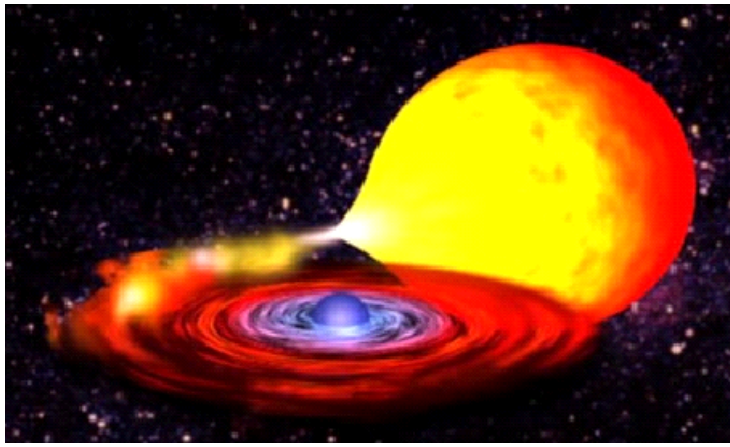
Direct (α,p) Reaction Measurements with HELIOS and the study of ^{20}Ne(α,p)^{23}Na

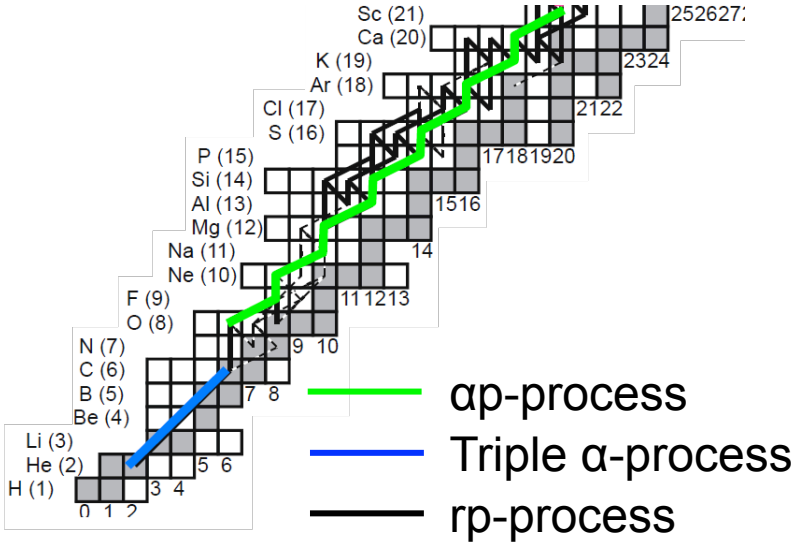
Jianping Lai, Daniel Santiago-Gonzalez
Catherine M. Deibel
Louisiana State University

(α,p) Reactions in Explosive Nucleosynthesis - XRBs



- Type I X-ray bursts (XRBs):
  - thermonuclear explosions on neutron star surface in binary system
  - T_{peak} = 1 – 2 GK
  - time scale 10 – 100 s
  - recurrent events (hours to days)

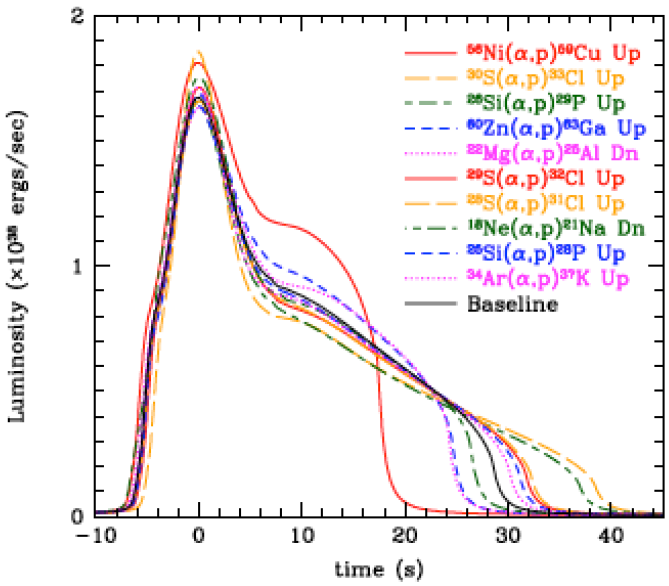
- Nucleosynthesis:
  - triple-α process
  - CNO breakout – ^{18}Ne(α,p)^{21}Na
  - (α,p) process
  - rapid proton capture (*rp*) process
  - synthesis up to A~100



