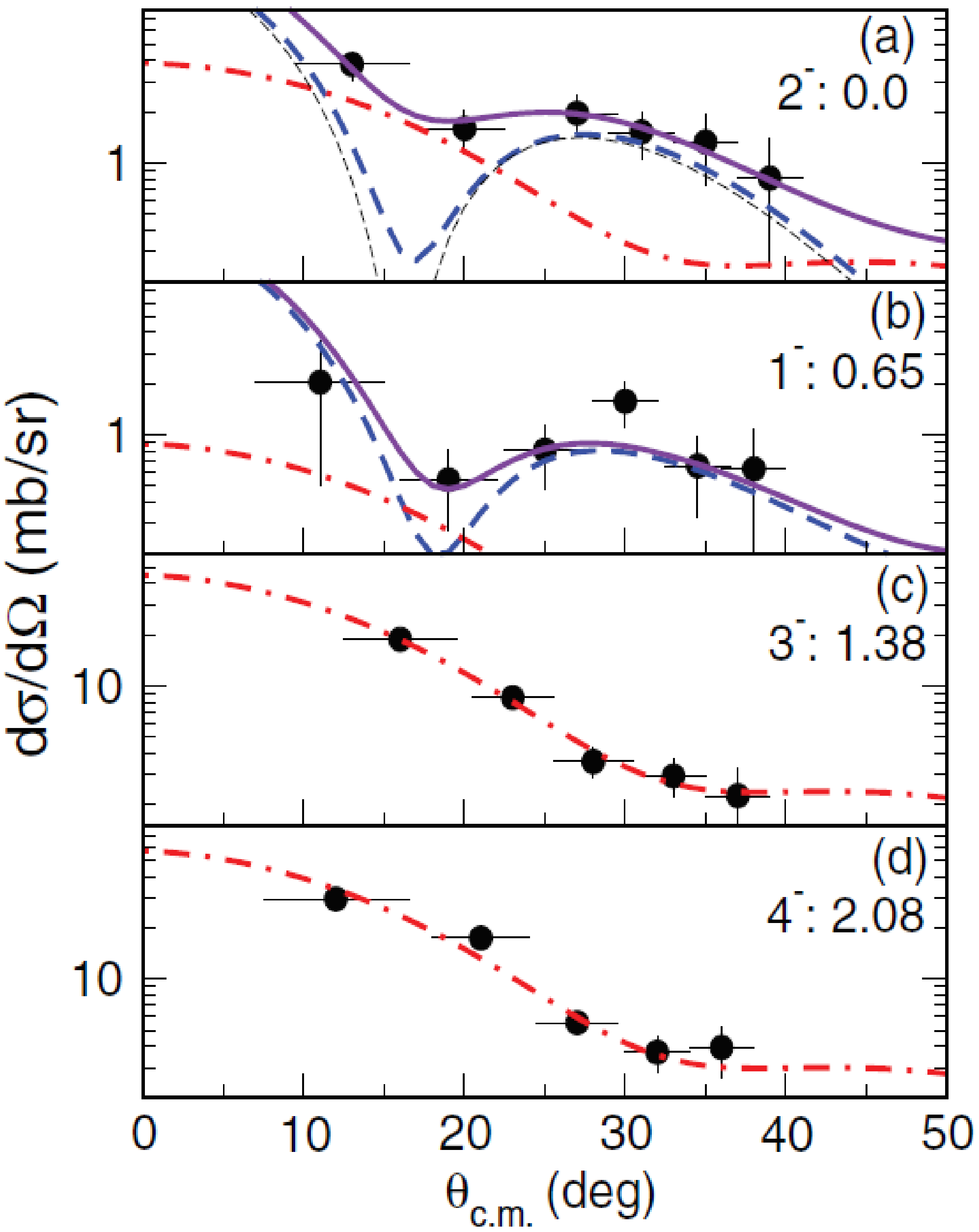
(d,p) spectroscopic factors give us the α's and the β's

^{14}B Excitation-energy spectrum



Bedoor et al., PRC **88** 011304 (2013)

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

Bedoor et al., PRC **88** 011304 (2013)

Sum rules with simple, pure states:

