Shell Evolution and Direct-Transfer Reactions

Opportunities with Reaccelerated Beams and ReA

University of Connecticut
Department of Physics

A. H. Wuosmaa

Outline

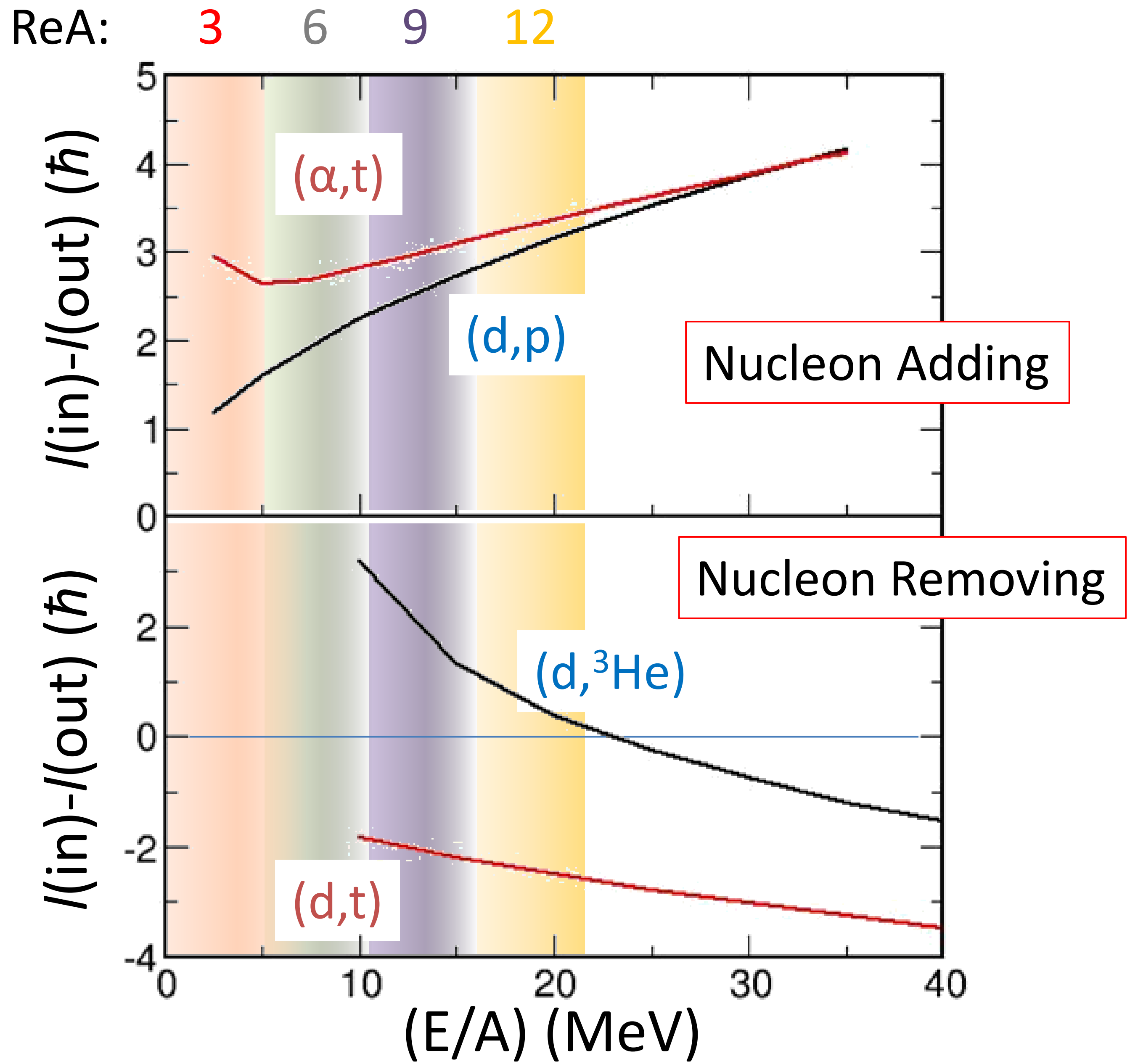
- Characteristics of different transfer reactions
- Two regions of interesting shell behavior, and some possible experiments
  - ^{32}Mg and the Island of Inversion
  - ^{52,54}Ca and N=32 (and maybe 34) shell closure
- Experimental feasibility (ReAX facility)
- Technical approach (one of many possible)

Direct reactions and shell evolution

- "Single-particle" states and properties
  - Energies and spin-parity assignments
  - Spectroscopic factors and effective S.P. energies
  - Study with nucleon-adding reactions, such as (*d,p*), (α,*t*), (^{3}He,*d*)
- Multi-nucleon correlations, particle-hole excitations
  - Core stability, orbital occupancies
  - Study with nucleon-removing reactions such as (*d,t*), (*d,*^{3}He)
- Pairing correlations
  - Study with two-nucleon adding or removing reactions such as (*t,p*), (*p,t*), (^{3}He,*p*), (α,*d*), (*d*,α)

Angular-momentum transfer and energy

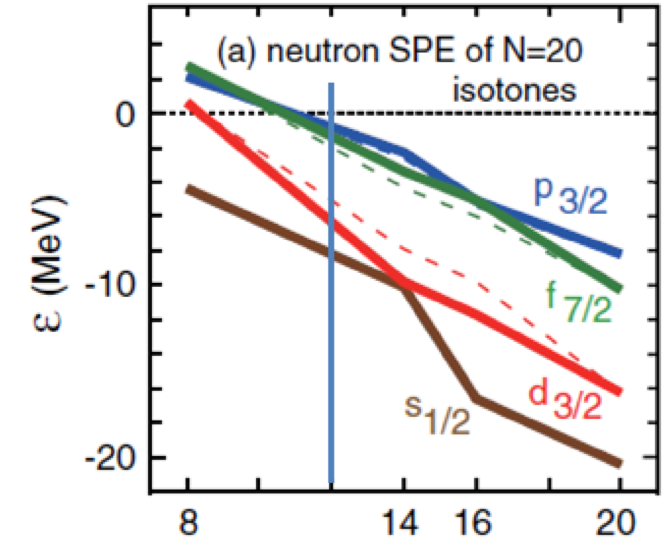
Q Values (MeV):
(*d,p*): near 0
(α,*t*): -5 to -10
(*d*,^{3}He): -12 to -18
(*d,t*): near 0 to +5



Values typical for neutron-rich nuclei around A=30-60

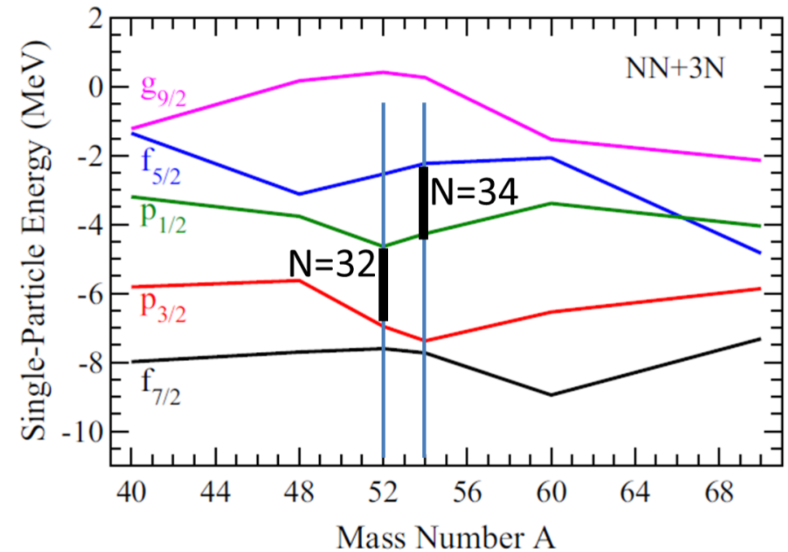
Interesting Regions (two of many)

- Near ^{32}Mg: Disappearance of N=20 magic number and *sd*-$f_{7/2}$ gap driven by tensor force and pairing; (*sd*)-(*fp*) mixing



T. Otsuka et al., Phys Rev Lett **104**, 012501 (2010)

- ^{52}Ca (^{54}Ca?): Appearance of N=32 (and N=34?) magic no. from decreased $\pi 0f_{7/2}$- $\nu 0f_{5/2}$ interaction as $\pi 0f_{7/2}$ is emptied

