Results from single-neutron adding reactions on light neutron-rich nuclei with HELIOS

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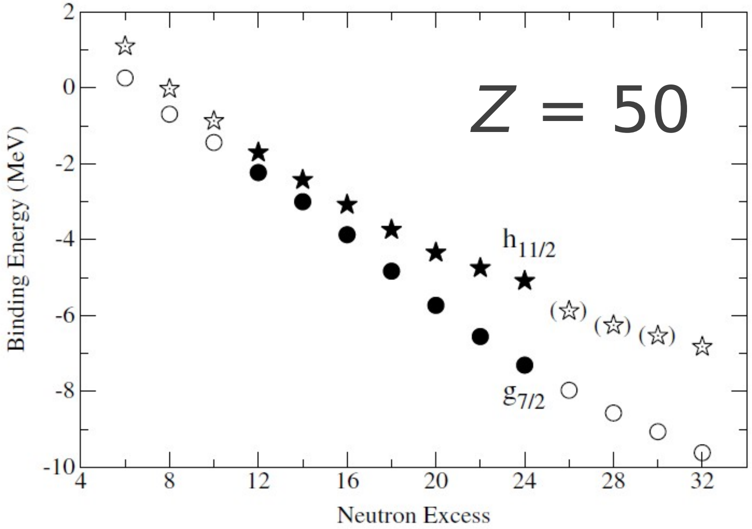
D4 – Nuclear Reactions

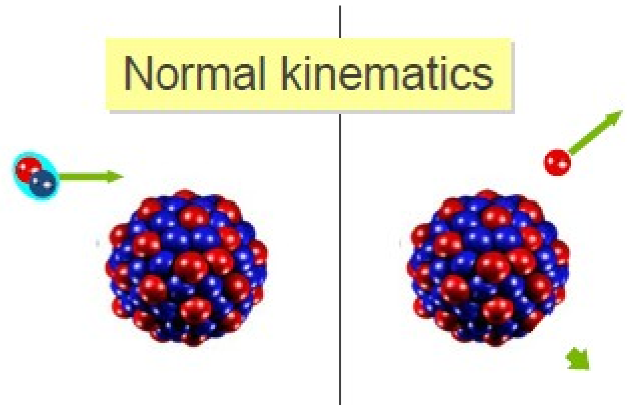
Direct nucleon transfer reactions

- Reduced cross sections give single-particle nature of final states
- Angular distributions
  - Orbital momentum of final state, *l*
  - Total angular momentum, *J*
- Single-particle distributions
  - Spectroscopic factors, C^2S
  - Single-particle energies
- Occupation and Vacancies
  - Absolute cross sections
  - Consistent theoretical approach
- Configuration mixing
- Pairing correlations
  - (p,t) (t,p) (^{3}He,p)
- Astrophysics
  - S-factors, surrogate reactions, *ANCs*
- Inverse kinematics needed for short lived nuclei

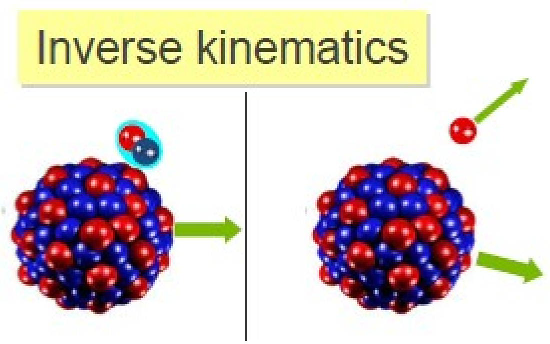


J. P. Schiffer et al., PRL 92, 162501 (2004)

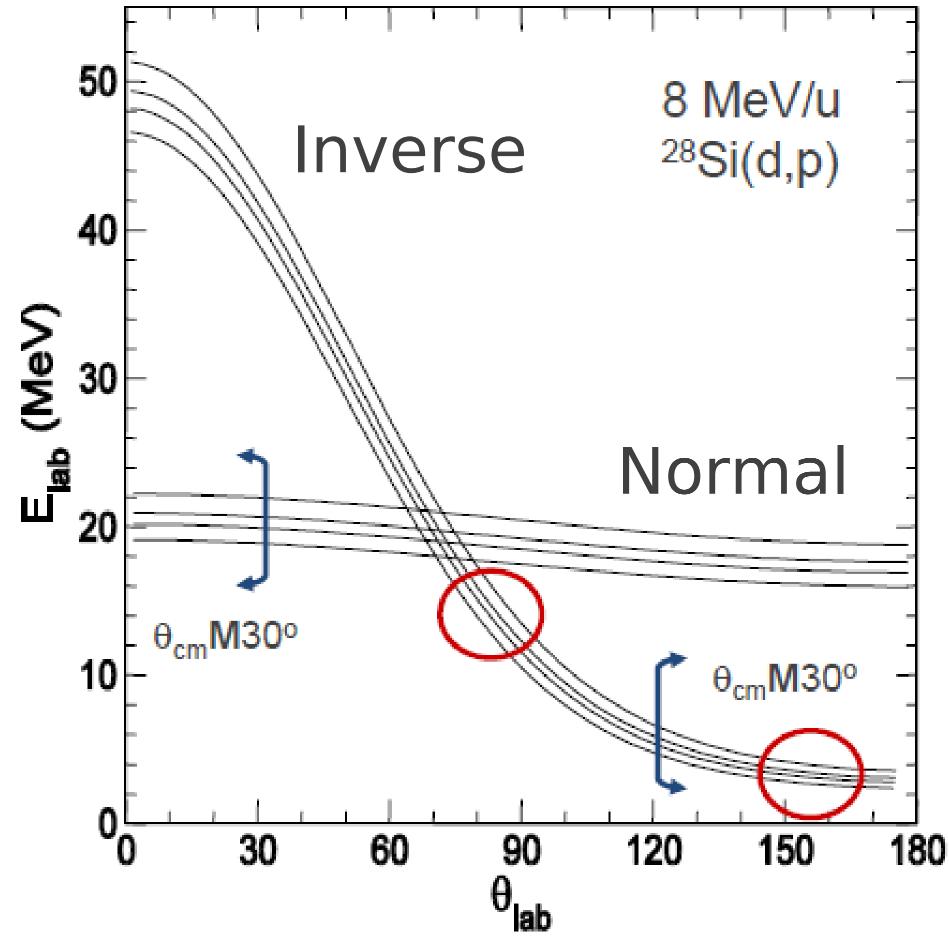
Difficulties in inverse kinematics



< 50 keV resolution

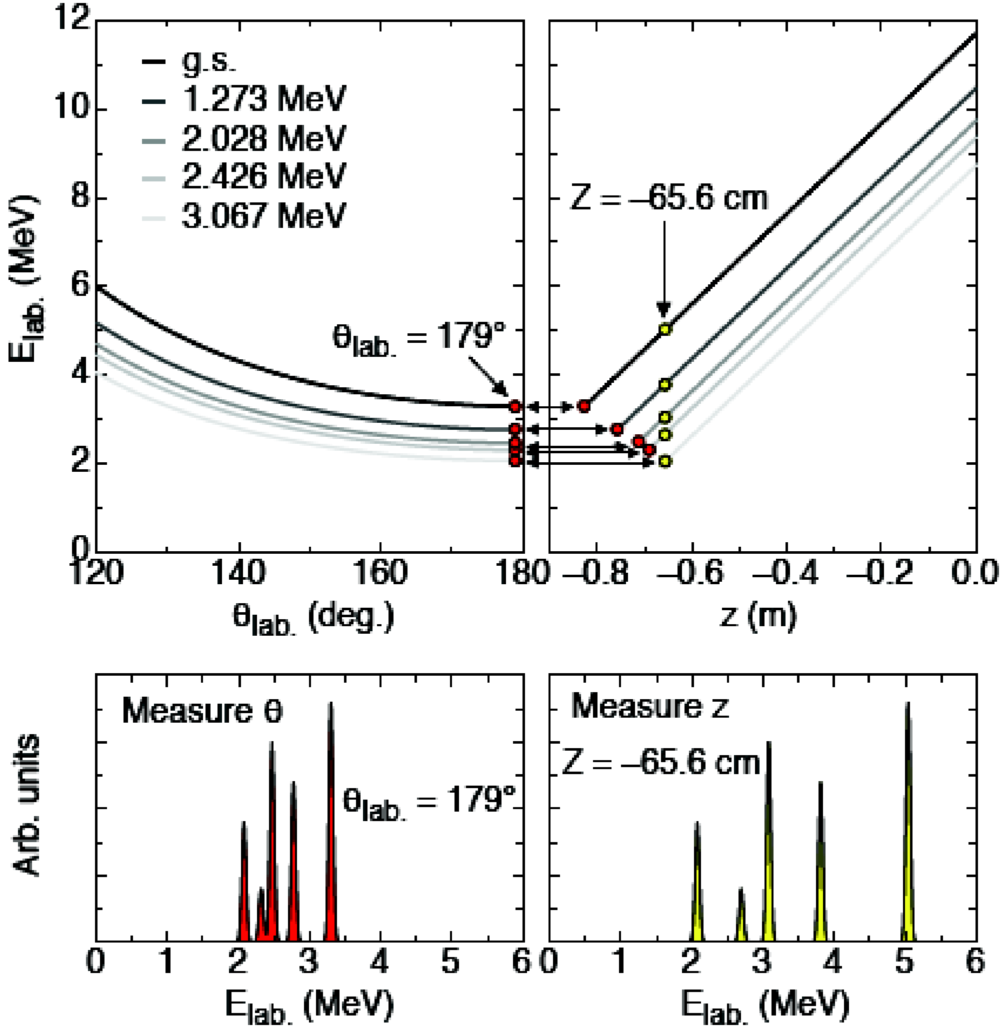


~100's keV resolution



Kinematics in a magnetic field

$^{28}Si(d,p)$ @ 6 MeV/u w/ 2-T field



Measured quantities

Flight time: $T_{flight} = T_{cyc}$
Position: z
Energy: E_{lab}

Derived quantities

Part. ID: m/q
Energy: E_{cm}
Angle: θ_{cm}

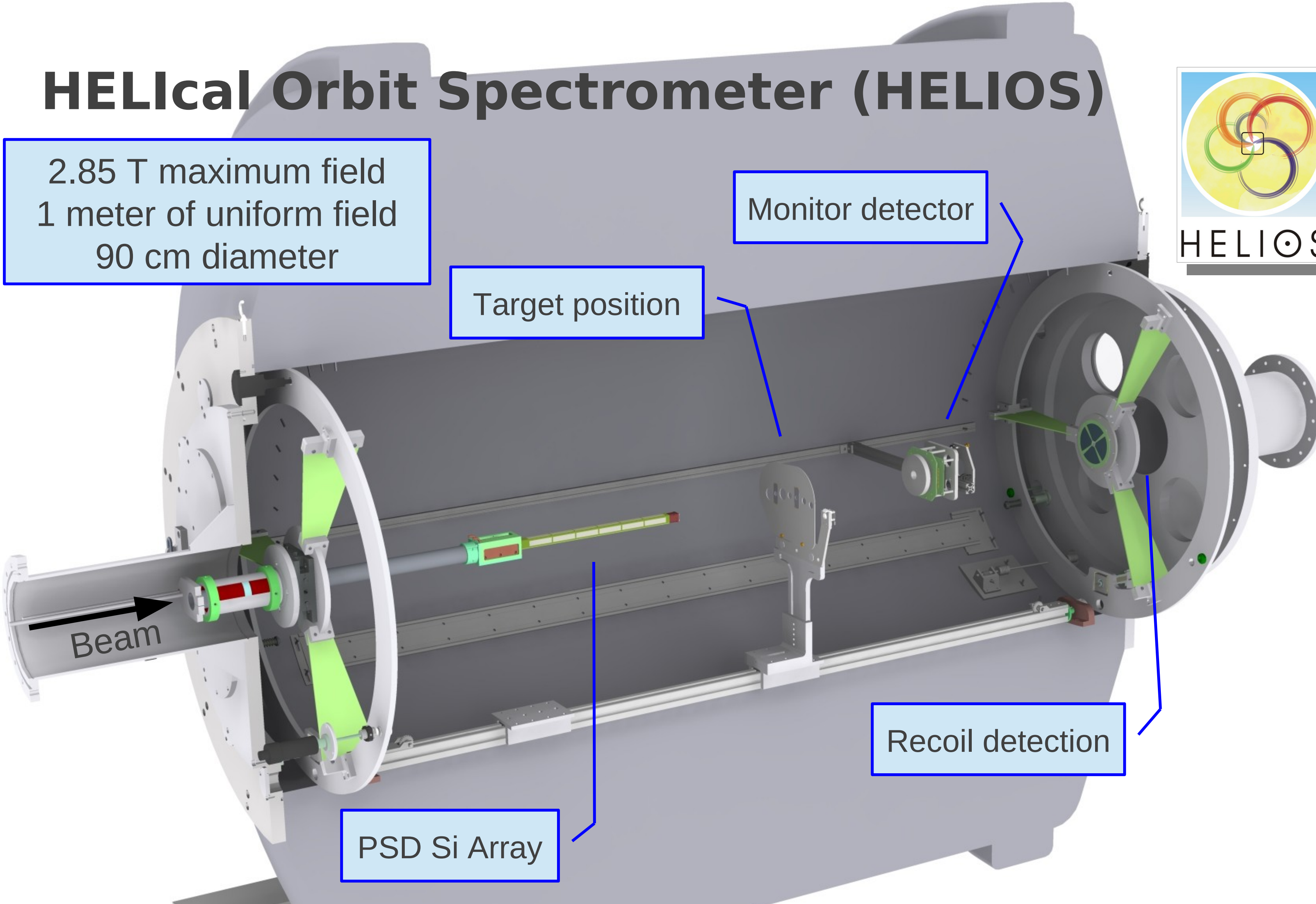
$$\frac{m}{q} = \frac{eB}{2\pi} \times T_{flight}$$