All S = 1.0 and ($2J_I$+1=4)

$$\#holes = 1 \times \frac{5}{4} + 1 \times \frac{3}{4} = 2\ (s_{1/2})$$

$$\#holes = 1 \times \frac{5}{4} + 1 \times \frac{3}{4} + 1 \times \frac{7}{4} + 1 \times \frac{9}{4} = 6\ (d_{5/2})$$

$J_F =$ 2 1 3 4

Sum rules with observed states:

Measured S $(2J_I+1=4)$

$$\#holes = 0.71 \times \frac{5}{4} + 0.96 \times \frac{3}{4} = 1.6\ (s_{1/2})$$

$$\#holes = 0.17 \times \frac{5}{4} + 0.06 \times \frac{3}{4} + 1 \times \frac{7}{4} + 1 \times \frac{9}{4} = 4.3\ (d_{5/2})$$

$J_F =$ 2 1 3 4

We're missing two states!

A game with sum rules…

$$\psi(2^-_1) = \alpha_2 \nu(1s_{1/2})\pi(0p_{3/2})^{-1} + \beta_2 \nu(0d_{5/2})\pi(0p_{3/2})^{-1}$$

$$\psi(2^-_2) = -\beta_2 \nu(1s_{1/2})\pi(0p_{3/2})^{-1} + \alpha_2 \nu(0d_{5/2})\pi(0p_{3/2})^{-1}$$

2^-

$$\psi(1^-_1) = \alpha_1 \nu(1s_{1/2})\pi(0p_{3/2})^{-1} + \beta_1 \nu(0d_{5/2})\pi(0p_{3/2})^{-1}$$

$$\psi(1^-_2) = -\beta_1 \nu(1s_{1/2})\pi(0p_{3/2})^{-1} + \alpha_1 \nu(0d_{5/2})\pi(0p_{3/2})^{-1}$$