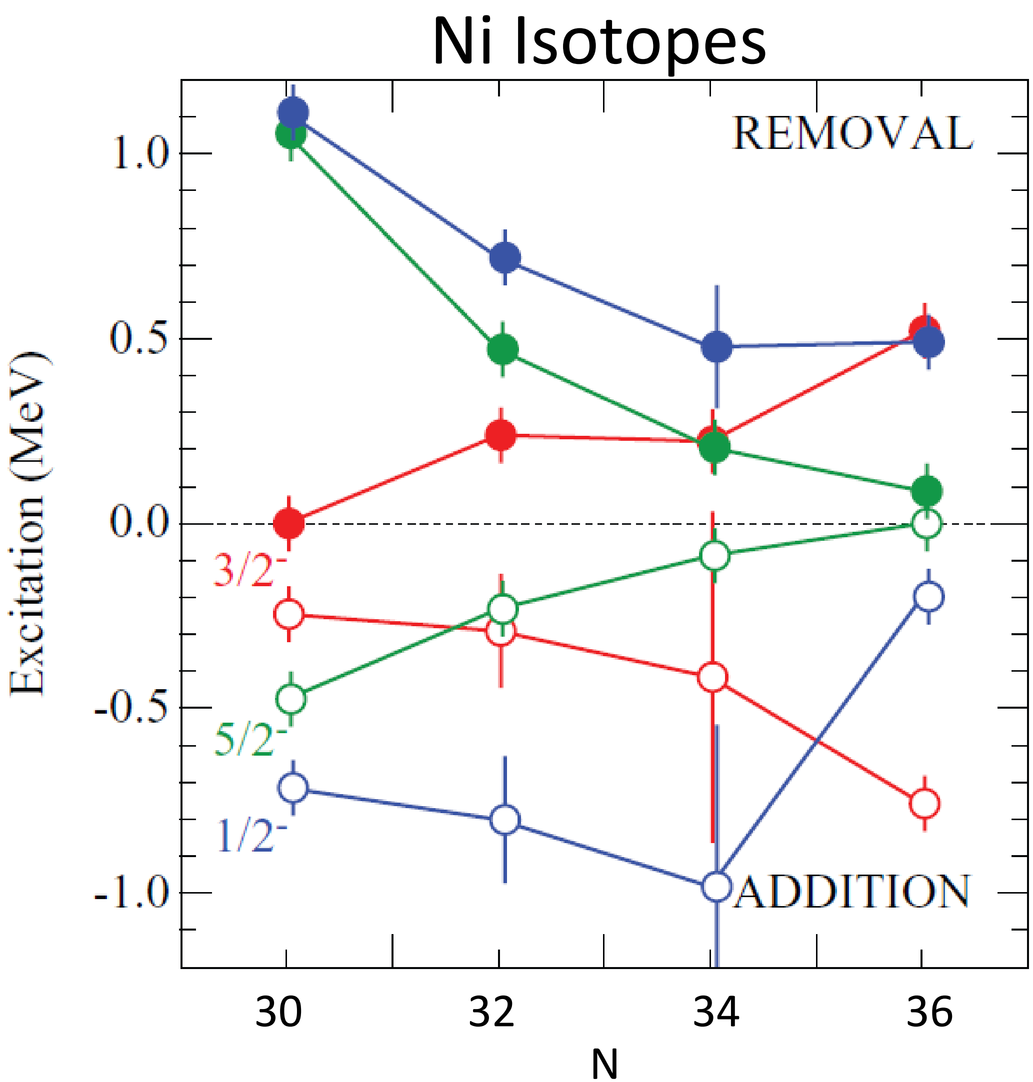


J. D. Holt et al., Phys Rev C **90**, 024312 (2014)

Some possible experiments

- Study evolution of *fp* neutron S.P.E. around ^{32}Mg and ^{52}Ca with (*d*,*p*) across neutron-rich Mg and Ca isotopes
  - E/A≈5-10 MeV, I>few X10^3/sec
- Pairing correlations, multi-*p*-*h* states near neutron-rich Mg isotopes with (*t*,*p*),(*p*,*t*):
  - ^{32}Mg(*p*,*t*)^{30}Mg, ^{28}Ne(*t*,*p*)^{30}Ne, ^{32}Mg(*t*,*p*)^{34}Mg
  - E/A≈5-10 MeV, I>few X10^4/sec
- Study stability of proton core with changing *N* using (*d*,^{3}He) on neutron-rich Mg or Ca isotopes
  - E/A≈15-20 MeV, I>few X10^4/sec

Single-particle energy centroids

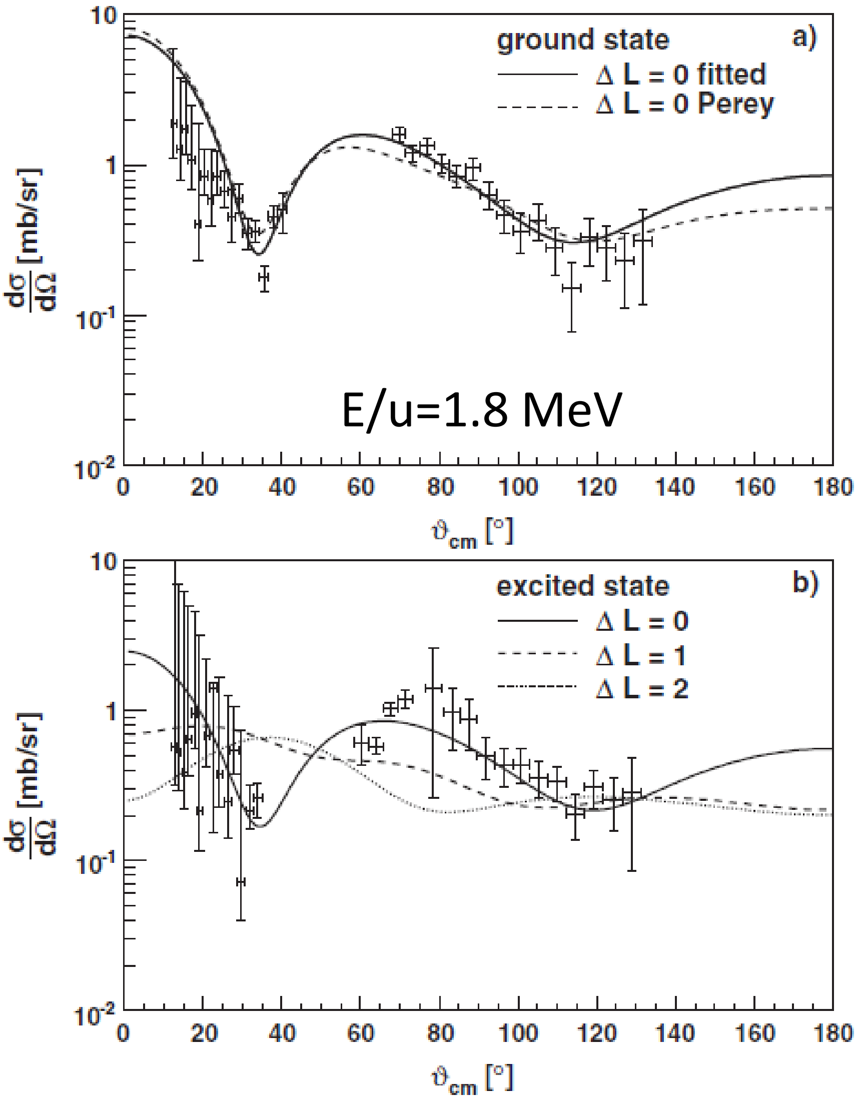


Spectroscopic-factor weighted neutron energy centroids for Ni isotopes from (*d,p*), (α,^{3}He), (*p,d*)

Survey of neutron- transfer reactions done in a consistent way across a chain of isotopes.

J. P. Schiffer et al., Phys. Rev. C **87**, 034306 (2013)

Pair transfer on the Island of Inversion



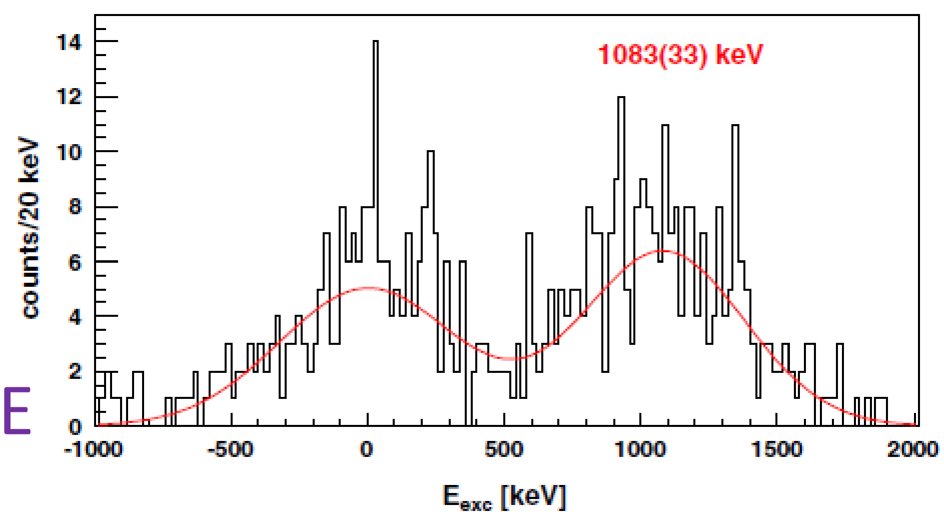
^{30}Mg(t,p)^{32}Mg suggests ^{32}Mg$_{g.s.}$ is ν(fp)^2(sd)$^{-2}$ (or 2p-2h)

Wimmer *et al*., Phys. Rev. Lett. **105**, 252501 (2010)