H. Grawe et al., "Rep. Prog. Phys." 70 1525 (2007).

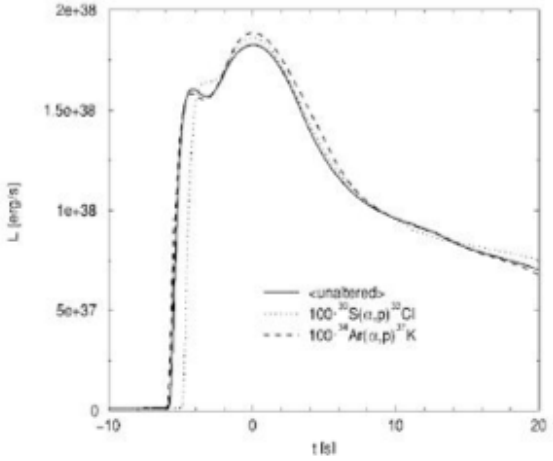
(α,p) Reactions in Explosive Nucleosynthesis - XRBs

- Sensitivity studies of XRB nucleosynthesis:
  - vary reactions individually
  - show only a handful of reactions significantly effect bursts



Cyburt *et al.*, 2016 (submitted)

- Effects of (α,p) reactions in XRBs:
  - shape of light curve
  - energy output
  - elemental abundances
  - double-peaked bursts(?)

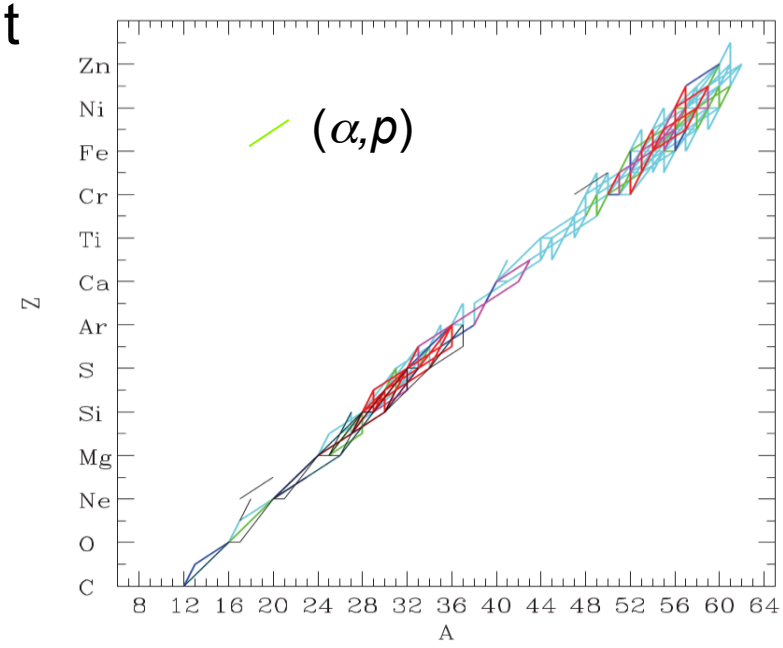


J.L. Fisker, *et al.,* ApJ (2004).

(α,p) Reactions in Explosive Nucleosynthesis - SNeIa

- Type Ia Supernovae:
  - thermonuclear explosion of white dwarf star in binary system
  - progenitor uncertain
  - disruptive explosion; no remnant
  - T_{peak} ~ 8 GK

- Nucleosynthesis in SNeIa:
  - C+C, C+O, O+O fusion
  - α-chain reactions
  - production of >50% Fe content of Galaxy

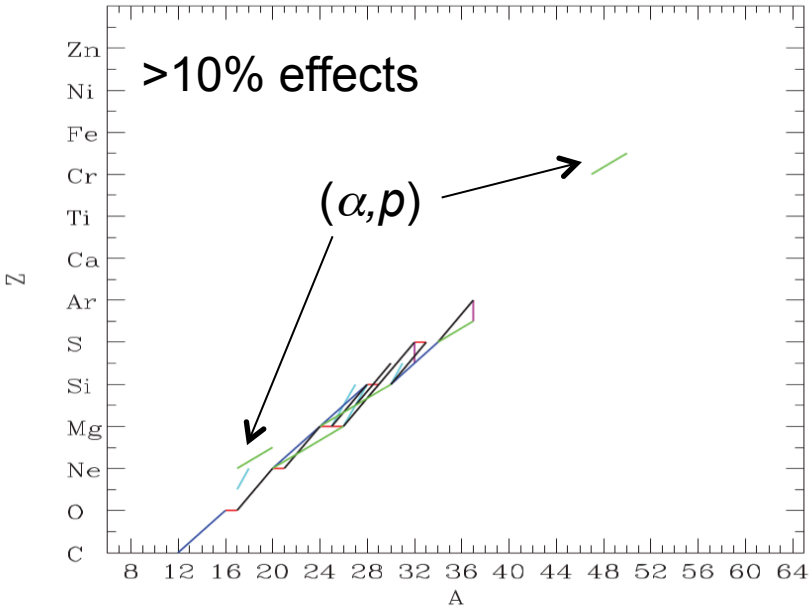


Bravo *et al.*, PRC **85**, 055805 (2012)