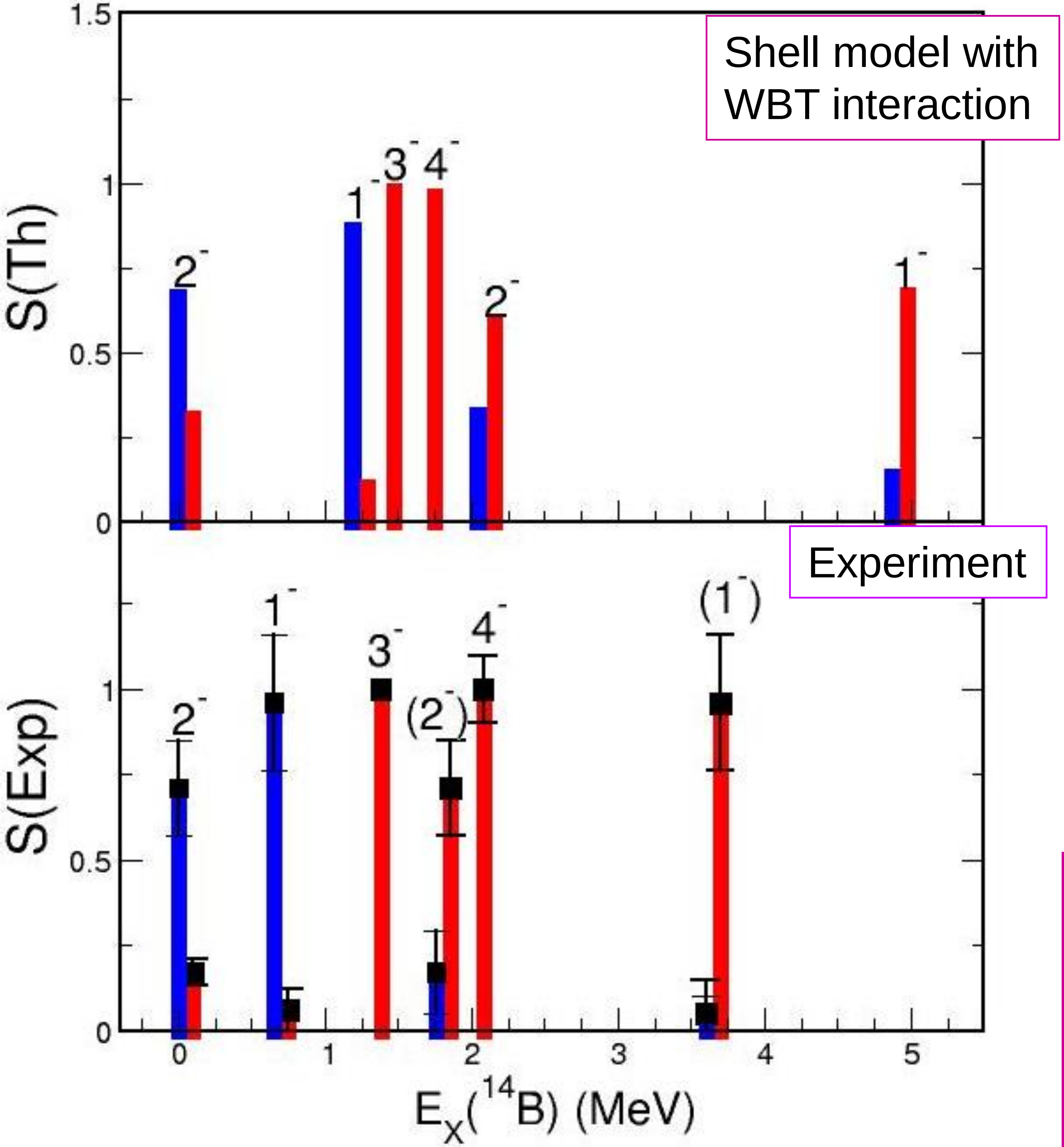
1^-

Assume $\psi(2^-_2)$ and $\psi(1^-_2)$ are the orthogonal partners of $\psi(2^-_1)$ and $\psi(1^-_1)$. We already know α_2,β_2 and α_1,β_1, so we can then guess the spectroscopic factors for $\psi(2^-_2)$ and $\psi(1^-_2)$.

Then:

Experimentally, $\Sigma S[J_f]/4$=5.9 (L=2) and 1.9 (L=0) compared to the sum-rule values of 6.0 and 2.0.

$^{13}B(d,p)^{14}B$ 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^- mostly L=0
Reasonable agreement
But *caveat emptor*!

Another game…

Can we *estimate* the $1s_{1/2}$ and $0d_{5/2}$ single-particle energies in ^{14}B?

No narrow states left.
We assume $^{14}B(2^-_2)$ is the broad state at 1.86 MeV, and we assume $^{14}B(1^-_2)$ is a broad state at 3.6 MeV (there seems to be something there in (*d*,*p*) with *L*=2).

$$\langle E_0 \rangle_j = \frac{\sum_i (2J_i + 1) S_i E_{xi}}{\sum_i (2J_i + 1) S_i}$$