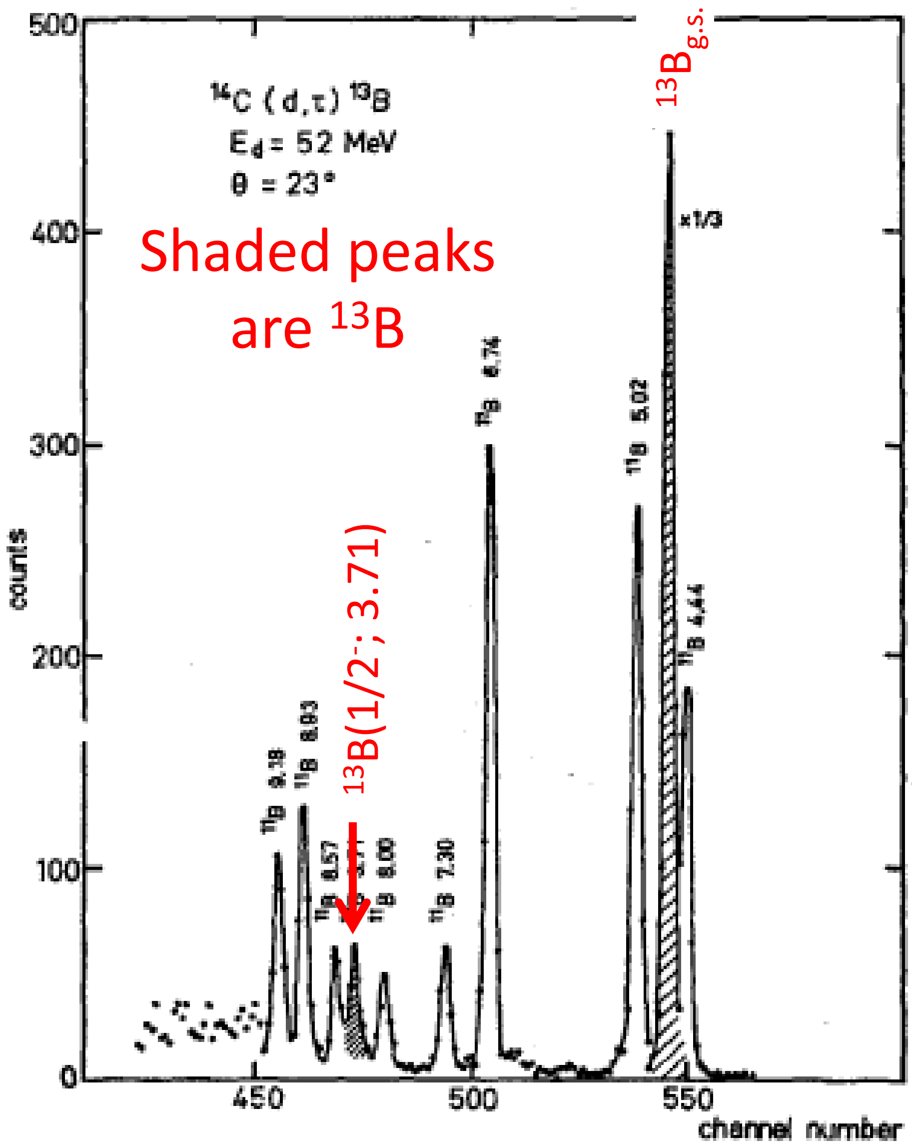
A different analysis suggests ^{32}Mg$_{g.s.}$ is ν(sd)^2 (or 0p-0h, rather than 2p-2h)

Fortune, Phys. Rev. C **84**, 024327 (2011)

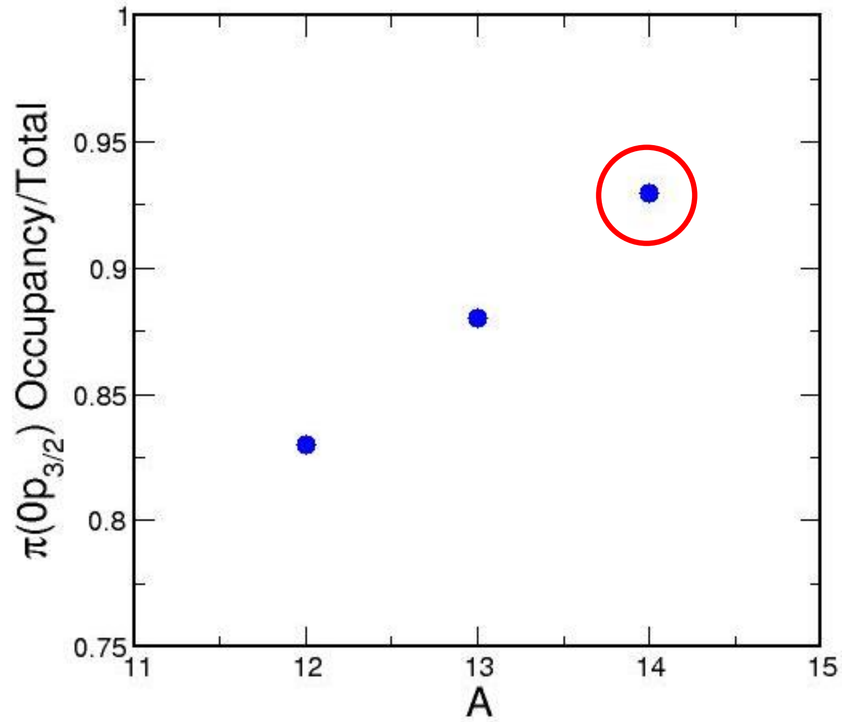
^{30}Mg(t,p)^{32}Mg from REX-ISOLDE



Proton correlations in carbon isotopes



Studied with the (d,^{3}He) reaction

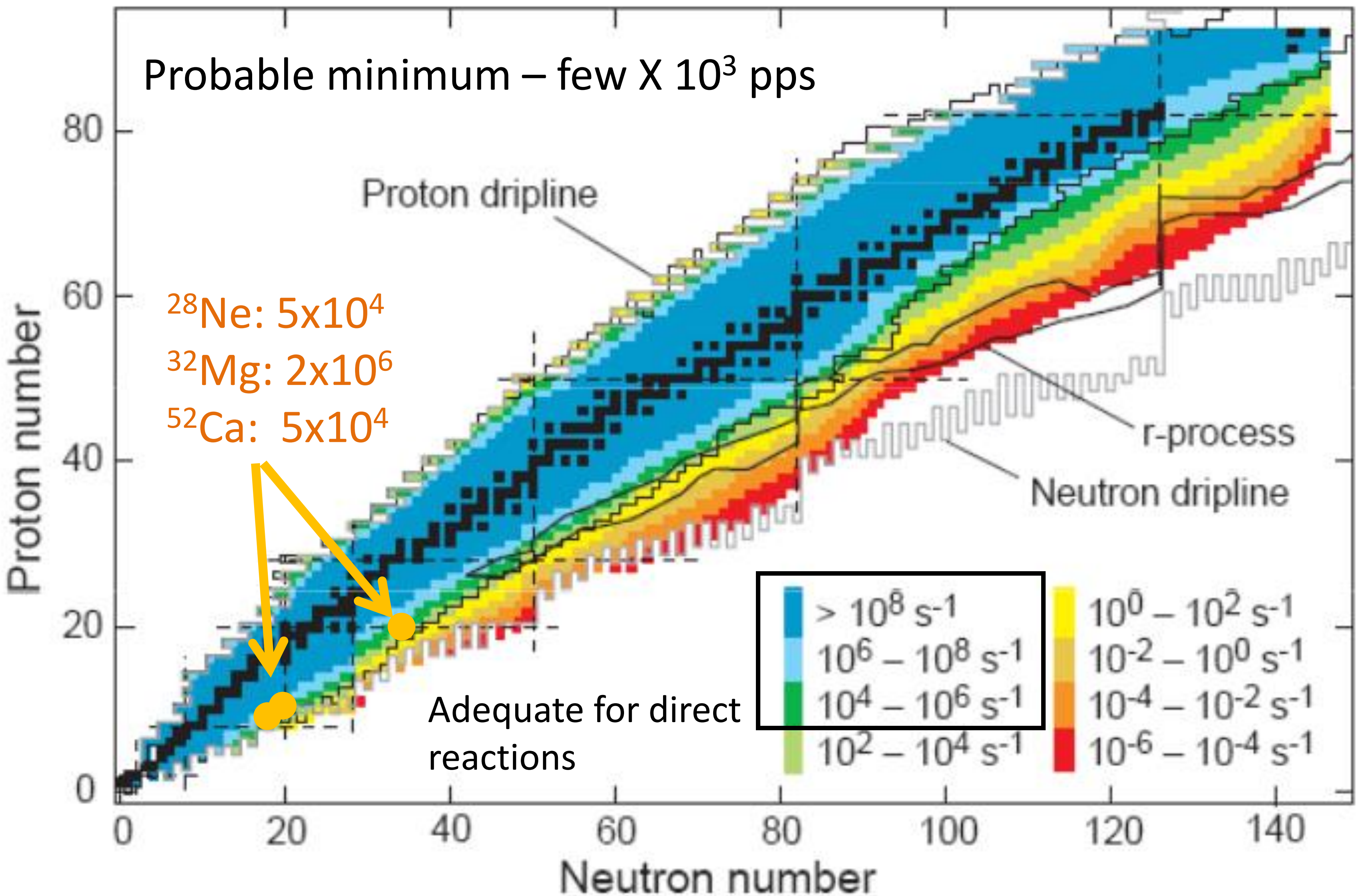


^{14}C measurement difficult due to 60% ^{12}C target impurity – weak states obscured?

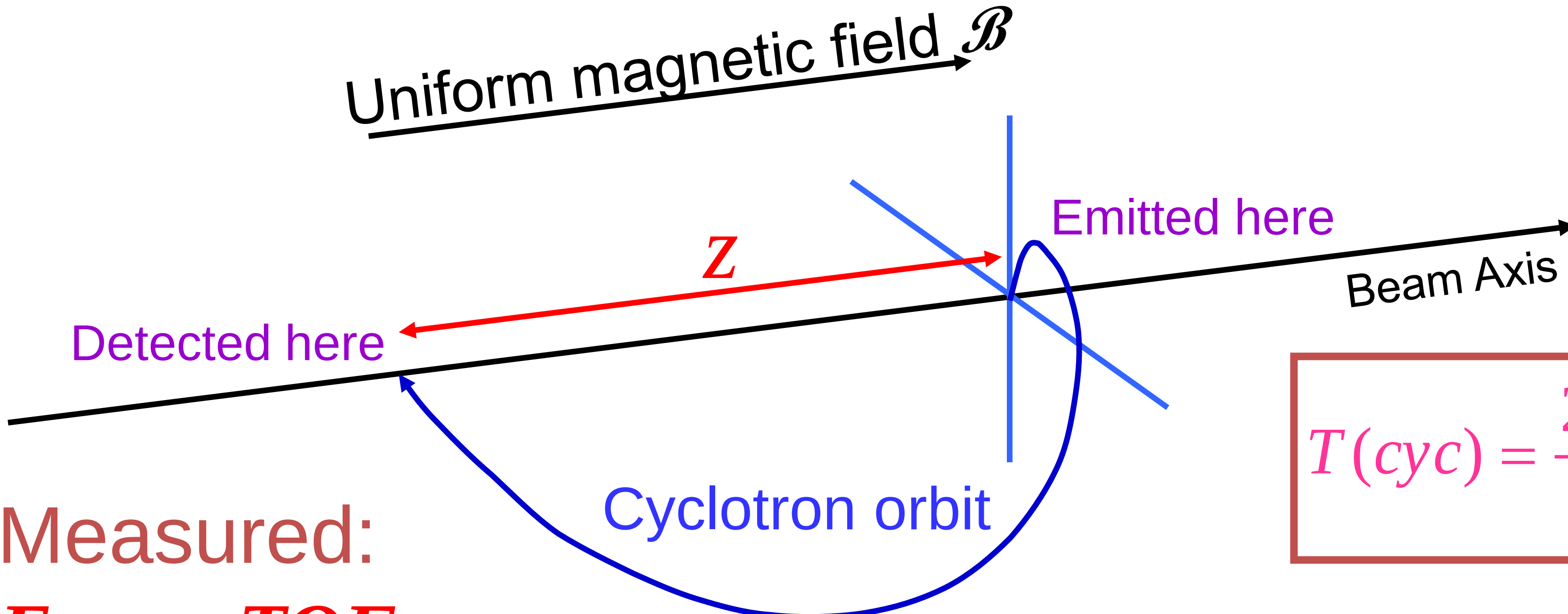
Complementary to (e,e'p) or knockout

Mairle and Wagner, NPA **253**, 253 (1975)