$$E_{cm} = E_{lab} + \tfrac{1}{2} m V_{cm}^2 - \frac{V_{cm} qeB}{2\pi} z$$

$$\theta_{cm} = \arccos\left(\frac{1}{2\pi} \frac{qeBz - 2\pi m V_{cm}}{\sqrt{2mE_{lab} + m^2 V_{cm}^2 - m V_{cm} qeBz / \pi}} \right)$$

- Map lab angle onto the longitudinal position (z)
- Linear relation between Q value and proton lab energy
- Q resolution
  - Target energy losses
  - Longitudinal (z) position
  - Detector resolutions

HELIcal Orbit Spectrometer (HELIOS)



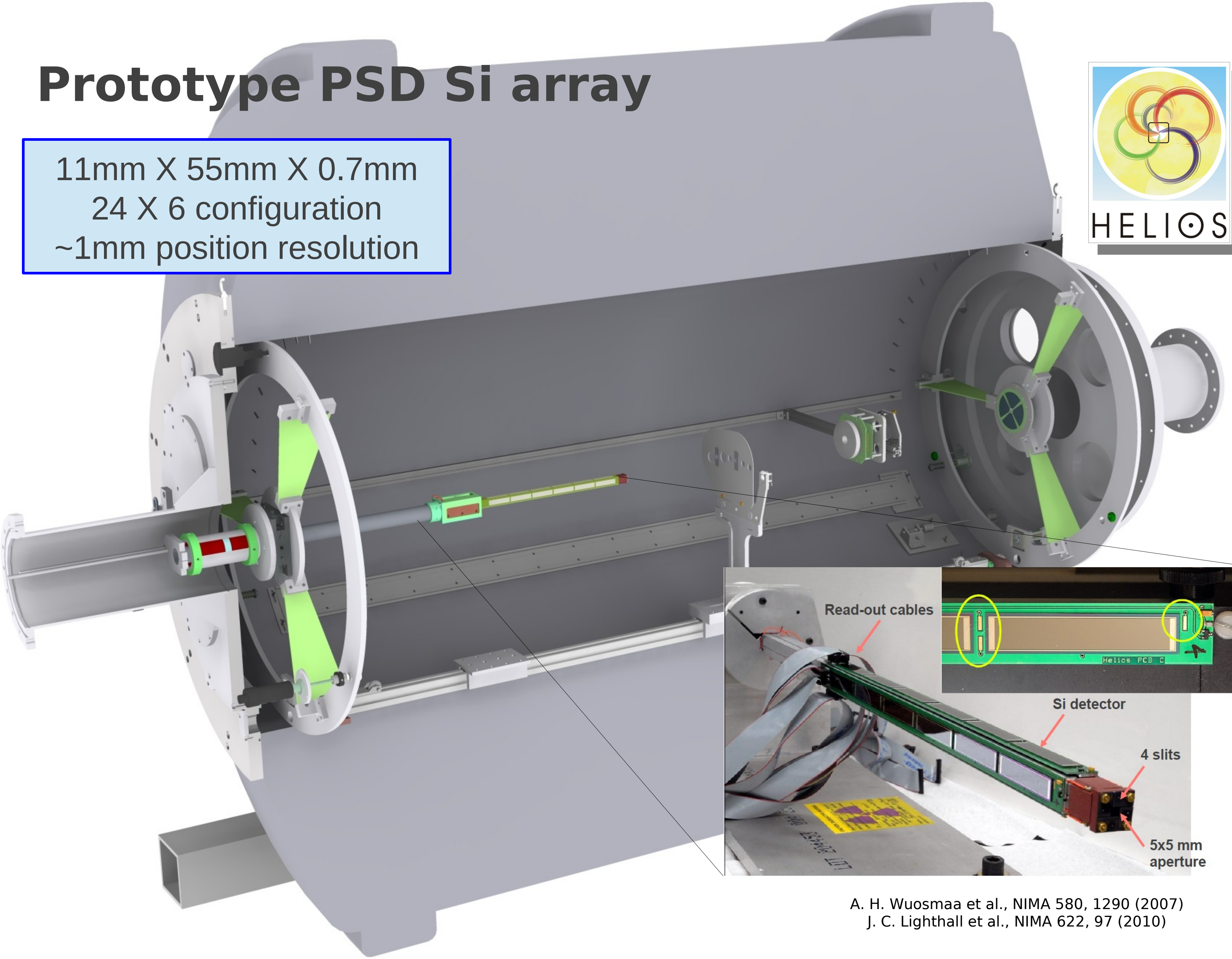
$$E_{\text{lab}} = E_{\text{c.m.}} - \frac{m}{2} V_{\text{c.m.}}^2 + \frac{m V_{\text{c.m.}} z}{T_{\text{cyc}}}.$$

$$\cos\theta_{\text{c.m.}} = \frac{1}{2\pi} \frac{qeBz - 2\pi m V_{\text{c.m.}}}{\sqrt{2mE_{\text{lab}} + m^2 V_{\text{c.m.}}^2 - m V_{\text{c.m.}} qeBz/\pi}}.$$