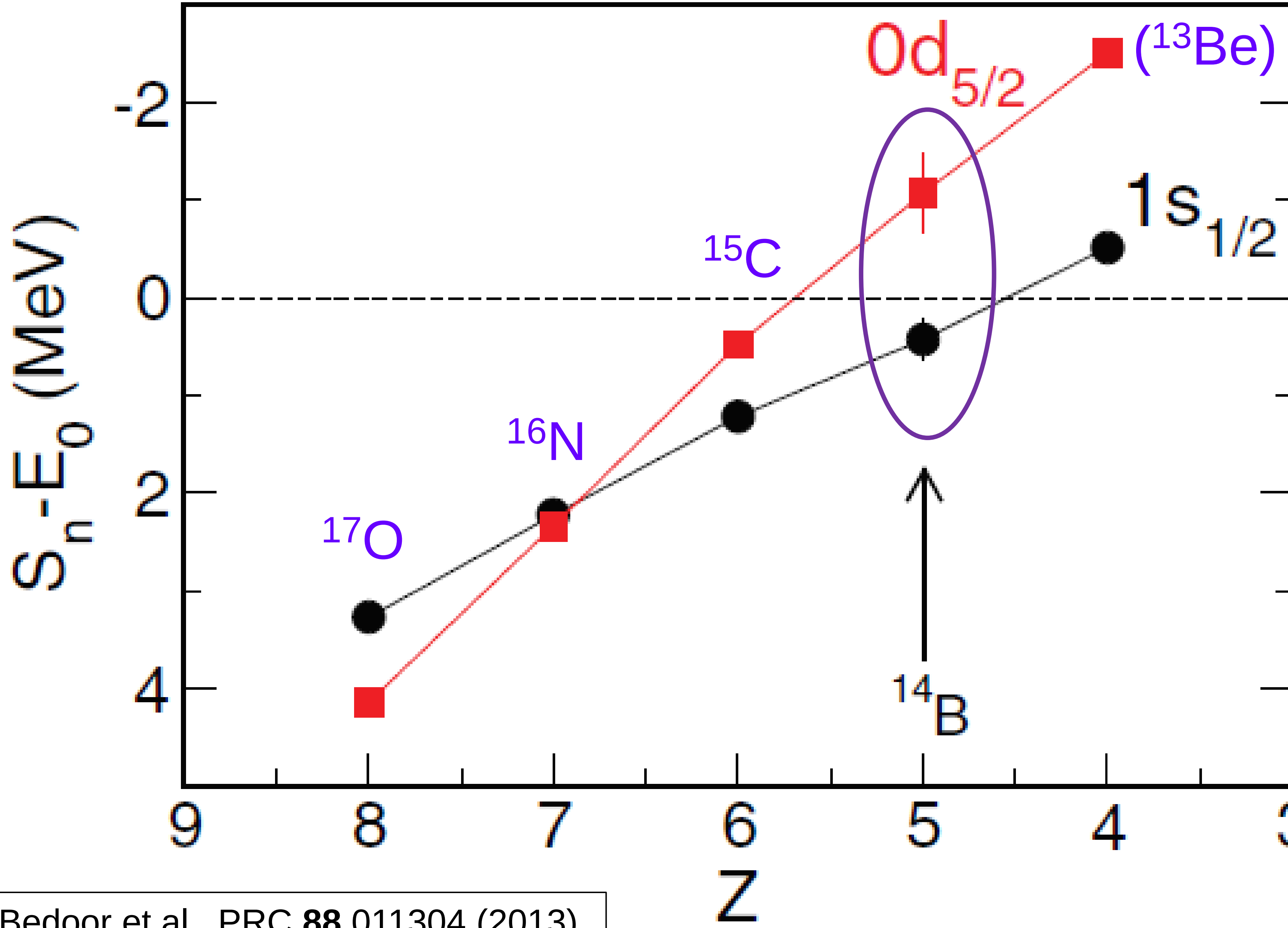
Then:

$\langle E_0 \rangle(1s_{1/2})$=0.55 MeV

$\langle E_0 \rangle(0d_{5/2})$=1.94 MeV

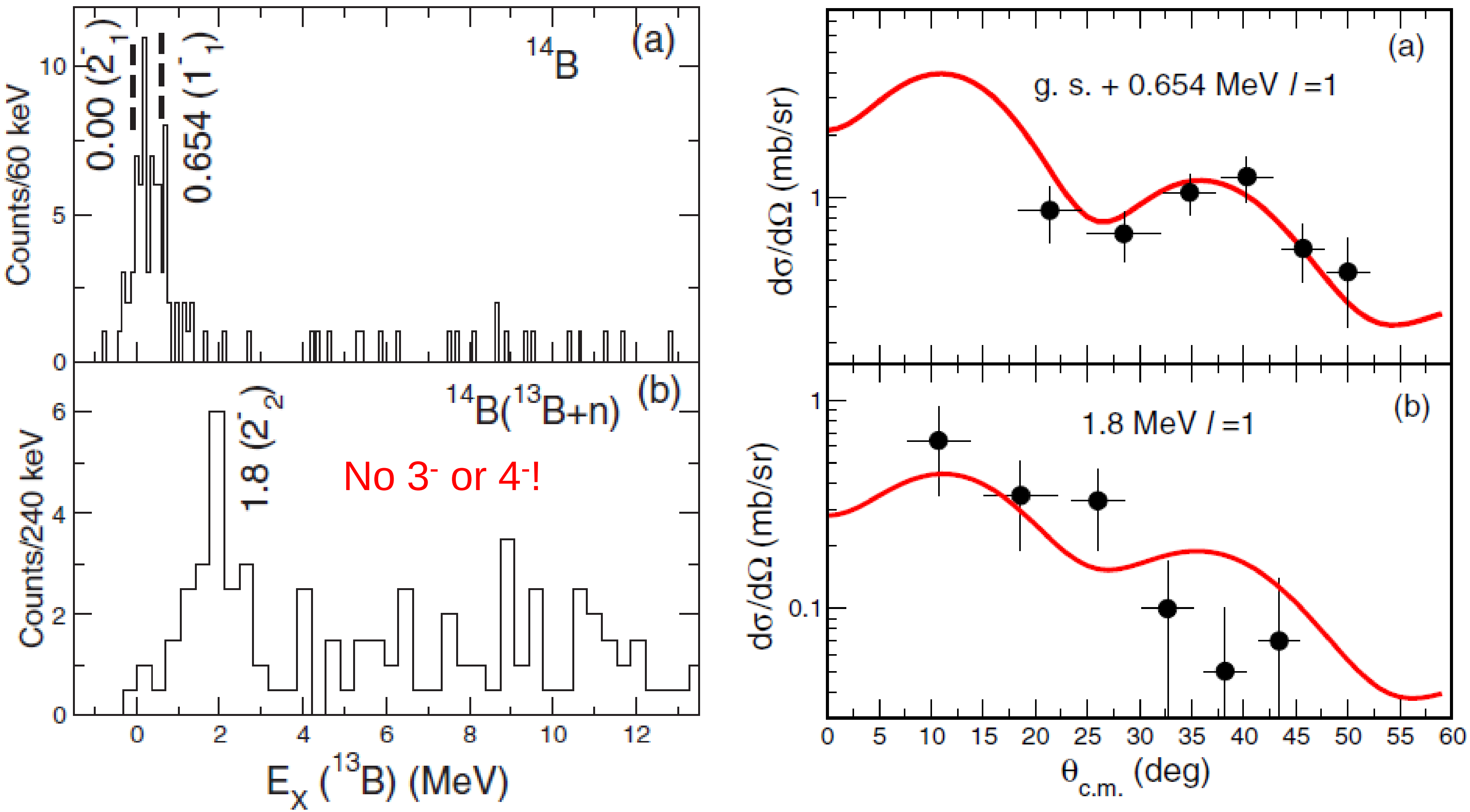
$\langle E_0 \rangle(0d_{5/2}) - \langle E_0 \rangle(1s_{1/2})$=1.39 MeV

Evolution of $1s_{1/2}$ and $0d_{5/2}$ energies



Bedoor et al., PRC **88** 011304 (2013)