FRIB yields: limits for direct-reaction studies



Particle transport in a solenoid



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

Measured:

E_{lab}, z, TOF

Deduced:

E_{CM}, θ_{CM}

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

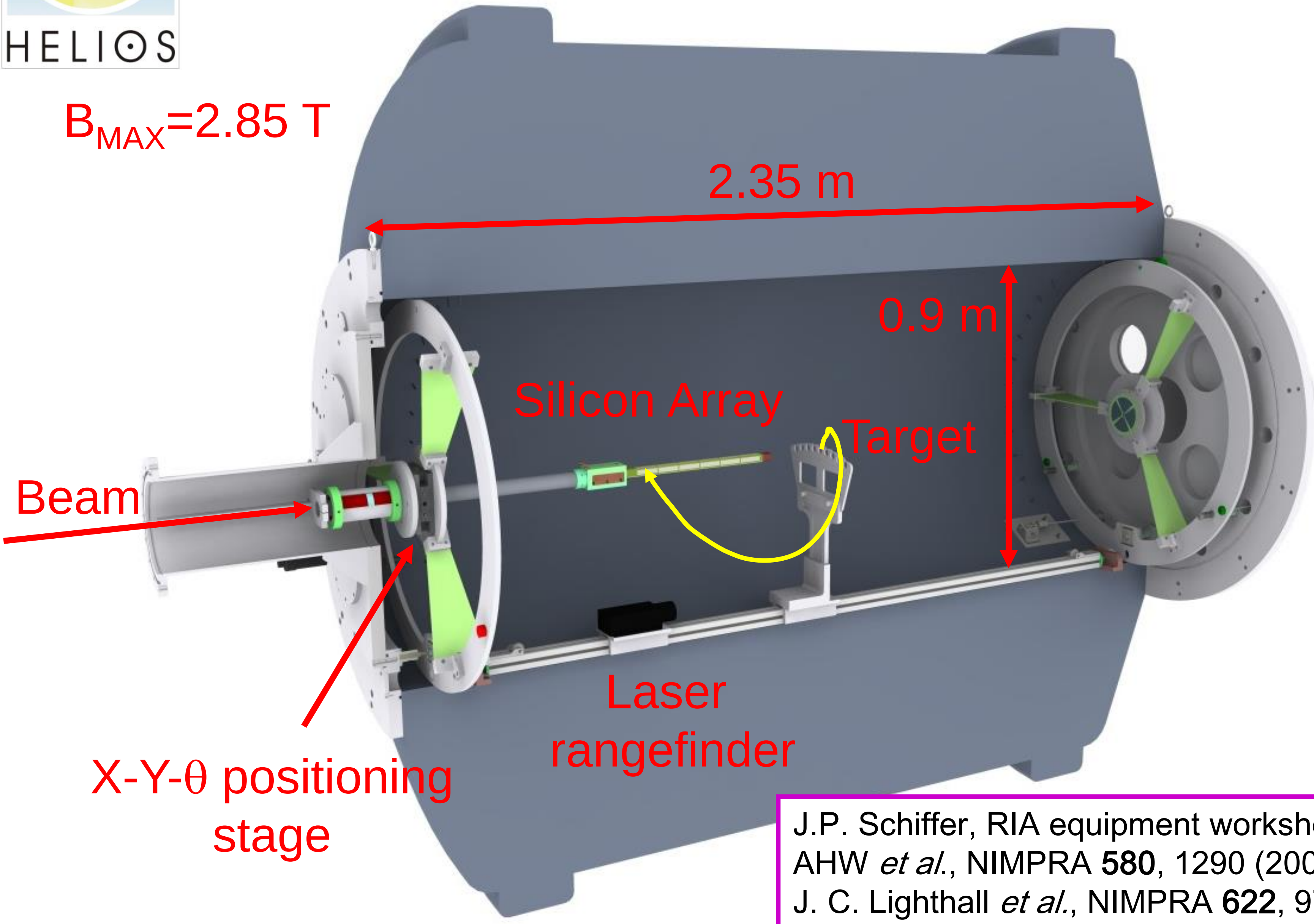
$$E_{lab} = E_{CM} - A + Bz$$

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

For a given state

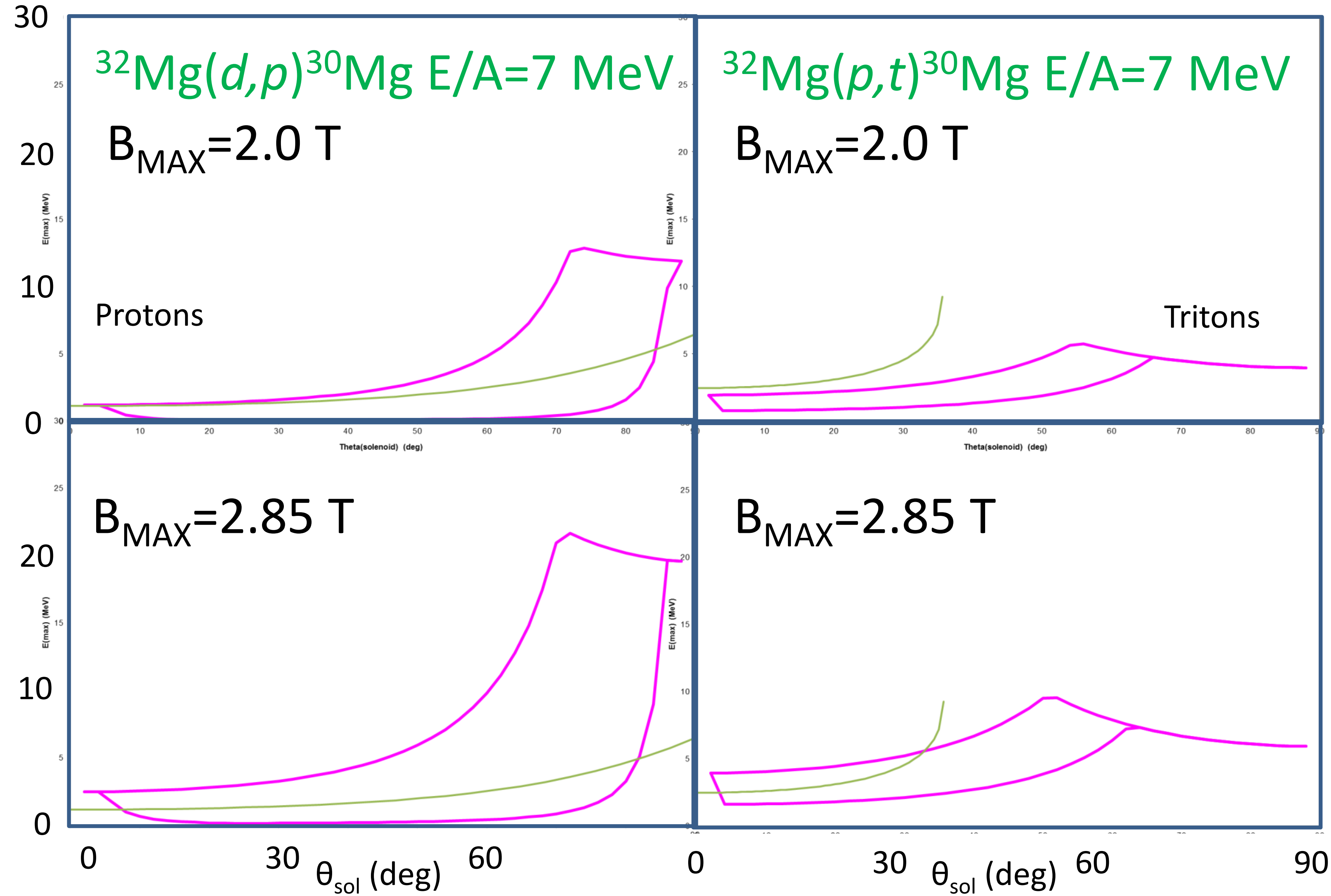
For two states at fixed z

HELIcal Orbit Spectrometer -HELIOS



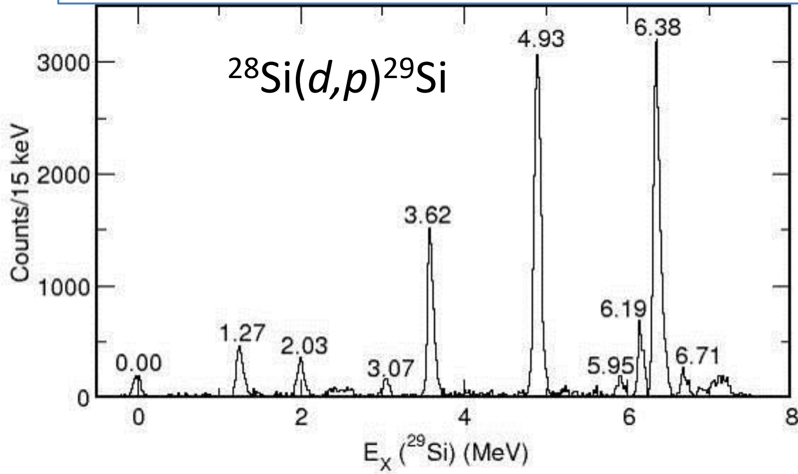
J.P. Schiffer, RIA equipment workshop 1999,
AHW *et al.*, NIMPRA **580**, 1290 (2007),
J. C. Lighthall *et al.*, NIMPRA **622**, 97 (2010)