$$T_{\text{cyc}} = \frac{2\pi}{B} \frac{m}{qe}.$$

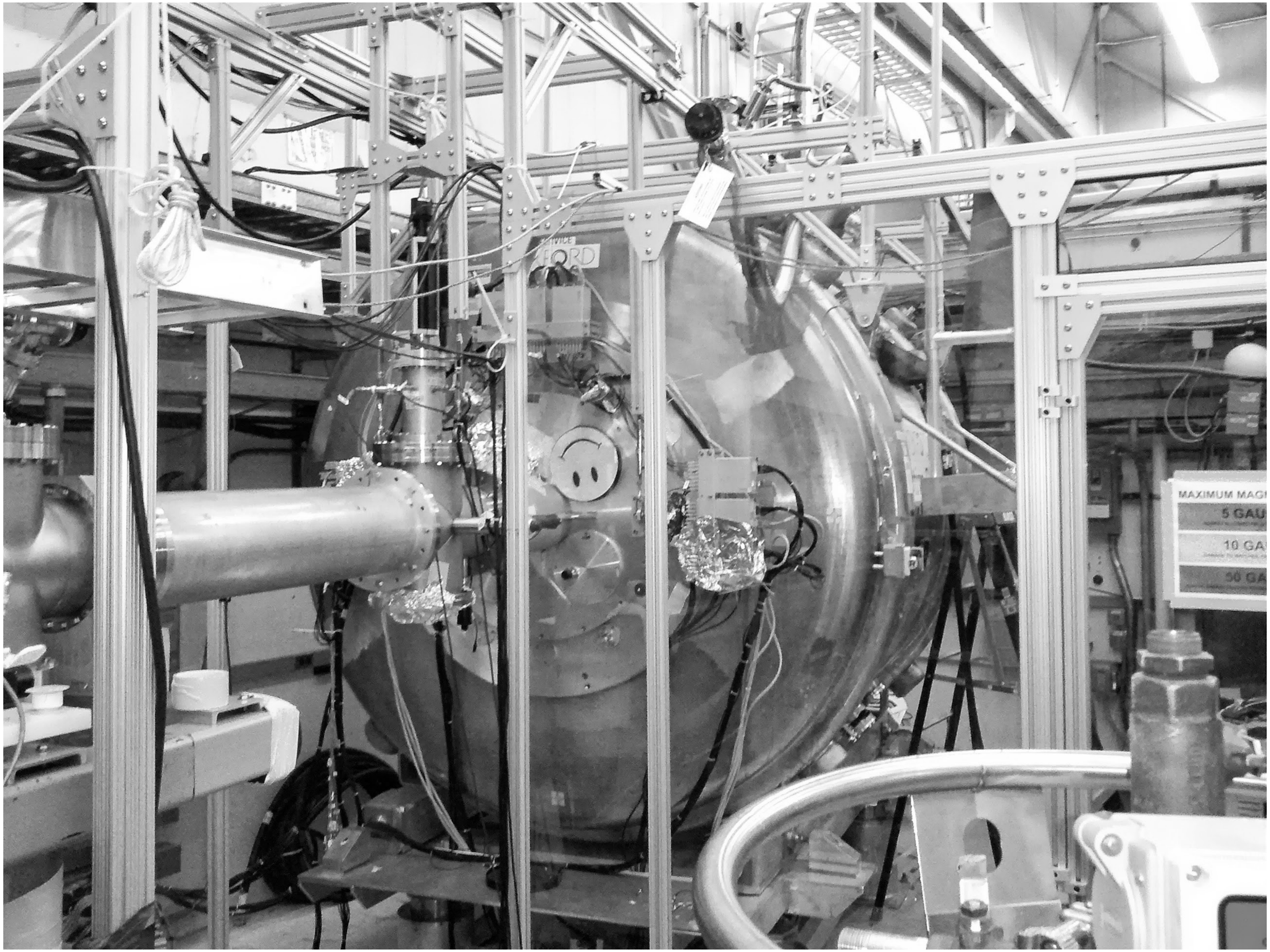
Prototype PSD Si array

11mm X 55mm X 0.7mm
24 X 6 configuration
~1mm position resolution

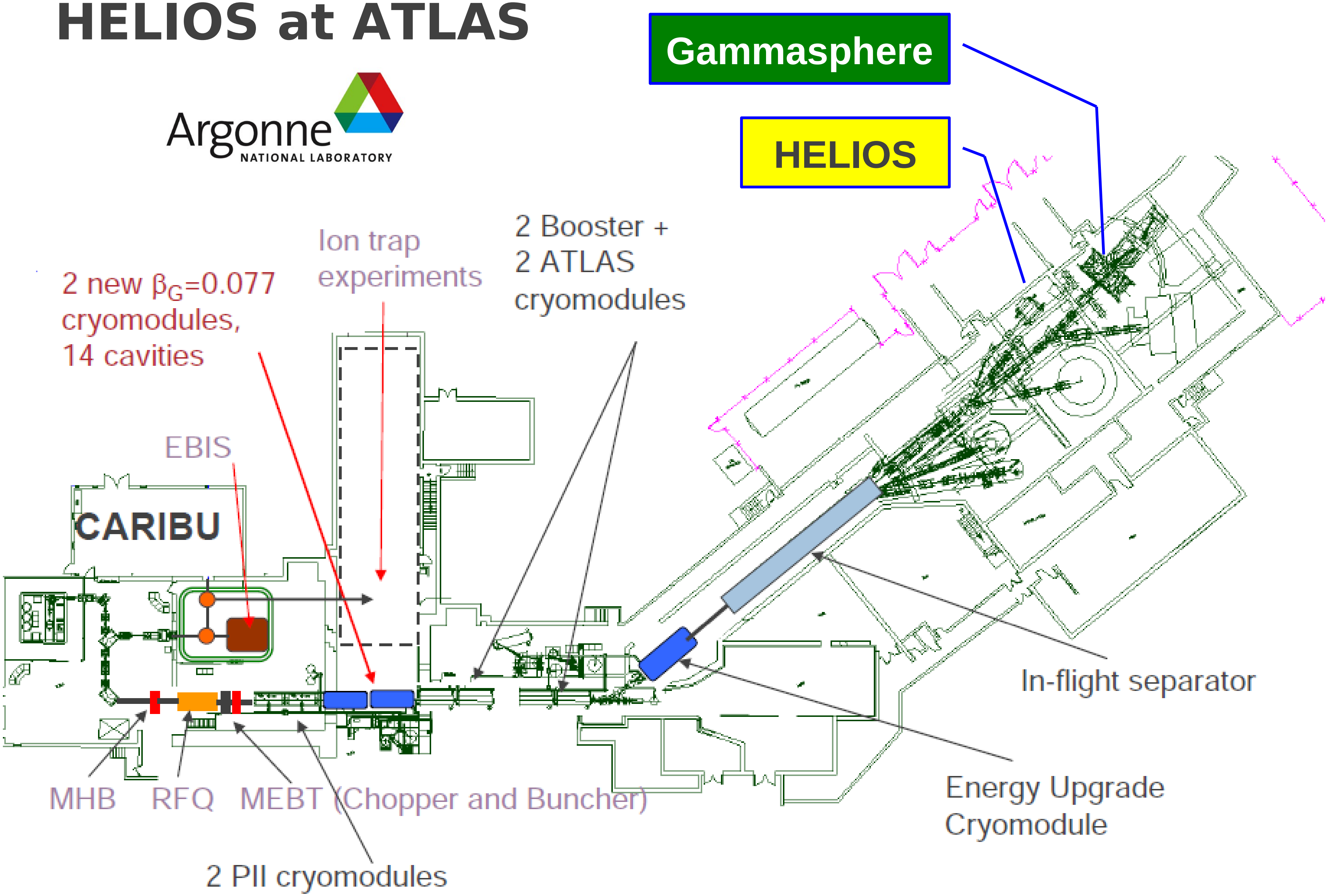


A. H. Wuosmaa et al., NIMA 580, 1290 (2007)
J. C. Lighthall et al., NIMA 622, 97 (2010)

HELIOS



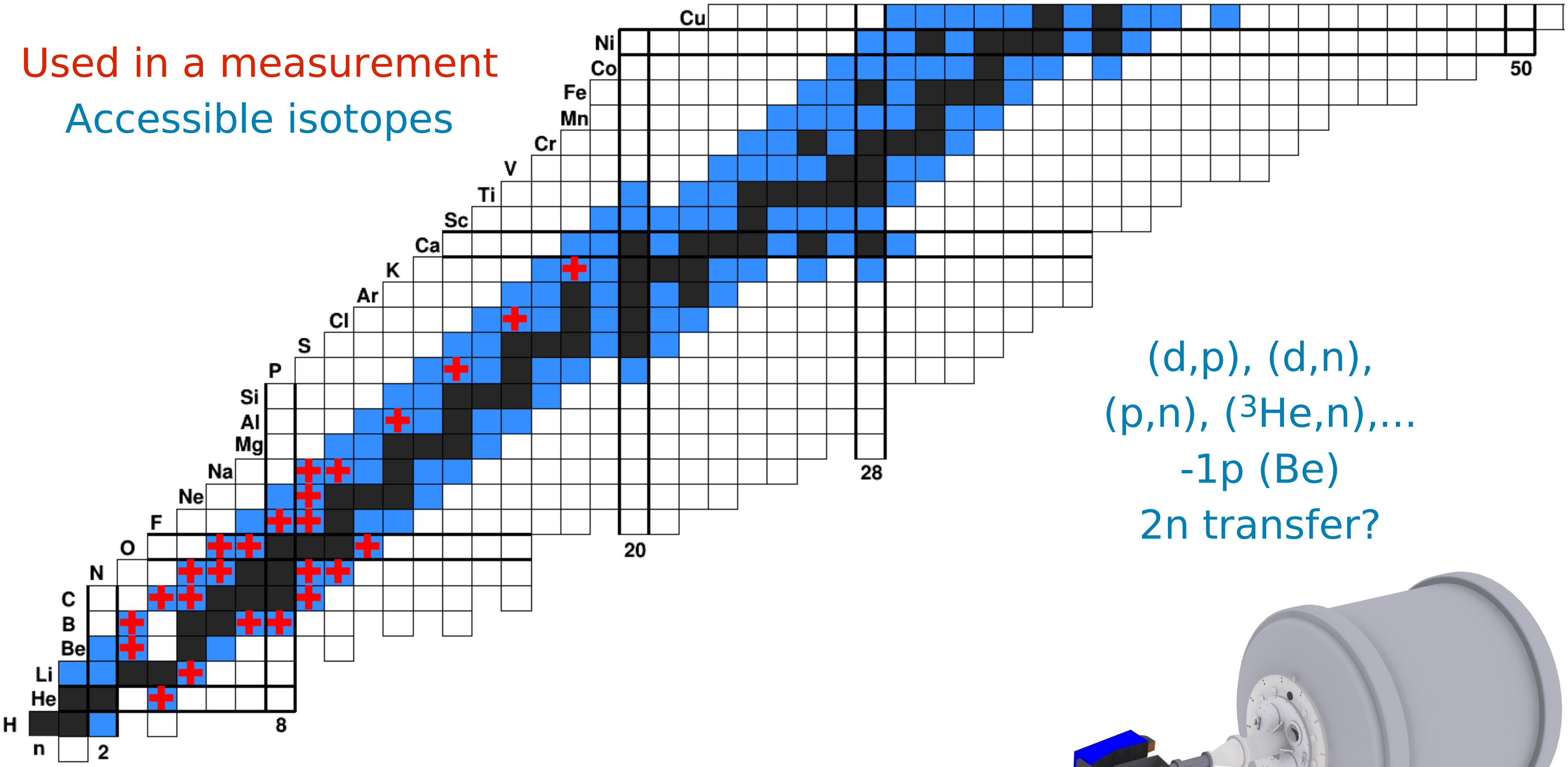
HELIOS at ATLAS



Secondary in-flight beams at ATLAS

Used in a measurement

Accessible isotopes



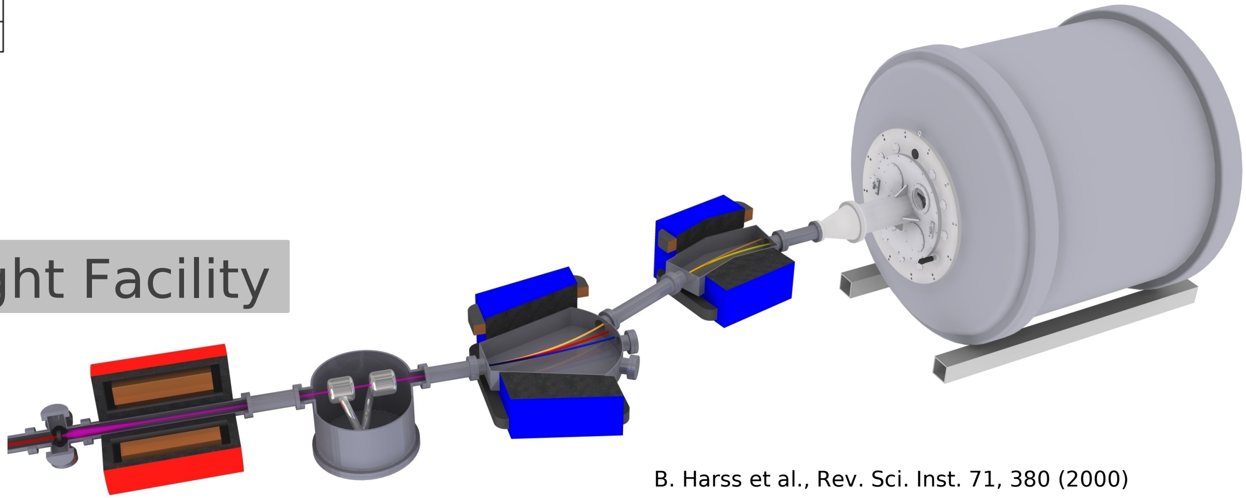
(d,p), (d,n),

(p,n), (^{3}He,n),...

-1p (Be)

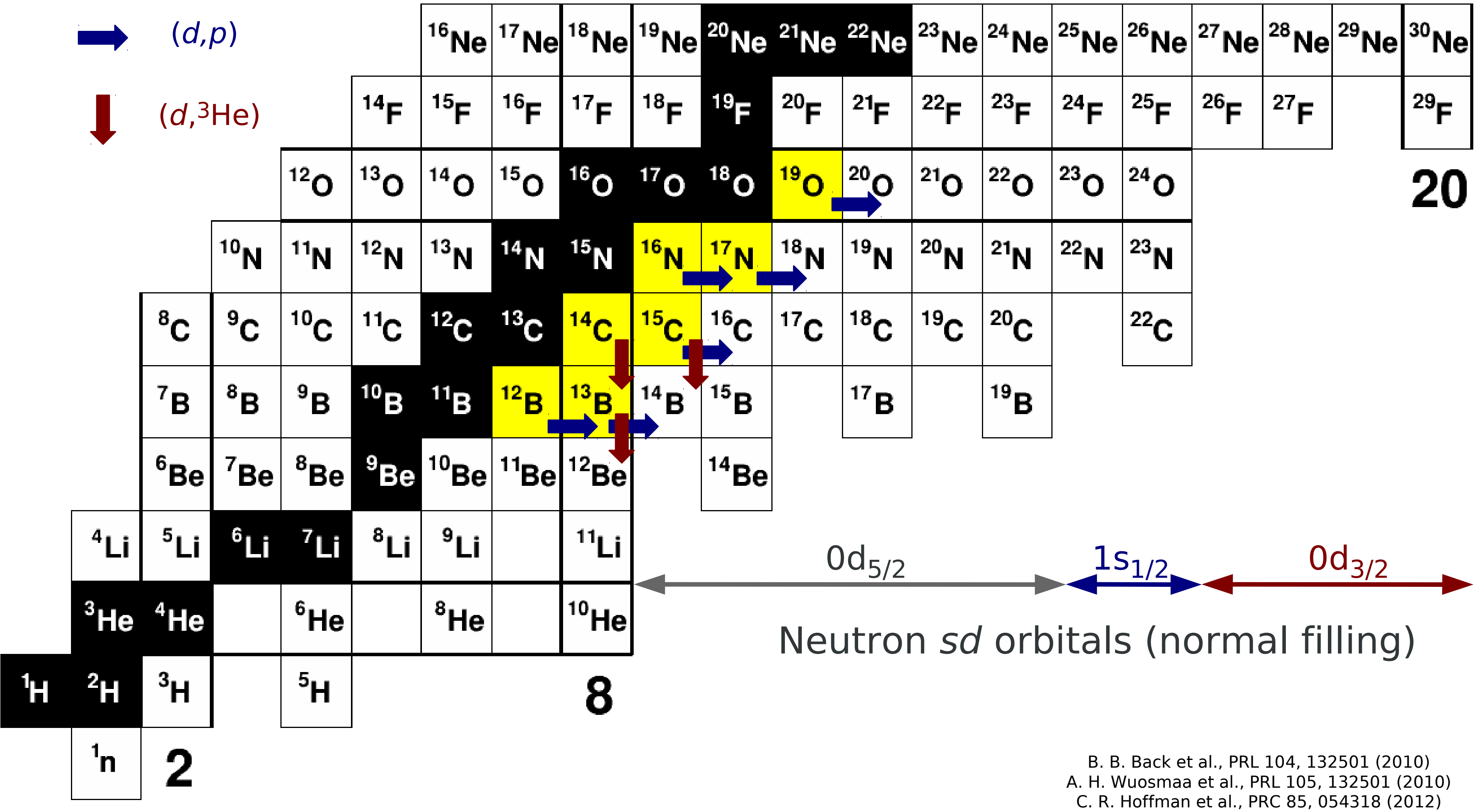
2n transfer?