Type Ia Supernovae Sensitivity Studies

- Variation of reaction rates by factor of 10 up and down

- Two independent studies show high sensitivity to:
  - $^{12}C(\alpha,\gamma)^{16}O$
  - $^{12}C + ^{12}C$
  - $^{20}Ne(\alpha,p)^{23}Na$
  - $^{20}Ne(\alpha,\gamma)^{24}Mg$
  - $^{30}Si(p,\gamma)^{31}P$



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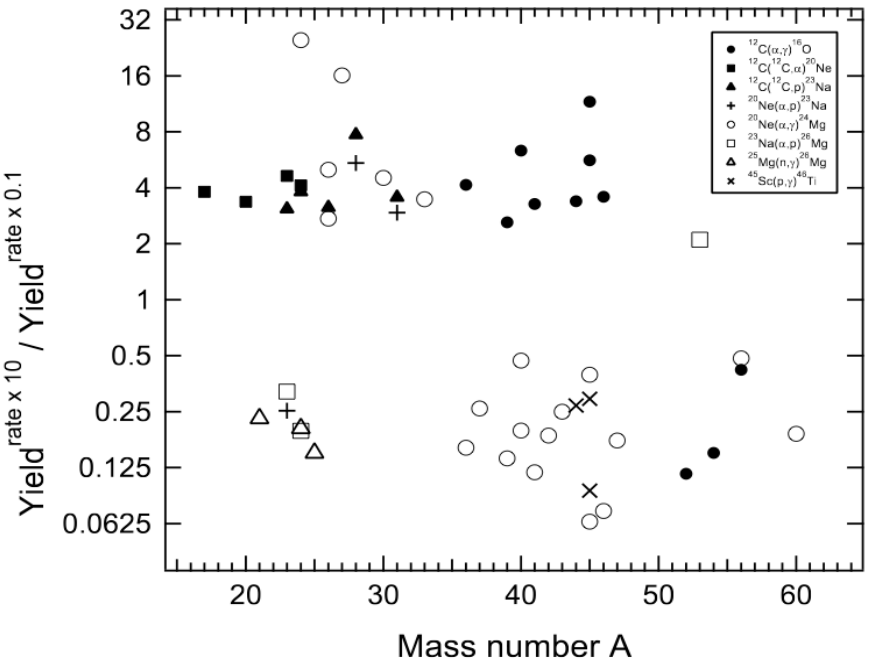

Reaction	Nuclide	W7 model		DDT model	
		×10	×0.1	×10	×0.1
$^{20}Ne(\alpha, p)^{23}Na$	^{18}O	0.44	2.4		
	^{23}Na	0.47	2.2	0.48	
	^{26}Al		2.1		
	^{28}Mg			5.4	
	^{31}Si			3.0	

A. Parikh *et al.*, A&A **557**, 11 (2013)

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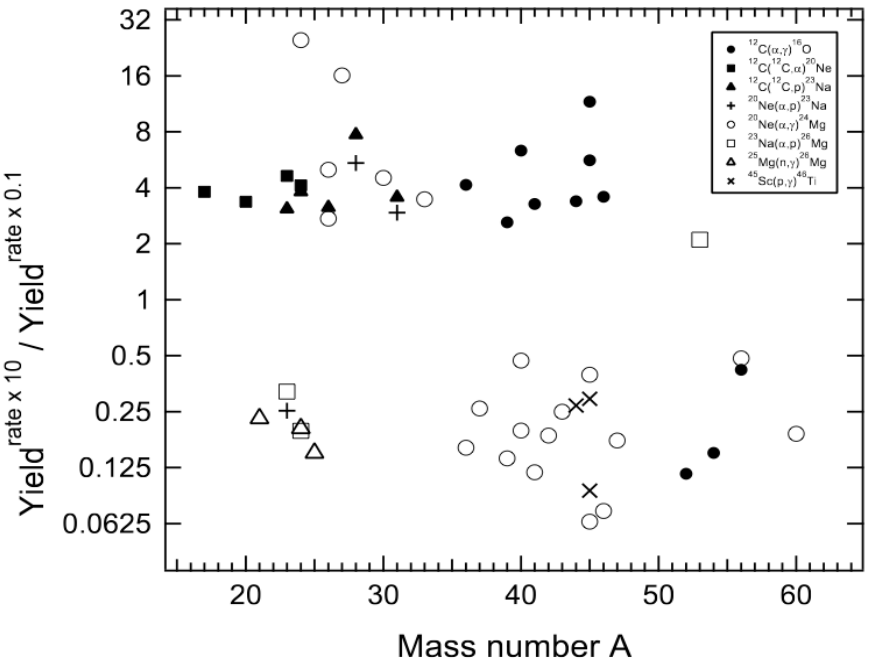