Spectrometer acceptance

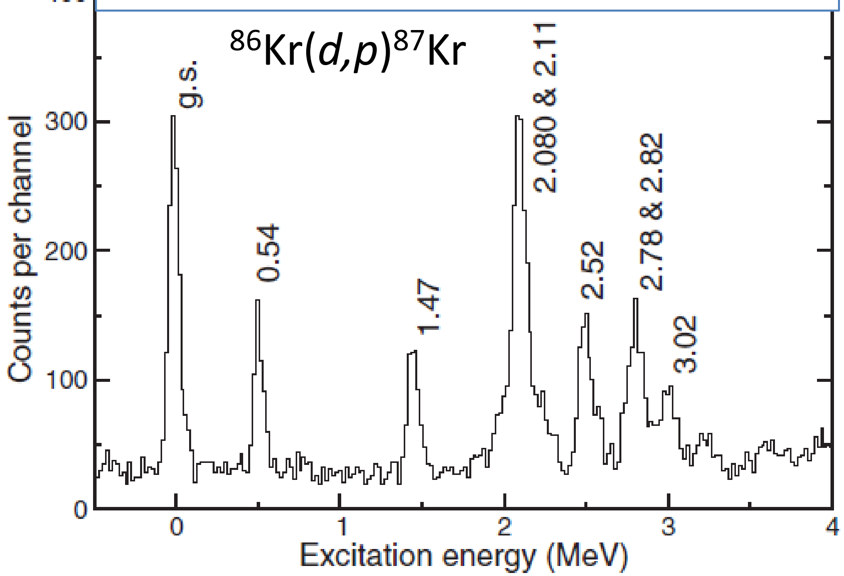


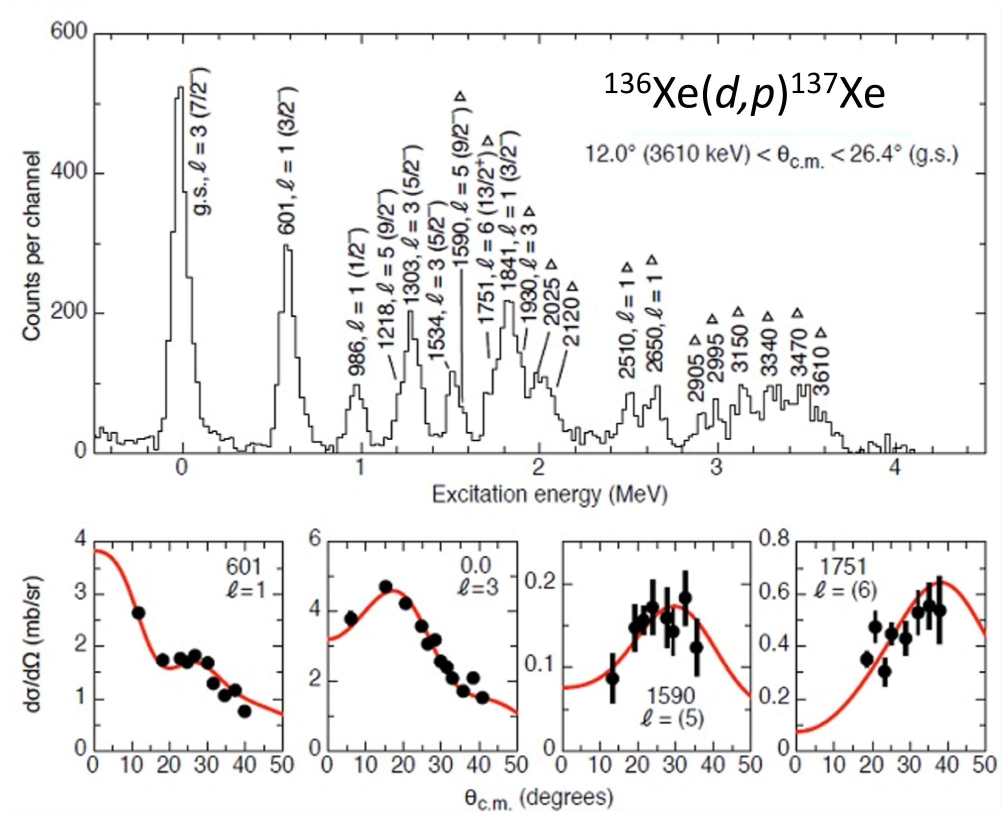
(*d,p*) with Stable beams

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



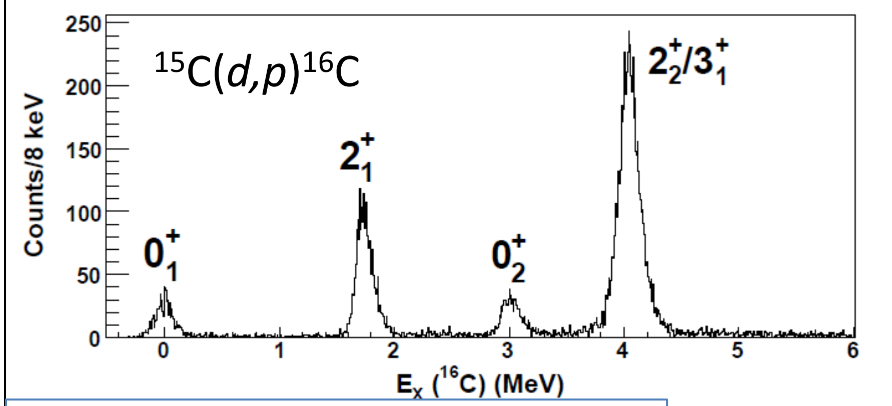
D. K. Sharp et al., PRC **87**, 014312 (2013)



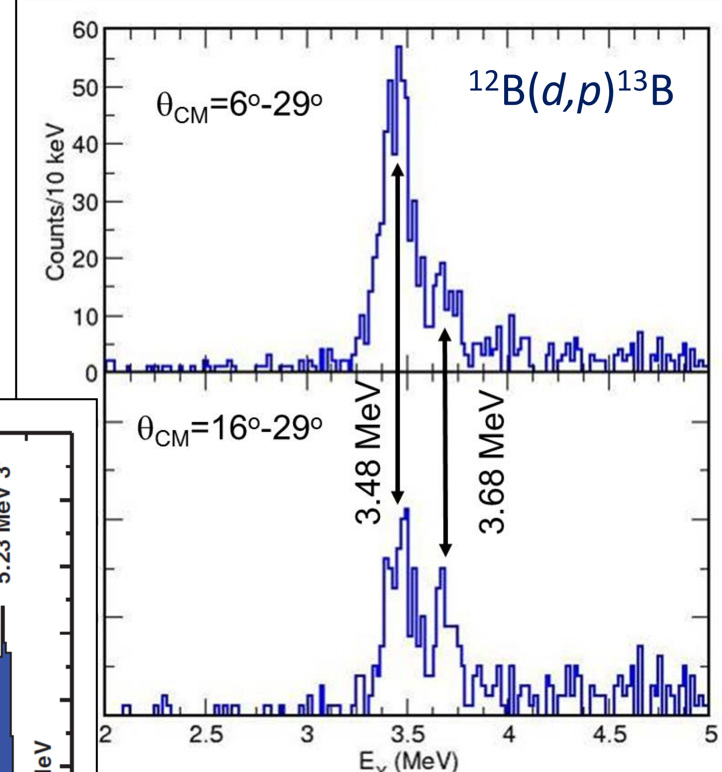


B. P. Kay et al., PRC 84, 024325 (2011)

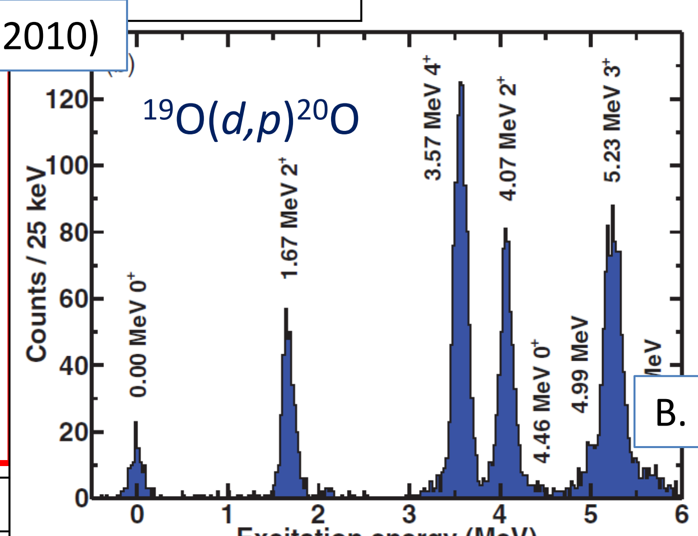
(*d,p*) with in-flight ATLAS RIBs



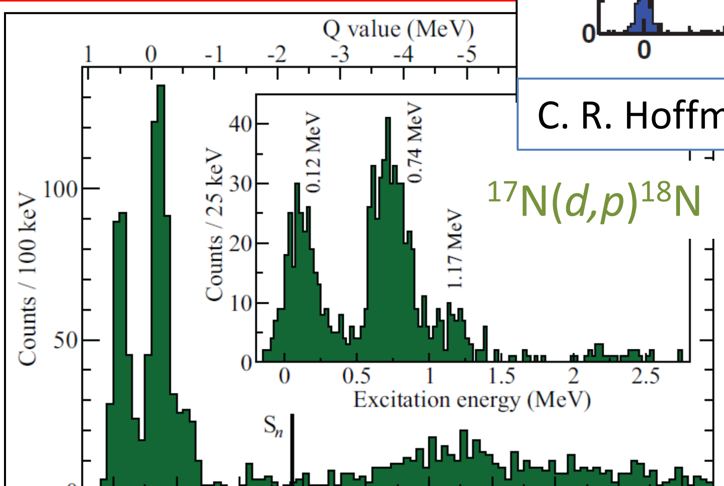
AHW et al., PRL **105**, 132501 (2010)