In-Flight Facility



B. Harss et al., Rev. Sci. Inst. 71, 380 (2000)

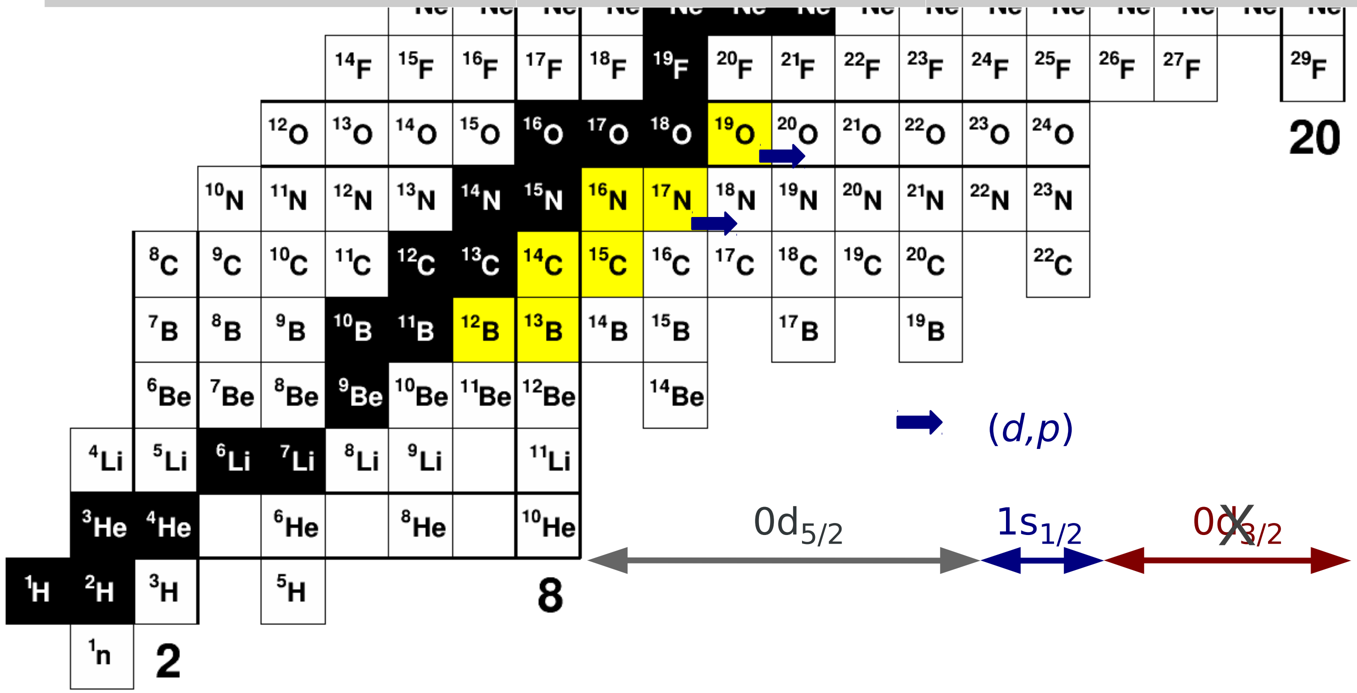
Reactions used to probe the neutron *sd* orbitals with HELIOS



B. B. Back et al., PRL 104, 132501 (2010)
A. H. Wuosmaa et al., PRL 105, 132501 (2010)
C. R. Hoffman et al., PRC 85, 054318 (2012)
S. Bedoor et al., Submitted for publication.

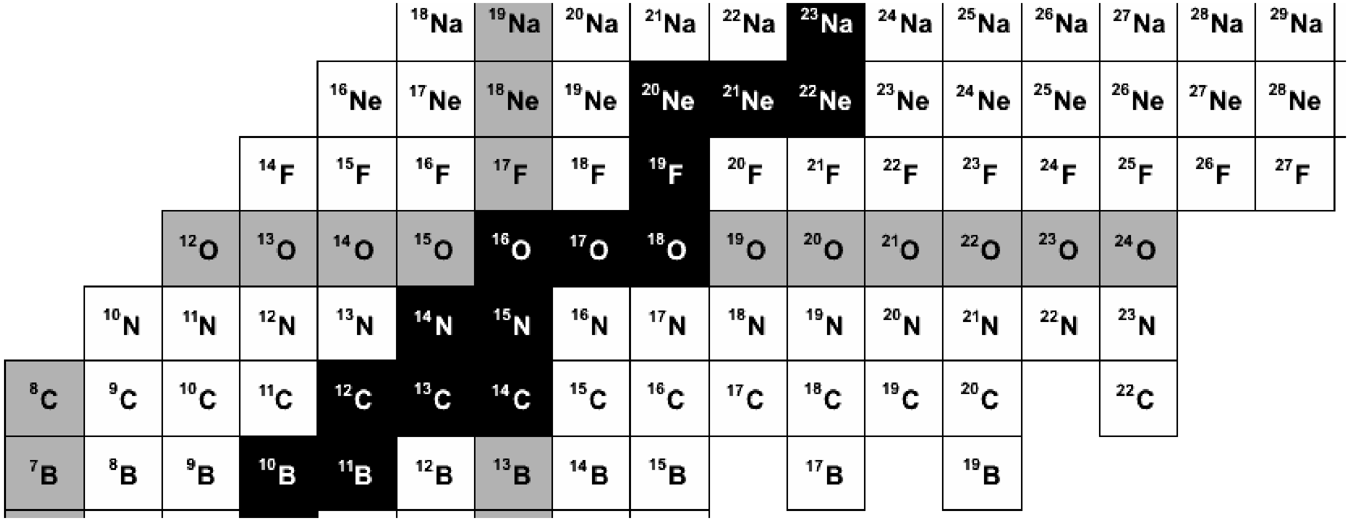
Single-neutron adding reactions

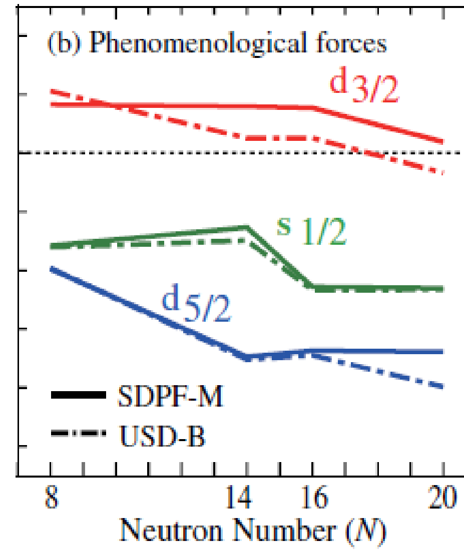
Reaction	$^{19}O(d,p)^{20}O$	$^{17}N(d,p)^{18}N$
RIB Beam:	^{19}O	^{17}N
Energy (MeV/u)	6.9	13.6
Rate (pps)	$>10^5$	$>10^4$
Production Target	1400 mbar D_2 gas	15 mg/cm^2 Be
CD_2 Target (ug/cm^2)	260	140 & 220