2^-_2 confirmation from $^{15}C(d,^{3}He)^{14}B$



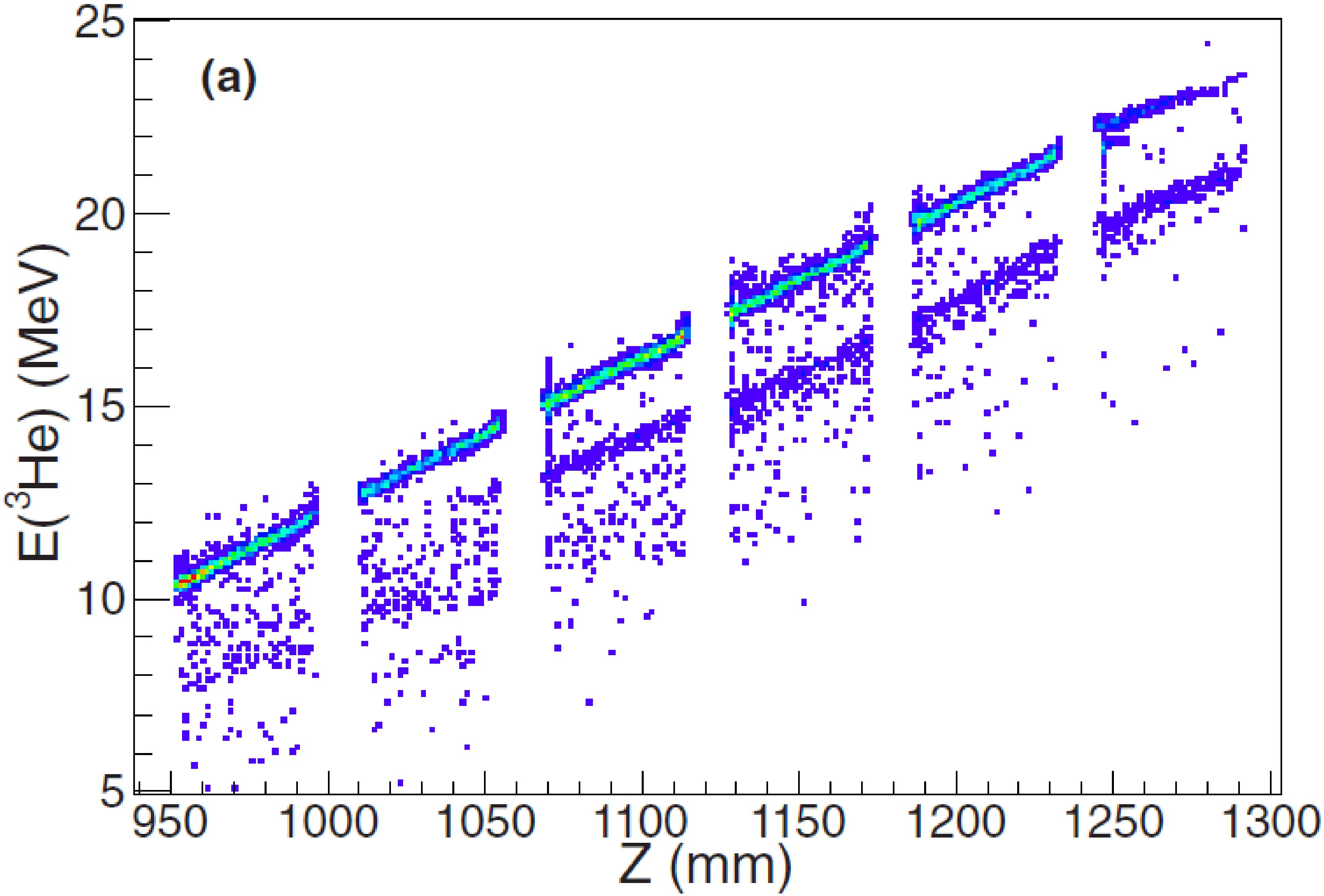
Removal of a $0p_{3/2}$ proton

Bedoor et al., PRC**93** 044323 (2016).

Preaching and Conclusion

- Remember history – basic understanding embedded in early work, often obscured by nuance and details accumulated over the years
- Put results in context – nuclear physics progresses by assembly of a puzzle with many parts, individual measurements are pieces but don’t lose sight of the Big Picture
- Technical advances can help provide better data, but equally important are imagination and insight in the design of experiments and the interpretation of data.
- There is a *lot* that I did not cover. Take this and run with it!