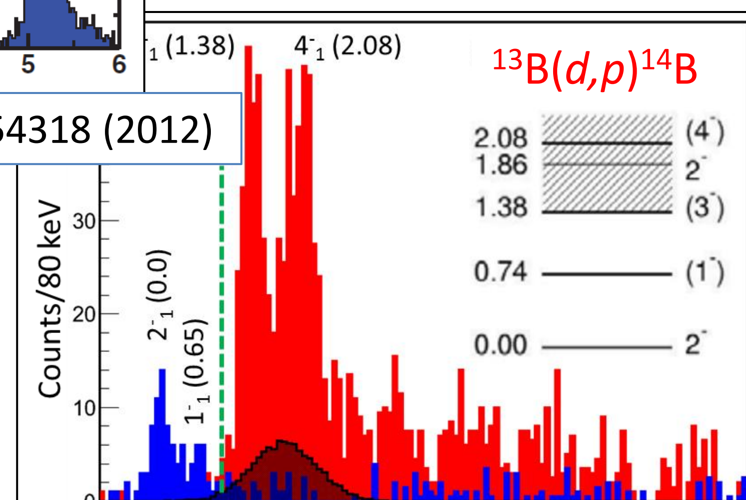
B. B. Back et al., PRL **104**, 132501 (2010)



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

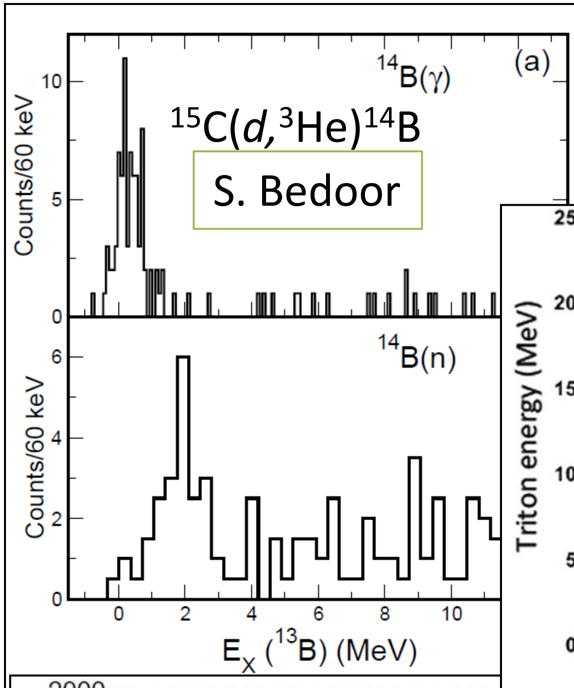


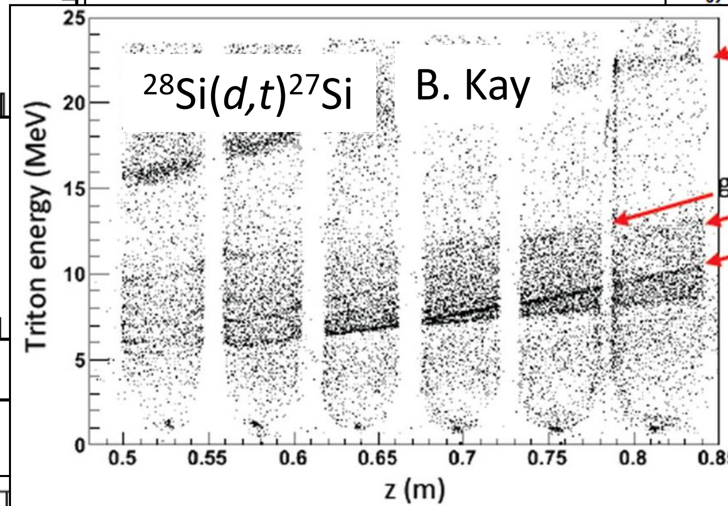
C. R. Hoffman et al., PRC **88**, 044317 (2013)

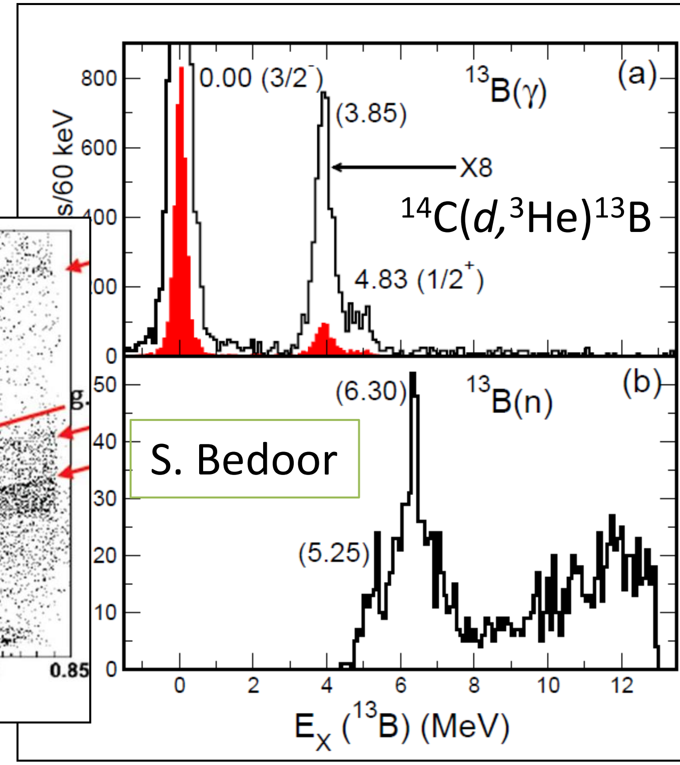


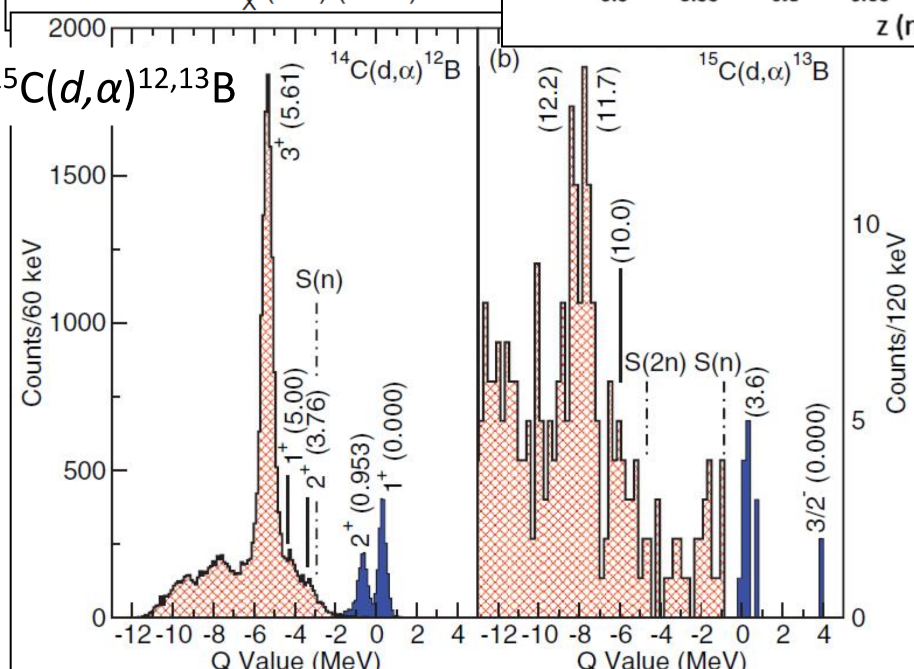
S. Bedoor et al., PRC **88**, 011304 (2013)