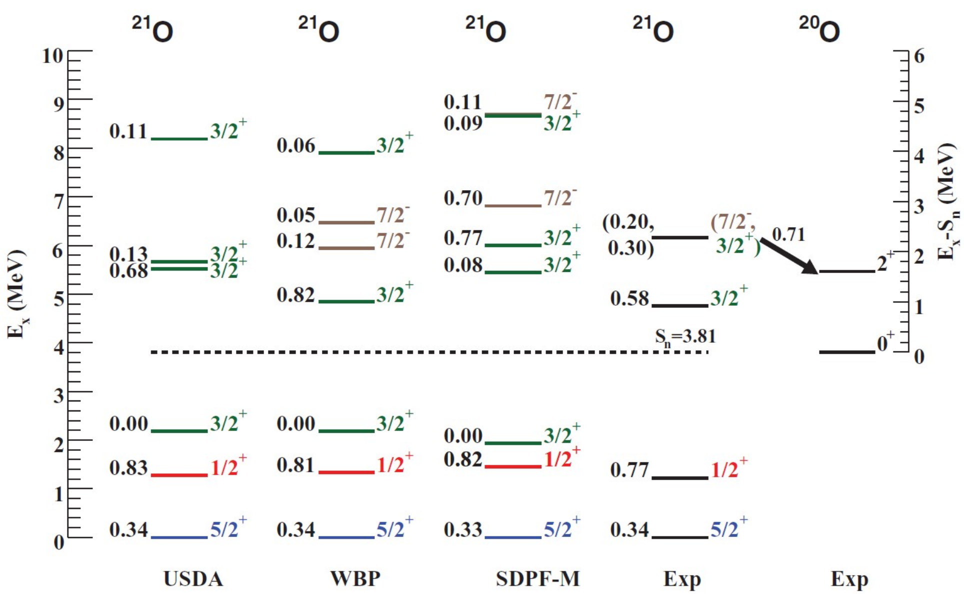


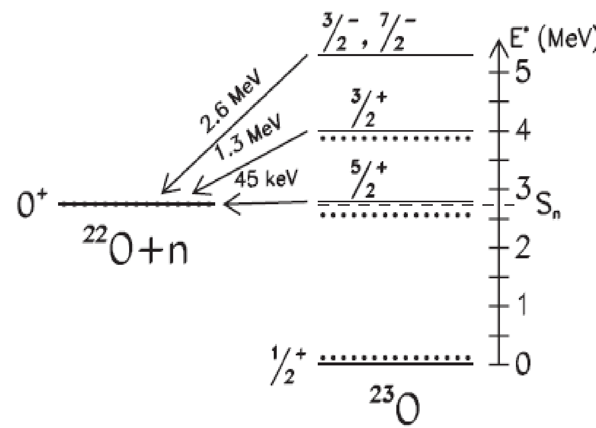
$^{19}O(d,p)^{20}O$

Single-particle evolution along *Z* = 8



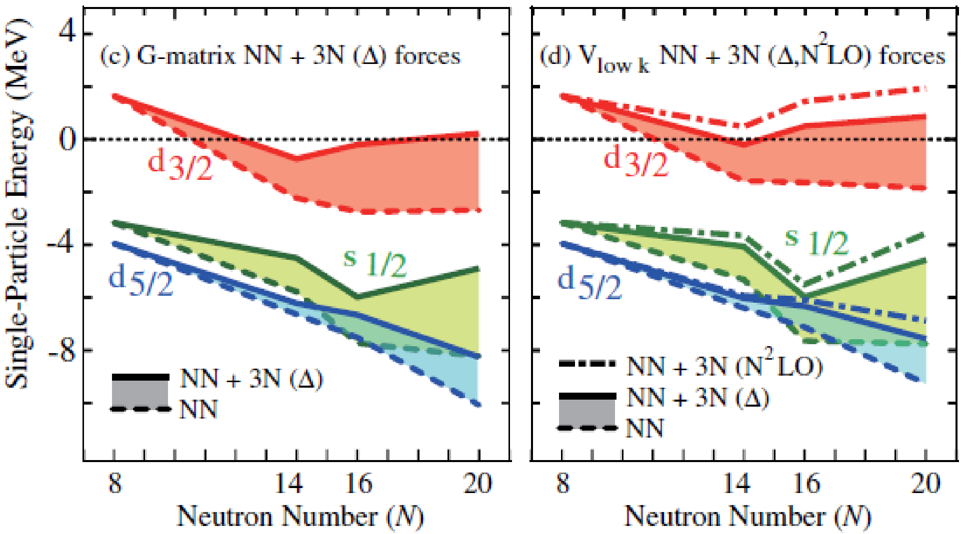


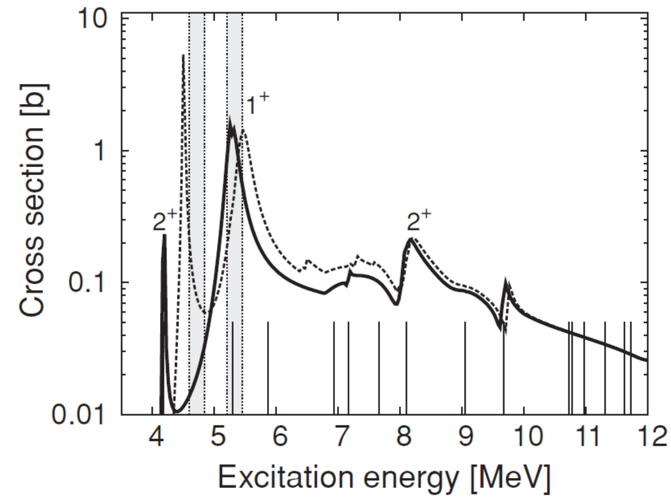


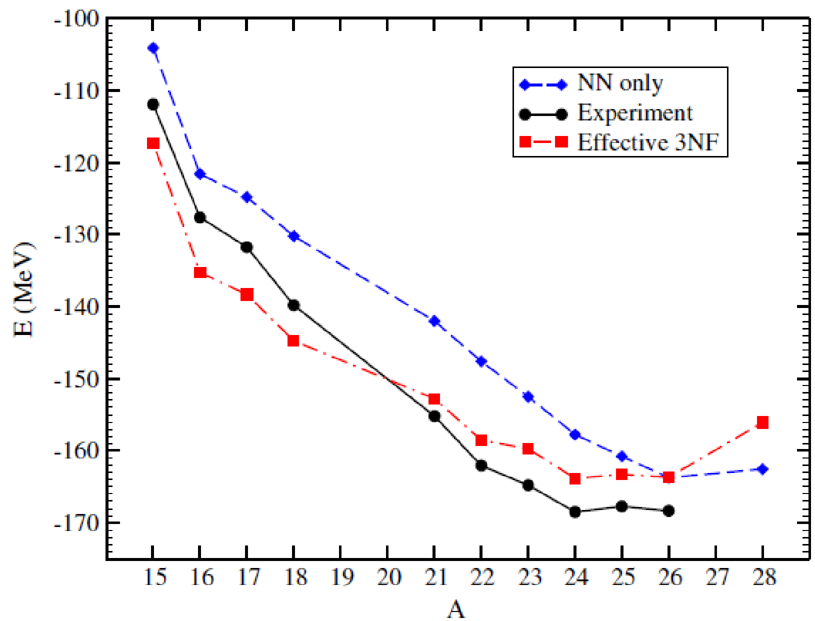


B. Fernandez-Dominquez et al., PRC 84, 011301 (2011)
A. Schiller et al., PRL 99, 112501 (2007)
Z. Elekes et al., PRL 98, 102502 (2007)
T. Otsuka et al., PRL 105, 032501 (2010)

Components driving the single-particle evolution





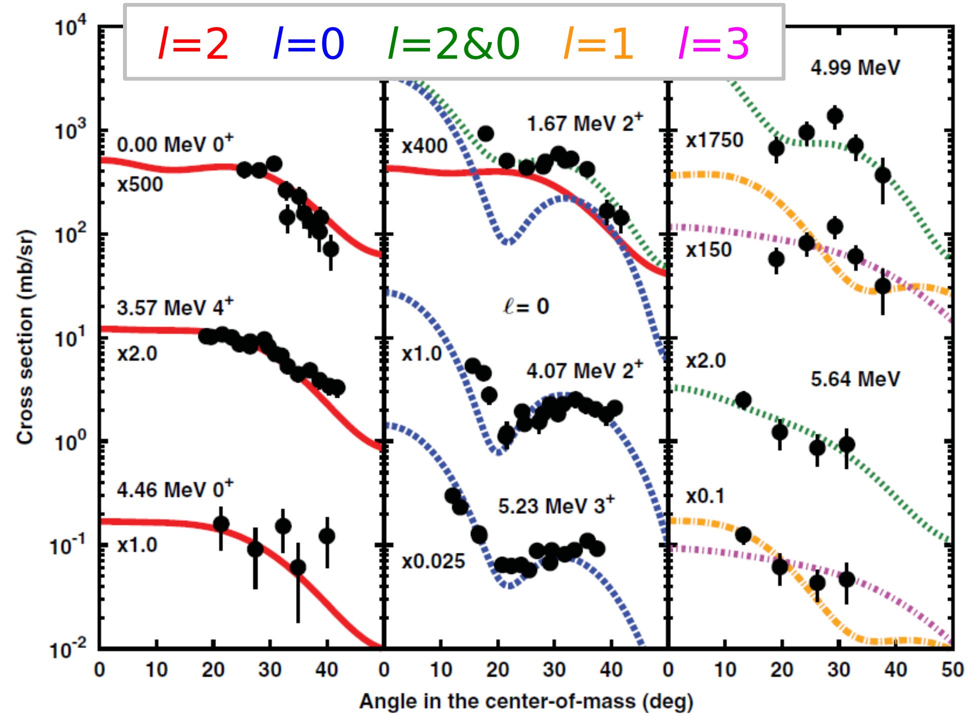


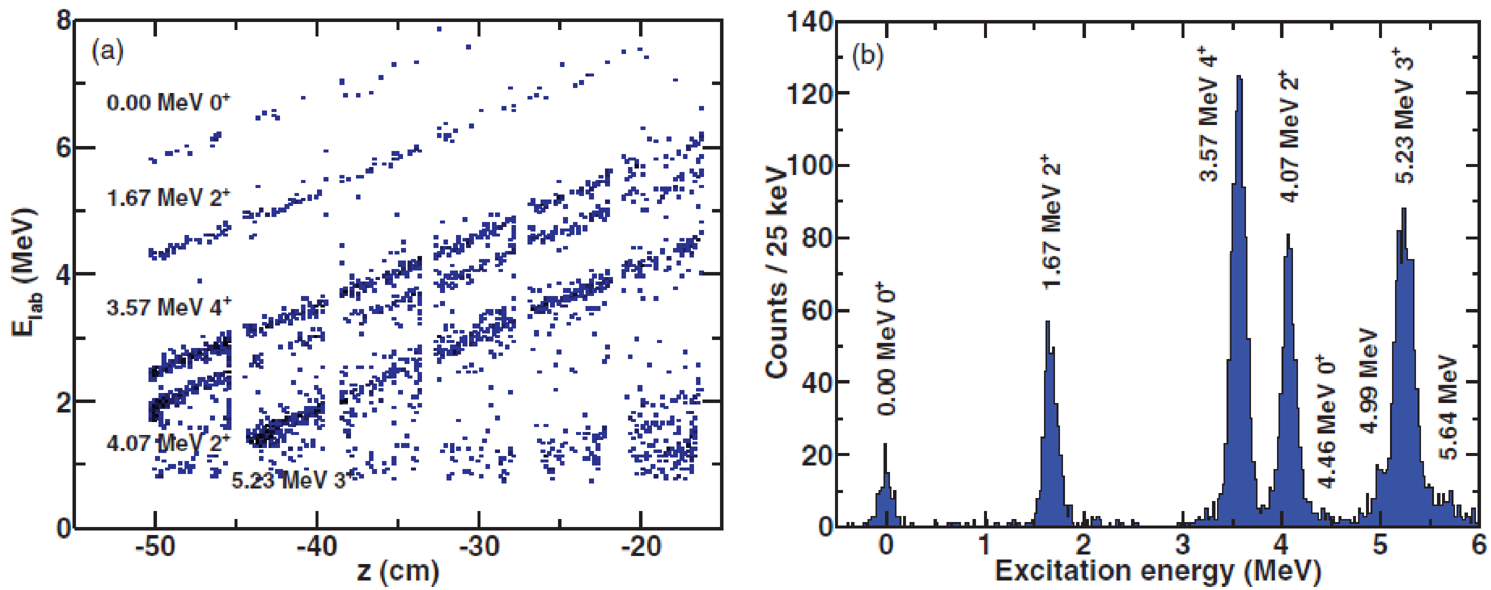
- Parts of the *NN* interaction
- Inclusion of three-body effects
- Impact of scattering into the continuum

S. C. Pieper and R. B. Wringa, Annu. Rev. Nucl. Part. Sci. 51, 53 (2001)
T. Otsuka et al., PRL 105, 032501 (2010)
G. Hagen et al., PRL 108, 242501 (2012)
A. Volya, PRC 79, 044308 (2009)
K. Tsukiyama et al. PRC 80, 051301(R); arXiv:1001.0729
T. Otsuka et al., PRL 87, 082502 (2001), 95, 232502 (2005)
T. Otsuka et al., 97, 162501, 104, 012501 (2010)
J. D. Holt et al., EPJA 49, 39 (2013)

$^{19}O(d,p)^{20}O$ data

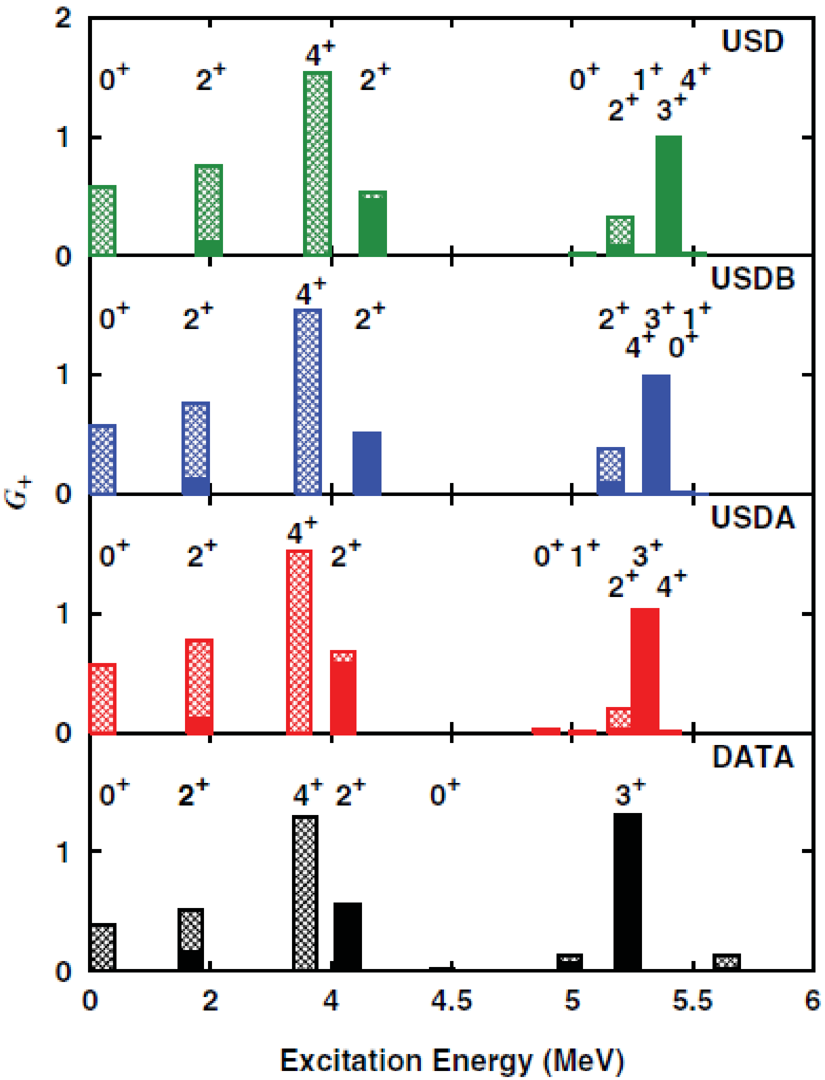
- 8 states identified up to 7 MeV
  - FWHM ~ 175 keV
- Absolute σ from deuteron scattering (20%)
- Angular distributions
  - Distorted wave Born approximation
  - Identified *l* = *0* 3^+ level at 5.23 MeV