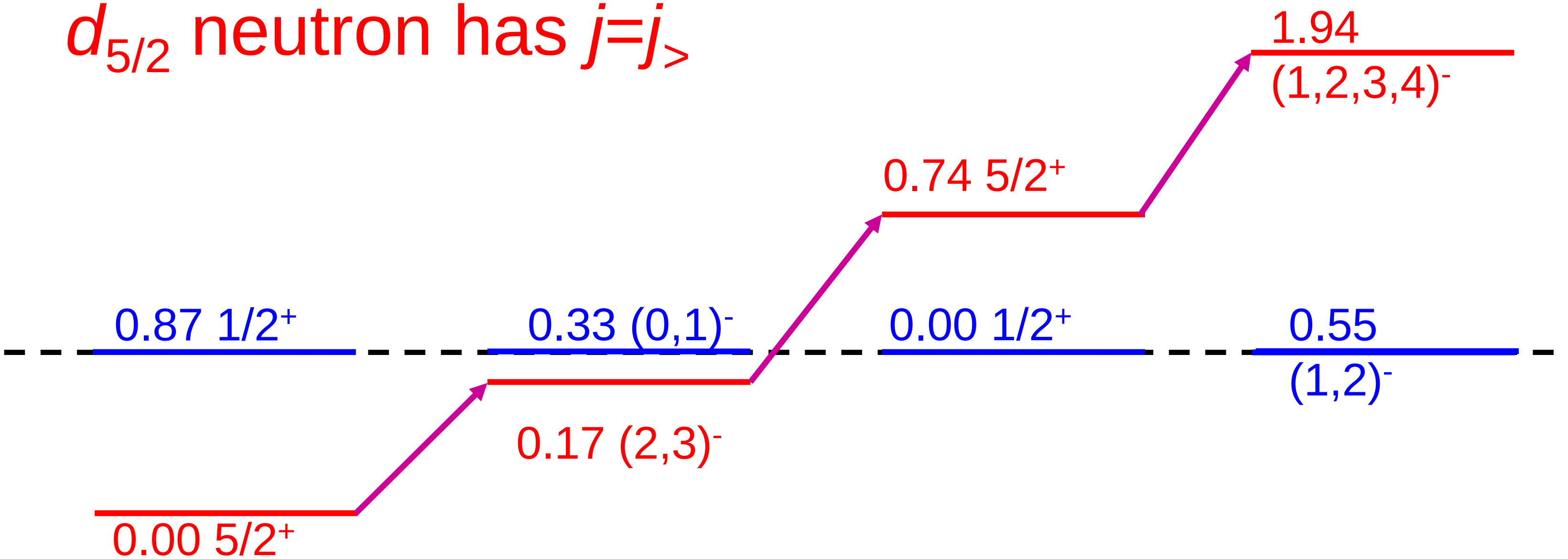
$^{14}C(d,^{3}He)^{13}B$ in HELIOS



Bedoor et al., PRC**93** 044323 (2016).

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

$d_{5/2}$ neutron has $j=j_>$



^{17}O	^{16}N	^{15}C	^{14}B
$\pi(p_{1/2})^2$	$\pi(p_{1/2})$	$\pi(p_{3/2})^4$	$\pi(p_{3/2})^3$
2 $p_{1/2}$ ($j_<$) protons: attraction	1 $p_{1/2}$ ($j_<$) proton: attraction	4 $p_{3/2}$ ($j_>$) protons: repulsion	3 $p_{3/2}$ ($j_>$) protons: repulsion

Heavy-Ion transfer and ANC's

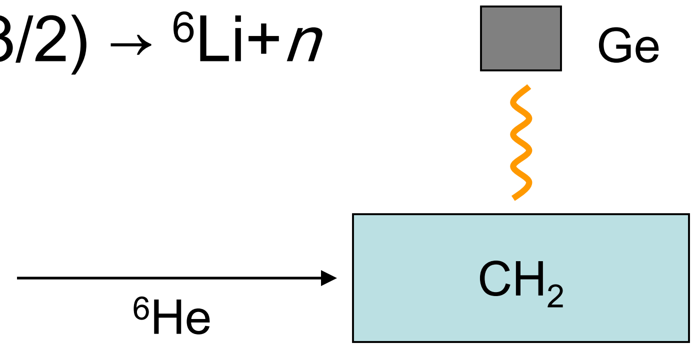
- Peripheral collisions – close or head-on collisions lead to more complex processes
- Samples the tail of the wave functions- "Asymptotic Normalization Coefficients" or "ANCs"
- Why do it this way? Many astrophysical processes occur at very low energies and are extremely peripheral.
- Analyze in a very similar way.
- Are the approaches consistent?...