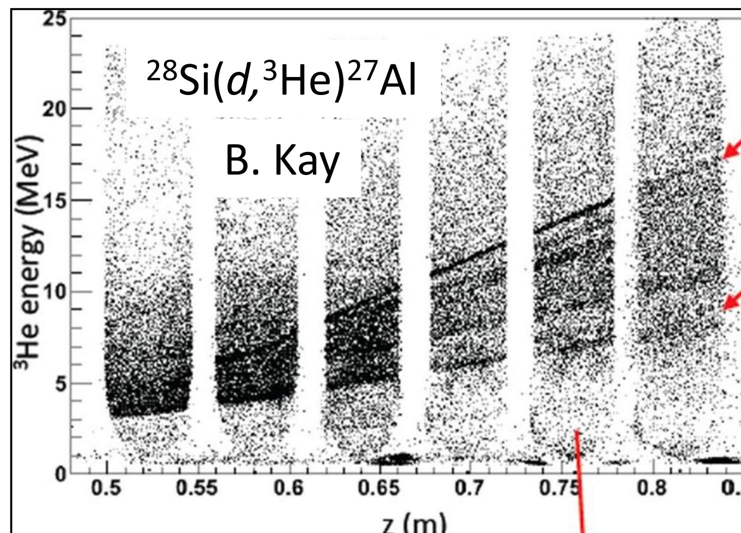
Other reactions







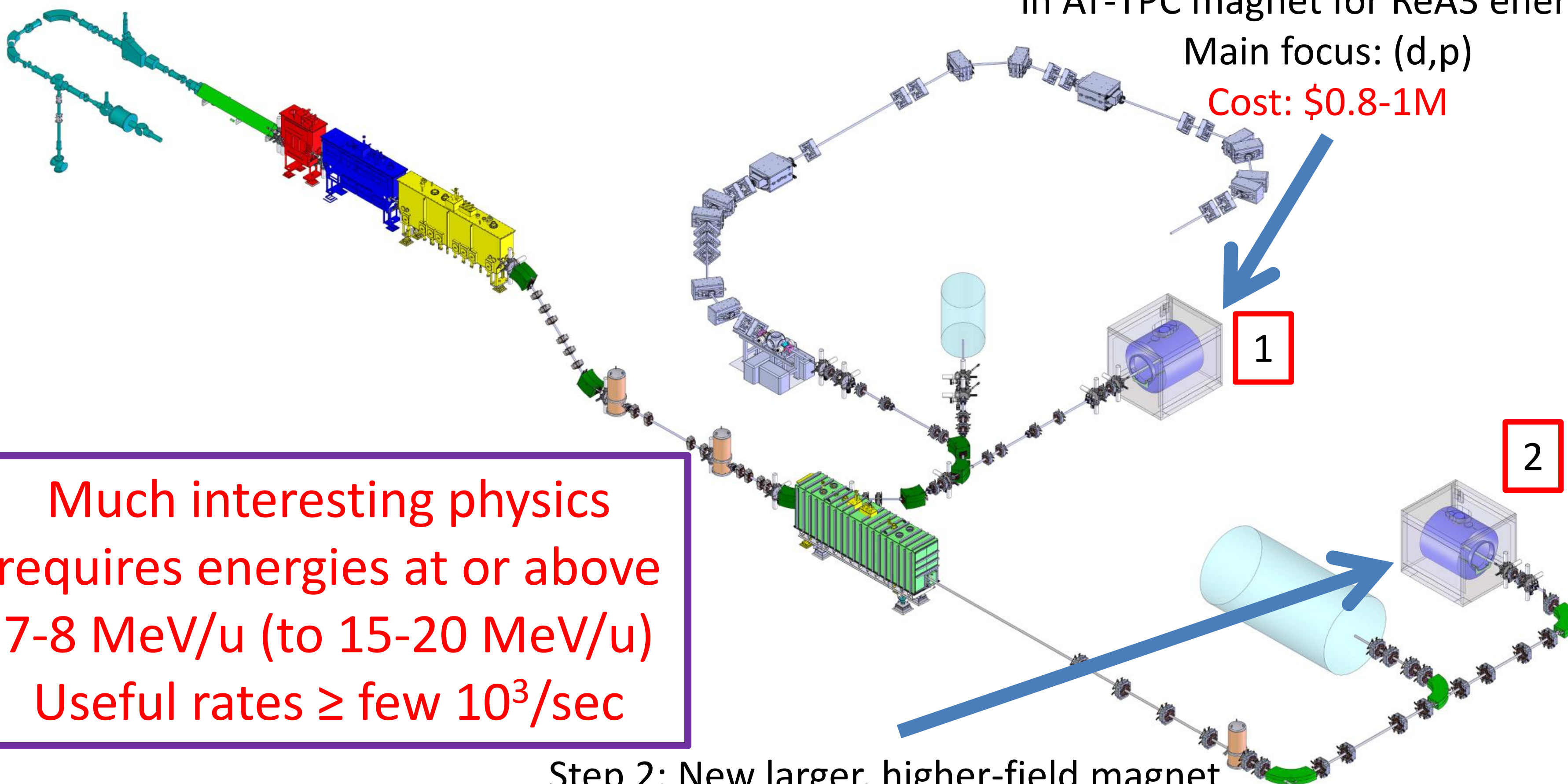




AHW et al., PRC **90**, 061301 (2014)

Two-stage approach at ReAX/FRIB

Step 1: Implement detectors
in AT-TPC magnet for ReA3 energies
Main focus: (d,p)
Cost: $0.8-1M



Much interesting physics
requires energies at or above
7-8 MeV/u (to 15-20 MeV/u)
Useful rates ≥ few 10^3/sec

Step 2: New larger, higher-field magnet
in ReA12 area using existing detectors, for
E>5 MeV/u: Expanded physics focus
(candidate magnet may already exist)
Cost: $2-3M

Summary

- Many interesting possibilities for direct-reaction studies on exotic nuclei at ReA.
- Necessary energy and intensity depend on the physics. (*d,p*): lower energy, (*d,*^{3}He): ALARA (***A***s ***L***arge ***A***s ***R***easonably ***A***chievable)
- Many experimental approaches are possible; I have highlighted only one.
- Direct-reaction studies at energies near the Coulomb barrier have been part of the ISL/RIA/FRIB physics portfolio for decades: ReA upgrades are ***essential*** for this physics.

Many thanks to:

M. Albers[1], M. Alcorta[1], S. Almaraz-Calderon[1], B. B. Back[1], S. Bedoor[2], P. F. Bertone[3], C. M. Deibel[3], C. R. Hoffman[1], B. P. Kay[1], J. C. Lighthall[2], S. T. Marley[2,1], R. C. Pardo[1], K. E. Rehm[1], J. P. Schiffer[1], D. V. Shetty[2]

[1]*Argonne National Laboratory, Argonne, IL USA*

[2]*Western Michigan University, Kalamazoo, MI USA*

[3]*Louisiana State University, Baton Rouge, LA USA*

This material is based upon work supported by the U. S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award numbers DE-FG02-04ER41320 and DE-AC02-06CH11357, and the U. S. National Science Foundation under Grant No. PHY-1068217. This research used resources of the Argonne National Laboratory ATLAS Accelerator Facility, which is a DOE Office of Science User Facility.

And …

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

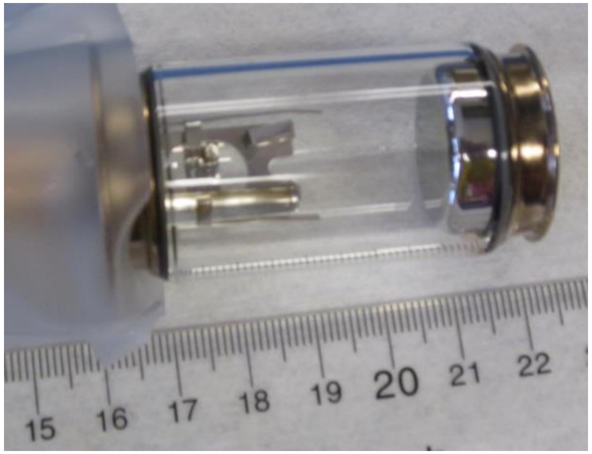
Work supported by the U. S. Department of Energy, Office of Nuclear Physics, under contract numbers DE-FG02-04ER41320 (WMU) and DE-AC02-06CH11357 (ANL)

Also, special thanks to:

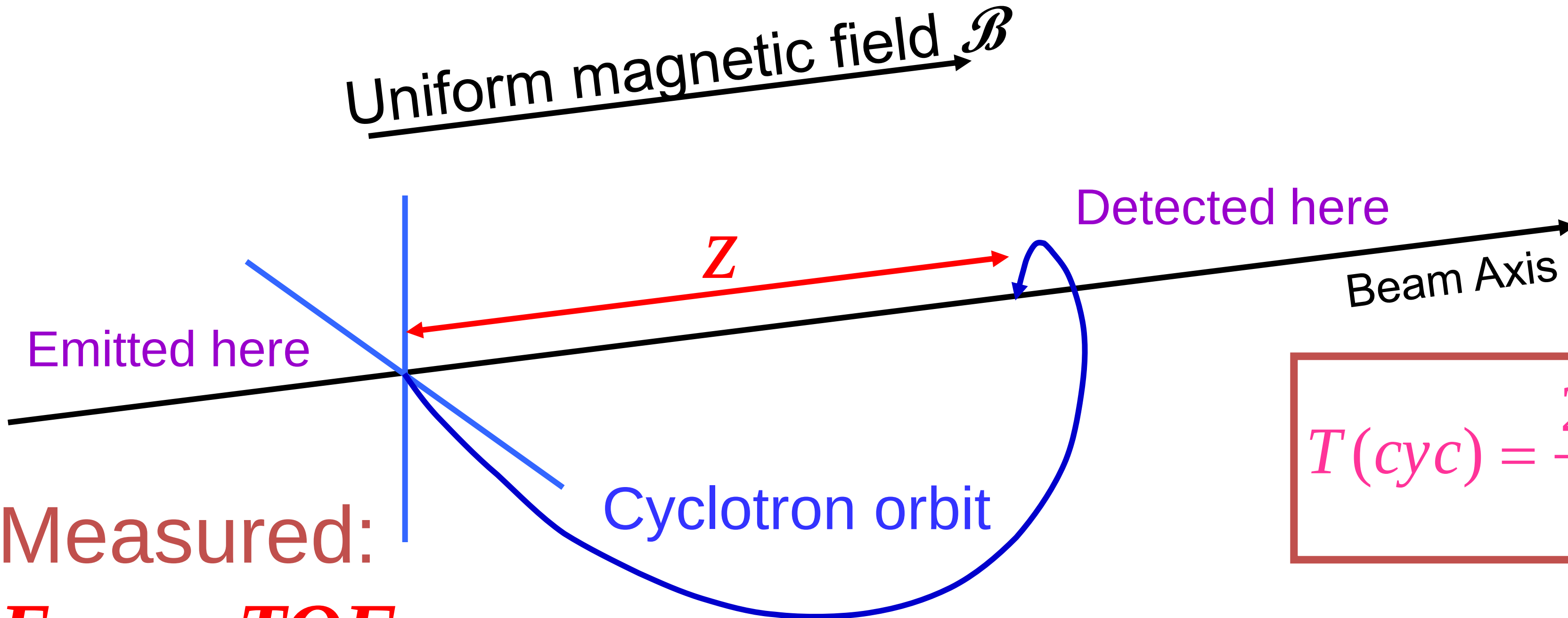
N. Antler, Z. Grelewicz, S. Heimsath, J. Rohrer, J. Snyder