C. R. Hoffman et al., PRC 85, 054318 (2012)

^{19}O(d,p)^{20}O results



- Distorted wave analysis to extract spectroscopic factors
  - Normalized to ^{16}O(d,p)^{17}O data
  - 30% uncertainty in total
  - 12% relative to one-another
- Checks w/ sum rules & ^{18}O(d,p)^{19}O data
- Superb reproduction of strength by sd shell interactions
- Some strength to 2p-2h (1p-1h) dominated states
  - 0^+ @ 4.46 MeV
  - 4.99 or 5.64 MeV states
- SOLID → l = 0
  HATCHED → l = 2

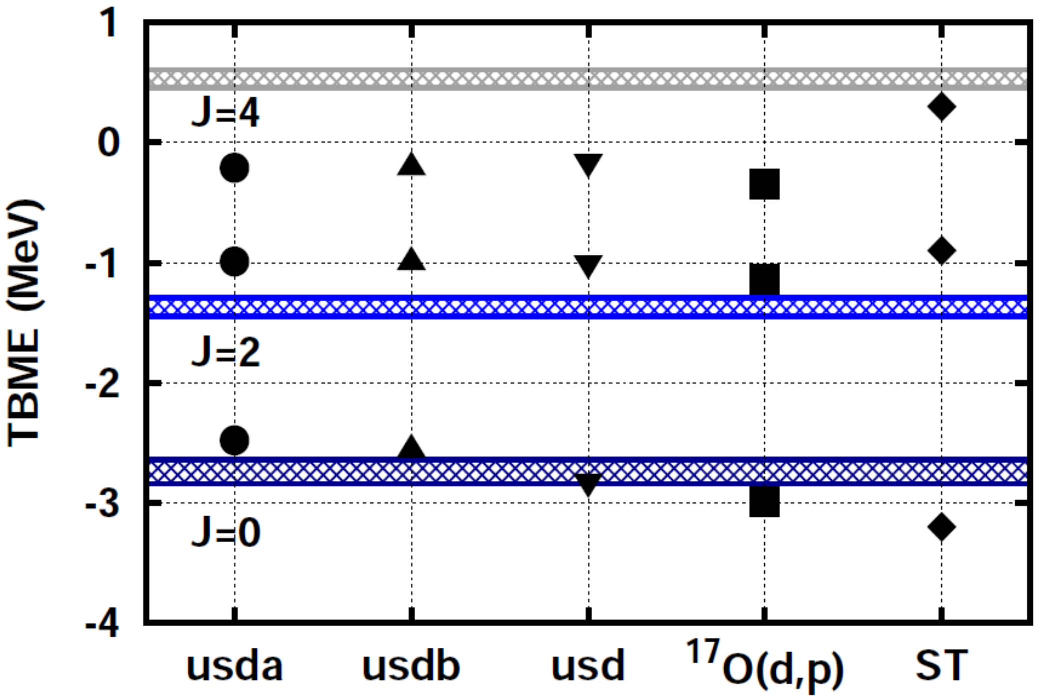
C. R. Hoffman et al., PRC 85, 054318 (2012)

C. M. Perey and F. G. Perey, PR 132, 755 (1963)
J. P. Schiffer et al., PR 164, 1274 (1967)

Diagonal $T = 1$ TBME of the empirical *NN* interaction

- Consider ^{20}O as two-neutron holes inside ^{22}O (N = 14 $0d_{5/2}$) neutron shell
  - ^{22}O is a good closed core & >97% of strength belongs to $0d_{5/2}$

$$E_0 = 2B[^{21}\mathrm{O}] - B[^{20}\mathrm{O}] - B[^{22}\mathrm{O}] = -3.04(6)\ \mathrm{MeV}, \quad \langle (d_{5/2})^2 J | V | (d_{5/2})^2 J \rangle = E_0 + \frac{\sum (2J+1) C^2 S \cdot E^*}{\sum (2J+1) C^2 S}.$$

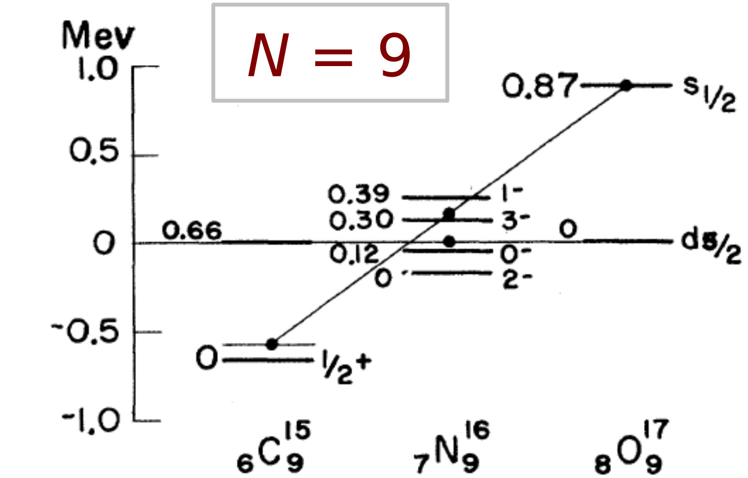


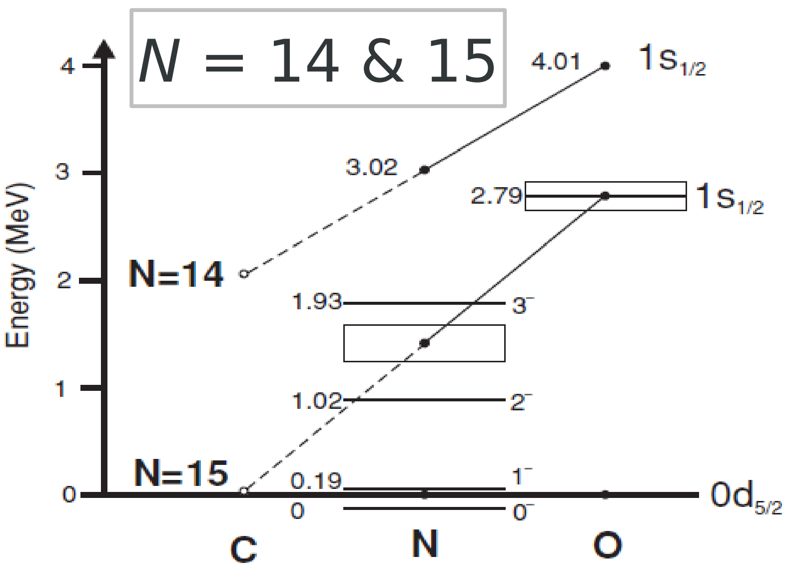
J. P. Schiffer and W. W. True, Rev. Mod. Phys. 48, 191 (1976)
T. K. Li et al., PRC 13, 55 (1976)

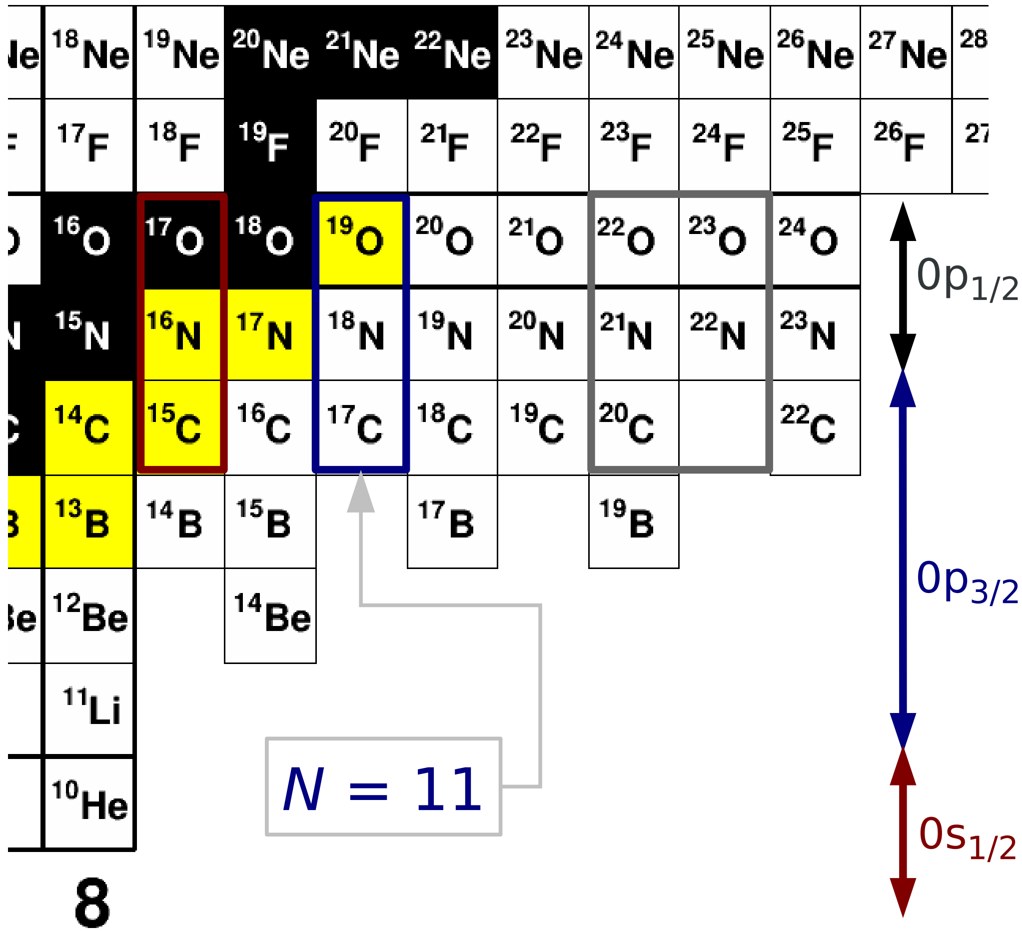
- Consistent with ^{18}O and survey results
  - Slight disagreement for smallest J=4 TBME
- No change between N = 10 – 12 for Z = 8
- Technique is applicable to unbound nuclei near closed shells