Two other direct processes: Charge exchange and knockout

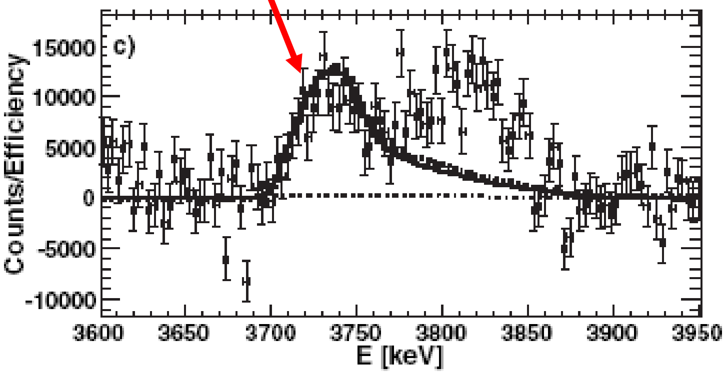
- Charge exchange – change a *p* to an *n* or vice-versa:
  - examples: (*p*,*n*), (^{3}He,*t*),(*d*,^{2}He)
  - Populates "Isobaric analog states"
  - Samples Gamow-Teller strength at small angles/low momentum transfer – like β decay.
- Knock-out: The projectile "knocks out" a particle from the target nucleus
  - examples: (*e*,*e'p*),(*p*,2*p*), (*p*,*np*) etc.
  - can be used to complement other direct transfer reactions, sensitive to nuclear structure

Charge exchange – an example

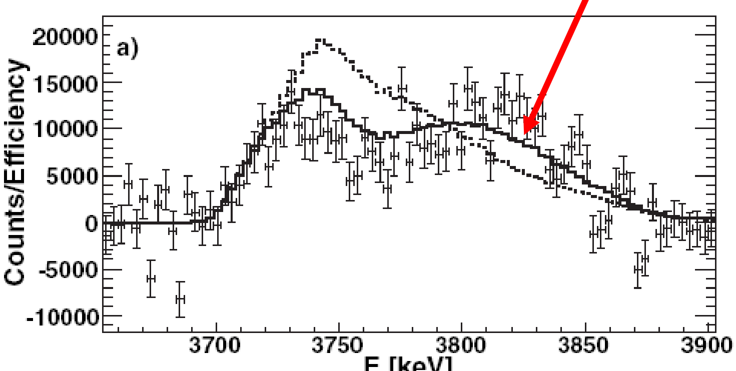
$^{6}He + p \rightarrow {}^{7}Li^{*}(T=3/2) \rightarrow {}^{6}Li + n$



Analog of ^{7}He g.s.



Tail of analog of ^{7}He $1/2^{-}$?



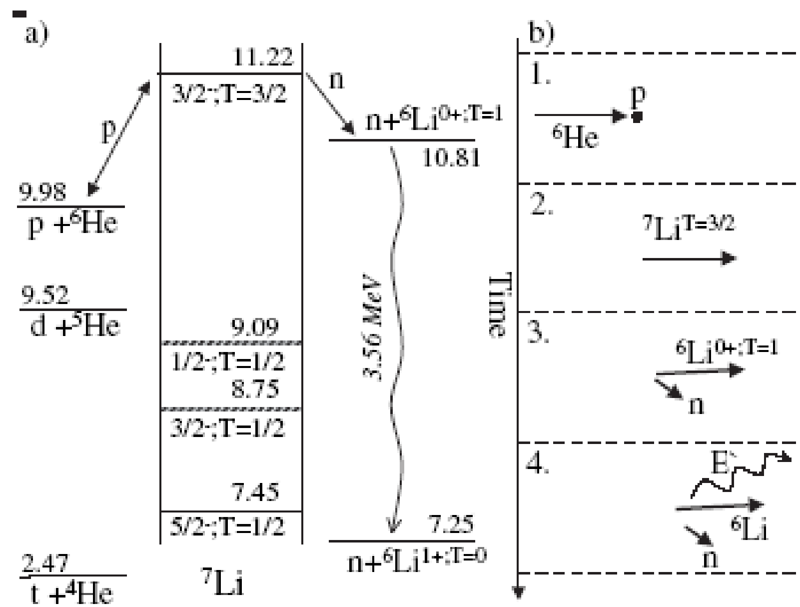


FIG. 1. (a) Decay pathways for the $T = 3/2$ resonance in ^{7}Li, and (b) the successive kinematics stages of the studied reaction.

P. Boutachkov et al, PRL **95**, 132502 (2005).

Typical CN angular distributions

$^{12}C(^{14}N, d)^{24}Mg$

Angular distributions are forward-backward symmetric