Targets beyond CD_2

- ^{6}LiF + C backing
  - For (^{6}Li,*d*) α-transfer, has been used in HELIOS
- Cryogenic gas target:
  - For (^{3}He,*d*), (^{3}He,*p*), (α,*p*), (α,*d*), (α,*t*) Has been built and tested in HELIOS
- ^{3}H/Ti foil targets:
  - For (*t*,*p*), (*t*,α): Have been used at CERN/ISOLDE and tested in HELIOS. New target is finished and delivered to ANL



Particle transport in a solenoid



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

Measured:

E_{lab}, z, TOF

Deduced:

E_{CM}, θ_{CM}

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

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

For a given state

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

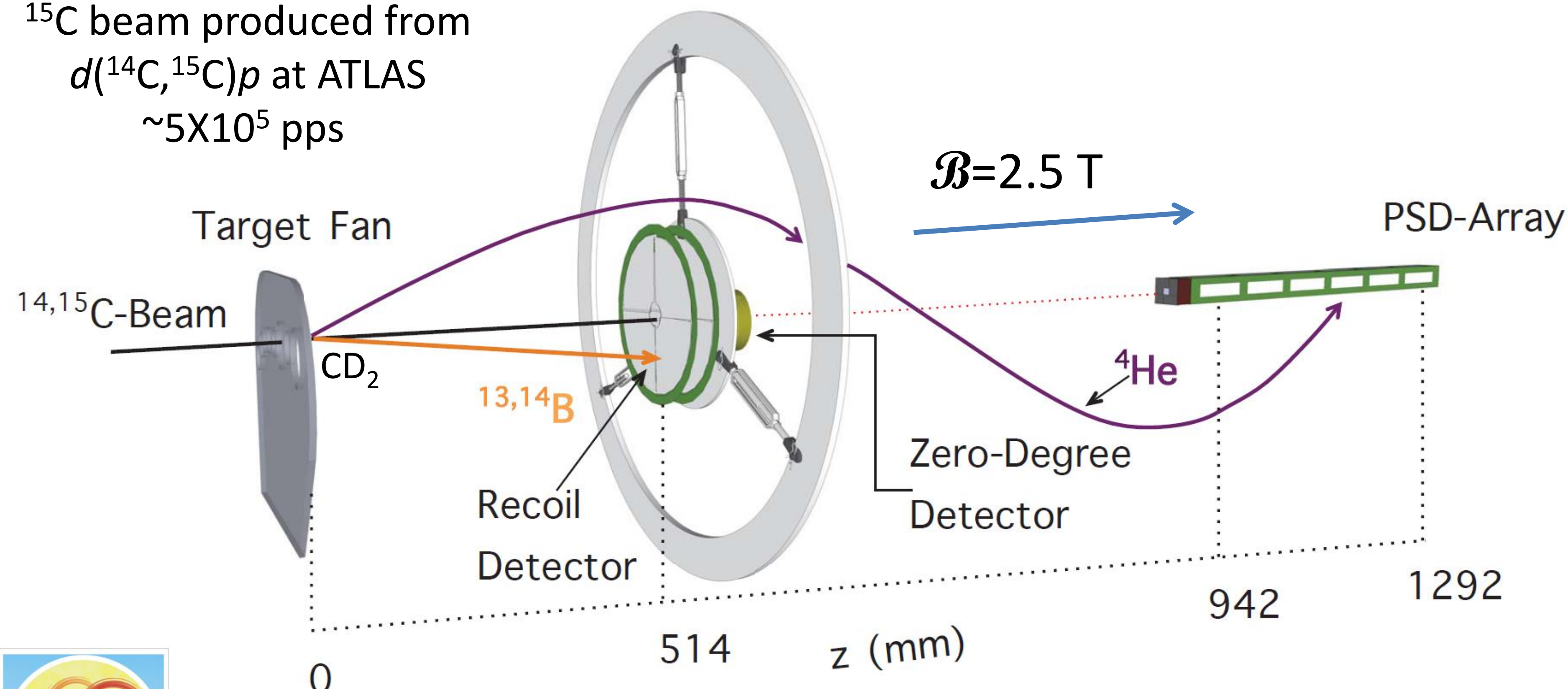
For two states at fixed z

Experiment inside HELIOS

E(^{14}C)=17.1 AMeV
E(^{15}C)=15.7 AMeV

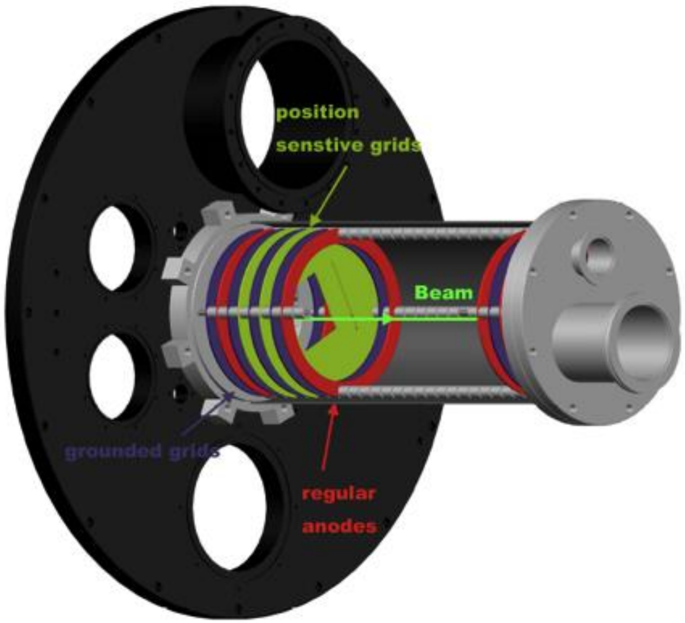
Interesting α particles from (d,α) go forward in the laboratory system

^{15}C beam produced from
d(^{14}C,^{15}C)p at ATLAS
~5X10^5 pps



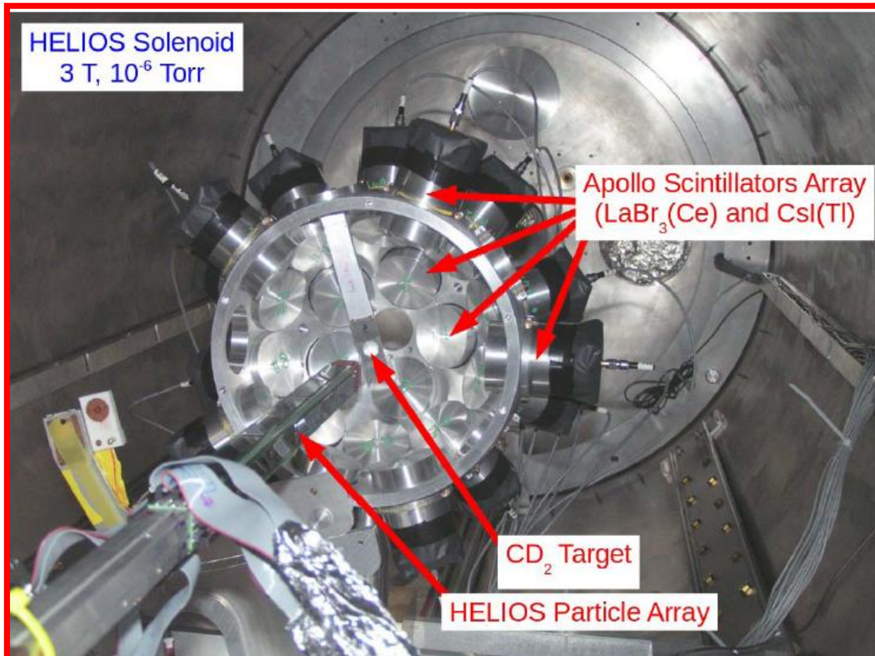
Measure $(E,z)_{\alpha}$, deduce E_X,θ_{CM}

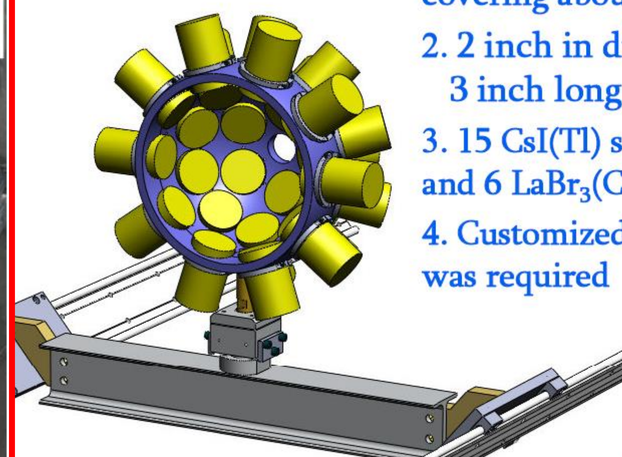
Ancillary detectors



Ion chamber (LSU)

Gamma-ray detector (LANL)





Realistic solid angle coverage :

1. 26-cylinder geometry covering about one π
2. 2 inch in diameter and 3 inch long
3. 15 CsI(Tl) scintillators and 6 $LaBr_3(Ce)$ scintillators
4. Customized light readout was required