$^{17}N(d,p)^{18}N$

Single-particle evolution across isotones



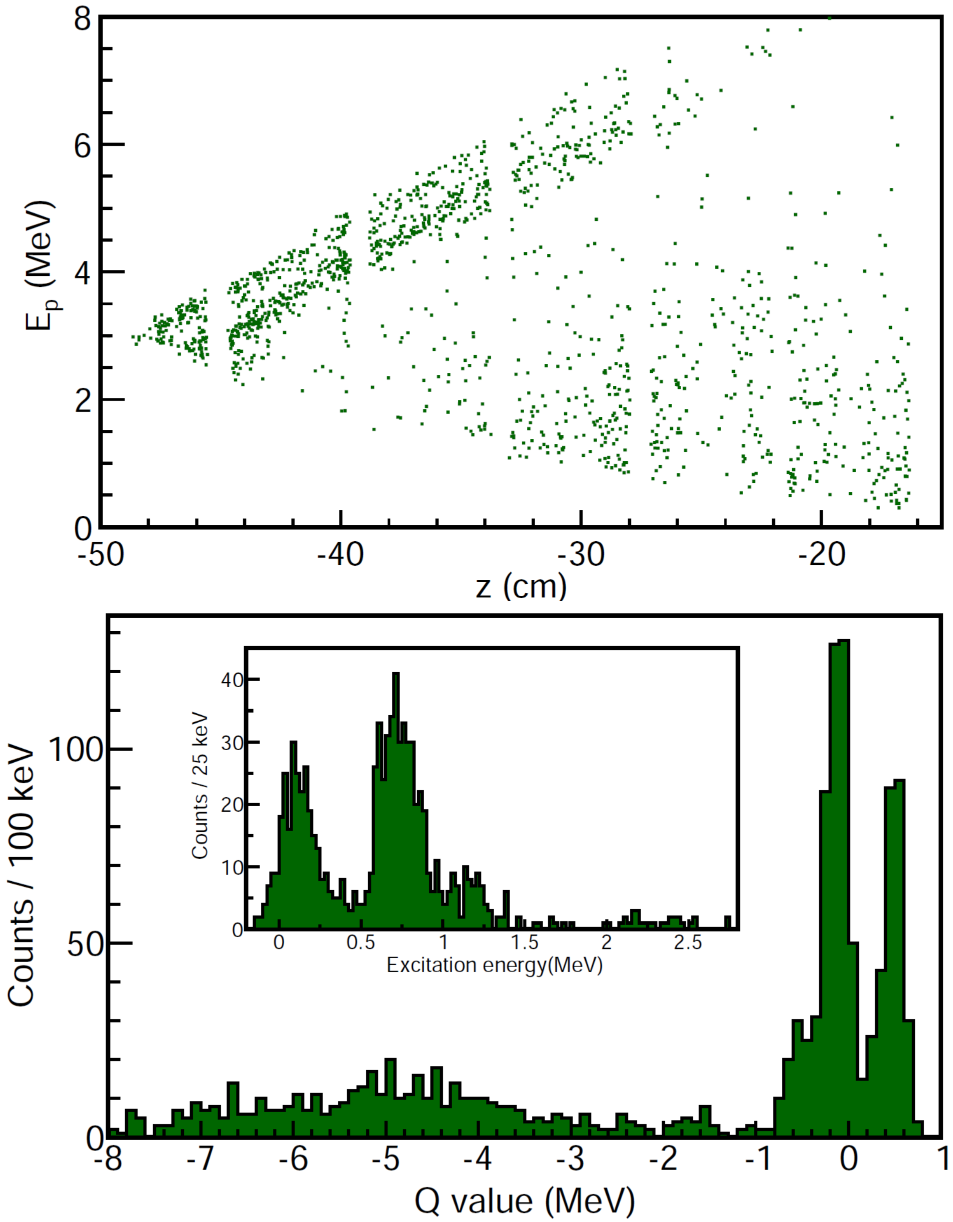




I. Talmi and I. Unna, PRL 4, 469 (1960)
M. J. Strongman et al., PRC 80, 021302 (2009)

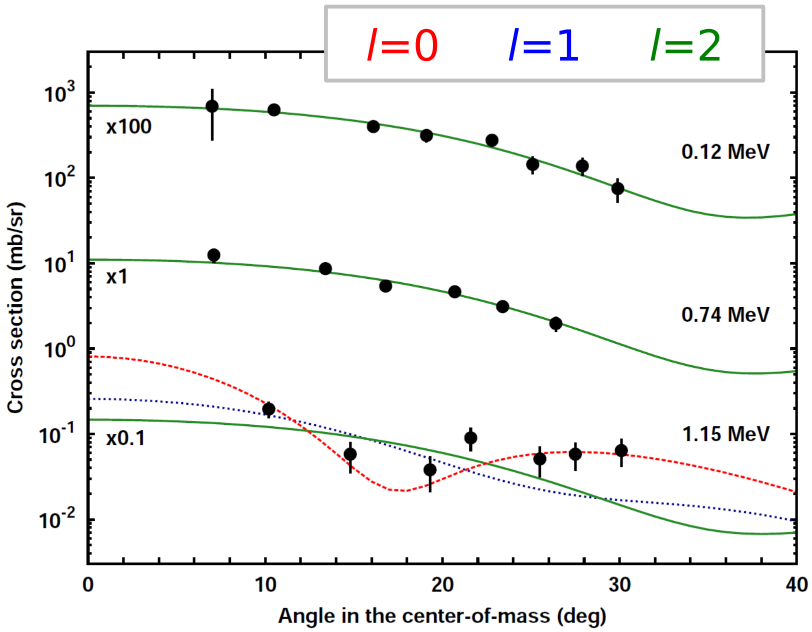
$^{17}N(d,p)^{18}N$ data

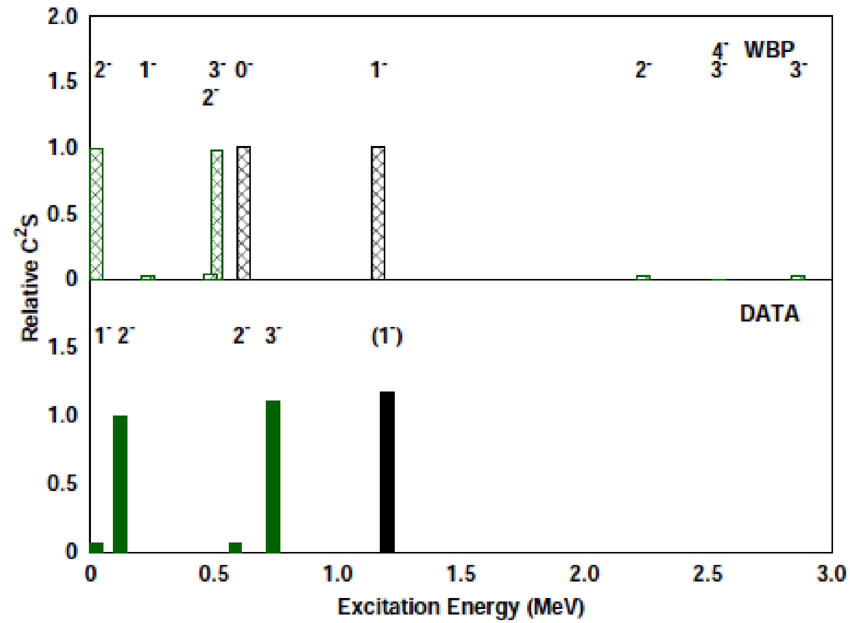
- ^{18}O beam (-1p) on Be
- Calculate Q value spectra
  - 30 keV systematic uncertainty in energy
  - ~275 keV FWHM
  - Test with $^{18}O(d,p)$ reaction
- Population of three strong states
  - 0.12 MeV (2-)
  - 0.74 MeV (3-)
  - 1.20 MeV unknown
  - Little ground state or 0.587-MeV state population
- Some strength at ~2.2 MeV and above S_n = 2.83 MeV



M. Wiedeking et al., PRC 77, 054305 (2008)

^{17}N(d,p)^{18}N results



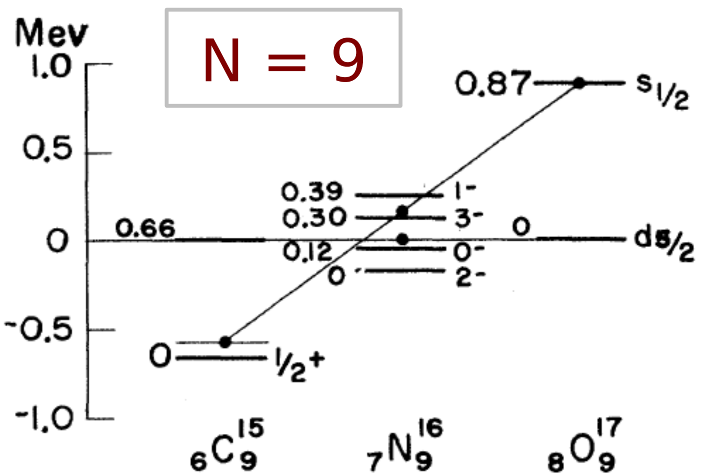


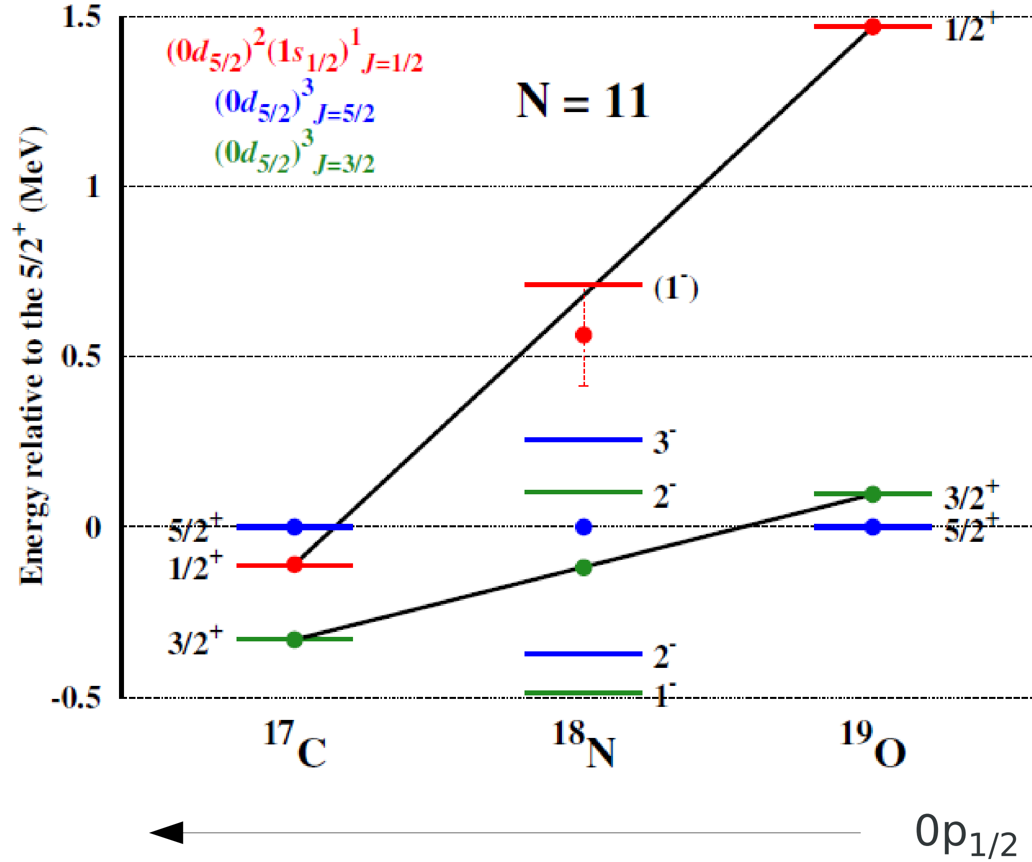
- Relative cross sections uncertain to a few percent
- Distorted wave Born approximation analysis
  - Angular distributions reproduced ^{18}O(d,p)^{19}O as well
  - Relative spectroscopic factors
- 0.12-MeV and 0.74-MeV (l = 2), identified as 2- & 3- states [$(0d_{5/2})^3$ w/ J=5/2]
- 1.2-MeV state is new l=0 state, likely 1- [$(0d_{5/2})^2(1s_{1/2})^1$ J=1/2]
- Strength distribution well reproduced by WBP shell model interaction

S. Sen et al., NPA 219, 249 (1974)
E. K. Warburton and B. A. Brown, PRC 46, 923 (1992)

N = 11 $(0d_{5/2})^3$ and $(0d_{5/2})^2(1s_{1/2})^1$ neutron systematics

- Centroids for $3/2^+$ and $1/2^+$ states relative to $5/2^+$
  - Function of $0p_{1/2}$ occupancy
- $C^2S(2J+1)$ weighting for ^{18}N
- $1/2^+$ - $5/2^+$ slope of 840 keV (210 keV)



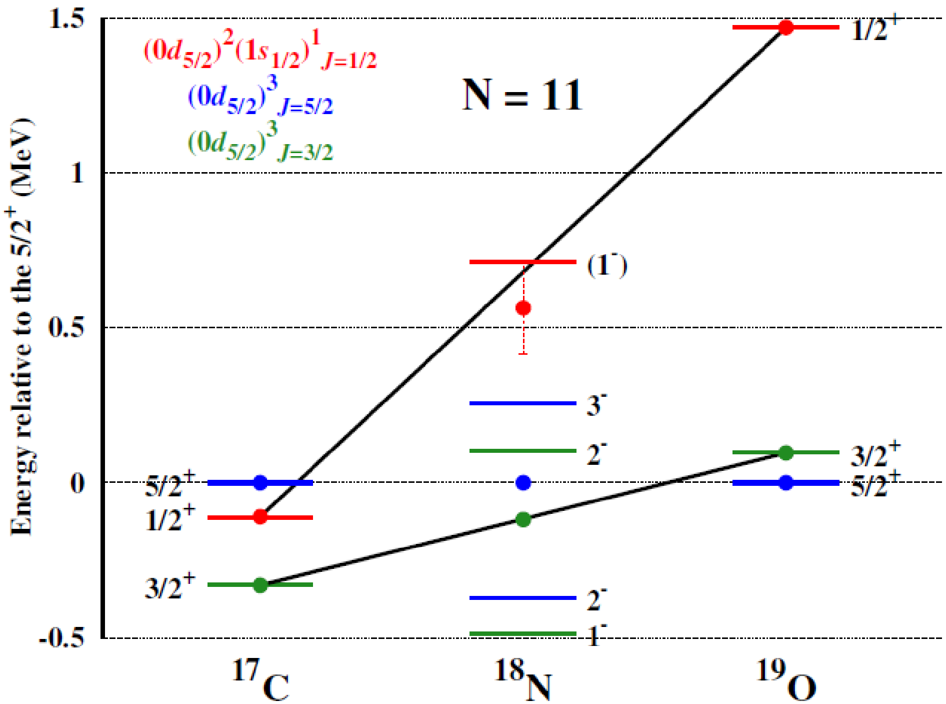


C. R. Hoffman et al., In preparation.

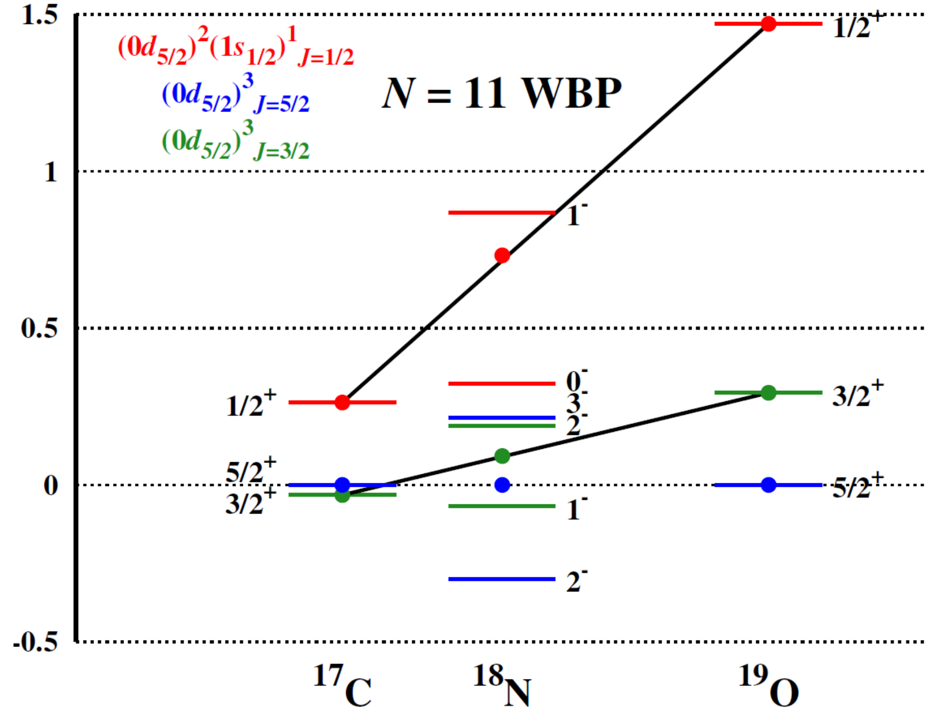
Calculated systematics for N = 11

- WBP shell model interaction
- Only linear if plotted with calculated $0p_{1/2}$ occupancies
- Too weak of an $0p_{3/2}$ – $0p_{1/2}$ gap?
- Improper neutron occupancies?

^{A}Z	J^{π}	$\pi 0p_{3/2}$	$\pi 0p_{1/2}$	$\nu 0d_{5/2}$	$\nu 1s_{1/2}$	$\nu 0d_{3/2}$
^{19}O	$5/2^+$	4.0	2.0	2.7	0.2	0.1
	$3/2^+$	4.0	2.0	2.6	0.3	0.1
	$1/2^+$	4.0	2.0	1.9	1.0	0.1
^{18}N	$2^- - 3^-$	3.9	1.1	2.5	0.4	0.1
	$1^- - 2^-$	3.9	1.1	2.4	0.5	0.1
	$0^- - 1^-$	3.9	1.1	1.9	1.0	0.1
^{17}C	$3/2^+$	3.6	0.4	2.3	0.5	0.2
	$5/2^+$	3.6	0.4	2.3	0.5	0.2
	$1/2^+$	3.6	0.4	1.9	1.0	0.1



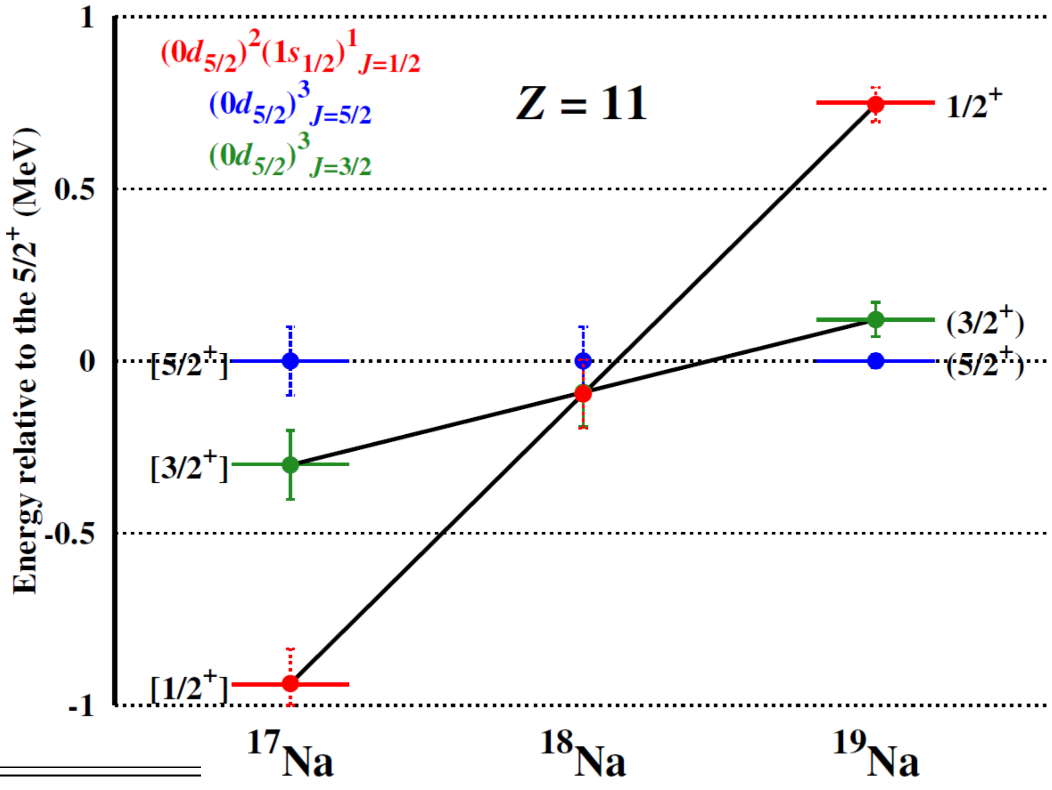
M. Stanoiu et al., PRC 78, 034315 (2008)



E. K. Warburton and B. A. Brown, PRC 46, 923 (1992)

Predictions of low-lying levels in neutron-deficient Z = 11 nuclei: ^{17,18}Na

- Use experimental relation to extrapolate to larger T
- Assumes isospin symmetry
- Anchor at ^{19}Na $5/2^+$, $3/2^+$, and $1/2^+$ levels
- Can binding energies be extracted?



	E*(^{17}Na)		
	Present	V2[SM] [31]	MCM [32]
$1/2^+$	0.0	0.0[0.0]	0.0
$3/2^+$	0.64	0.67[0.33]	0.17
$5/2^+$	0.94	1.03[0.67]	0.57

F. de Olivera Santos et al., EPJA 24, 237 (2005) and Ref. therein
[31] H. T. Fortune and R. Sherr, PRC 82, 027310 (2010)
[32] N. K. Timofeyuk and P. Descouvemont, PRC 81, 051301 (2010)

Summary and conclusions

- Transfer reactions in inverse kinematics are important and difficult
- HELIOS provides improved Q value resolution, particle-ID, solid angle coverage etc...
- Used direct reactions with HELIOS to characterize the neutron sd orbitals
  - $^{17}N(d,p)^{18}N$ – track evolution as a function of proton occupancy
  - $^{19}O(d,p)^{20}O$ – track evolution as a function of neutron occupancy
- $^{19}O(d,p)^{20}O$ & $^{17}N(d,p)^{18}N$ results
  - $0d_{5/2}$ and $1s_{1/2}$ neutron strengths are well described by standard shell model calculations [USD, USDA (B), WBP(T)]
  - Extracted diagonal two-body matrix elements are in agreement with $^{17}O(d,p)^{18}O$ results as well as global survey
  - Linearity of N = 11 single-particle evolution for Z = 6 – 8
    - Challenge for WBP interaction
  - Prediction of ^{17}Na spectrum from measured relations
- Expanding program utilizing HELIOS and the Argonne National Laboratory's ATLAS Facility

Acknowledgments

M. Albers, M. Alcorta, S. Almaraz-Calderon, B.B. Back, S.I. Baker, S. Bedoor, P.F. Bertone, J.A. Clark, A. Couture, C.M. Deibel, B. DiGiovine, S.J. Freeman, J.P. Greene, D. Henderson, M. Hendricks, B. P. Kay, J. Lai, H.-Y. Lee, J.C. Lighthall, S.T. Marley, T. Palchan-Hazan, R.C. Pardo, G. Perdikakis, K.E. Rehm, A.M. Rogers, J. Rohrer, A. Rojas, D. Santiago-Gonzalez, G. Savard, J.P. Schiffer, B. Scott, D.K. Sharp, D.V. Shetty, J.S. Thomas, A.W. Vann, R. C. Vondrasek, M. Wiedeking, I. Wiedenhover, J. Winkelbabuer, and A.H. Wuosmaa

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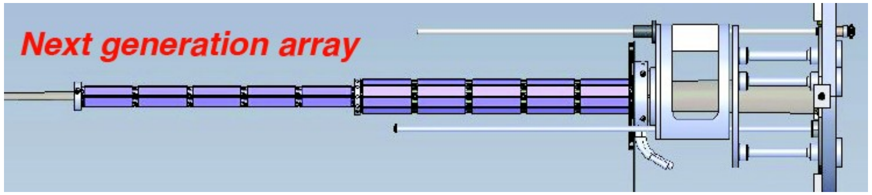
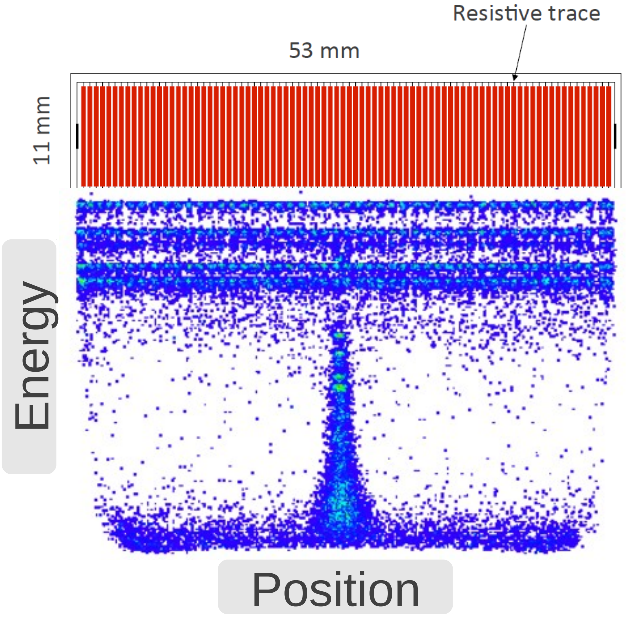
Future developments and plans





- New position sensitive Si detector array (ANL/WMU)
  - Quantized resistive readout
  - ~30-40% increase in solid angle coverage
  - Digital electronics
  - High flexibility
- Gas target has been commissioned (ANL/LSU)
  - ^{3}He, ^{4}He, etc. targets available
  - 1, 2, 3mm thickness w/ cryo-cooling
  - ~300 keV FWHM
- Development of new RIBs
  - 2n transfer for in-flight beams
  - First experiments with CARIBU beams