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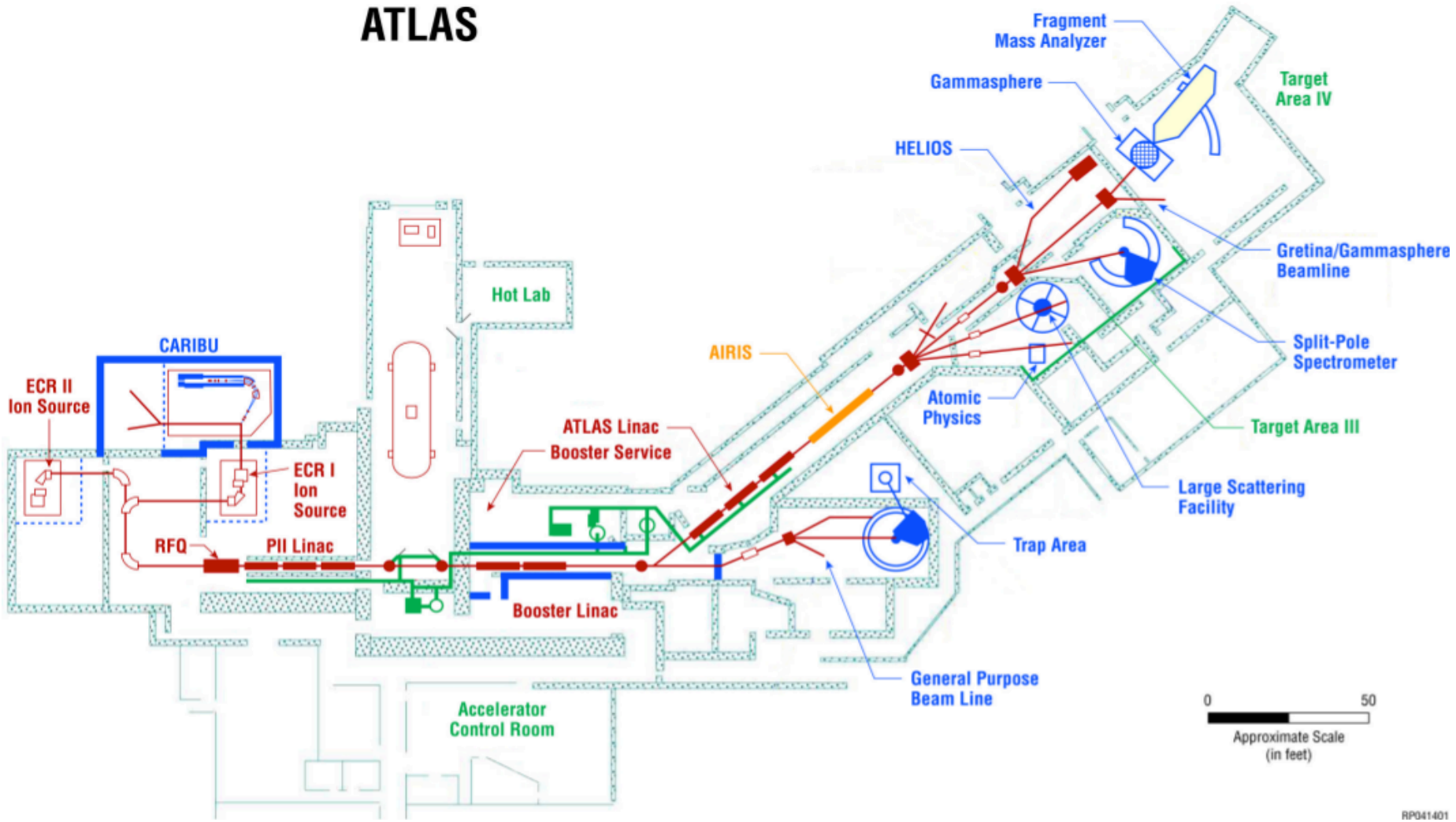
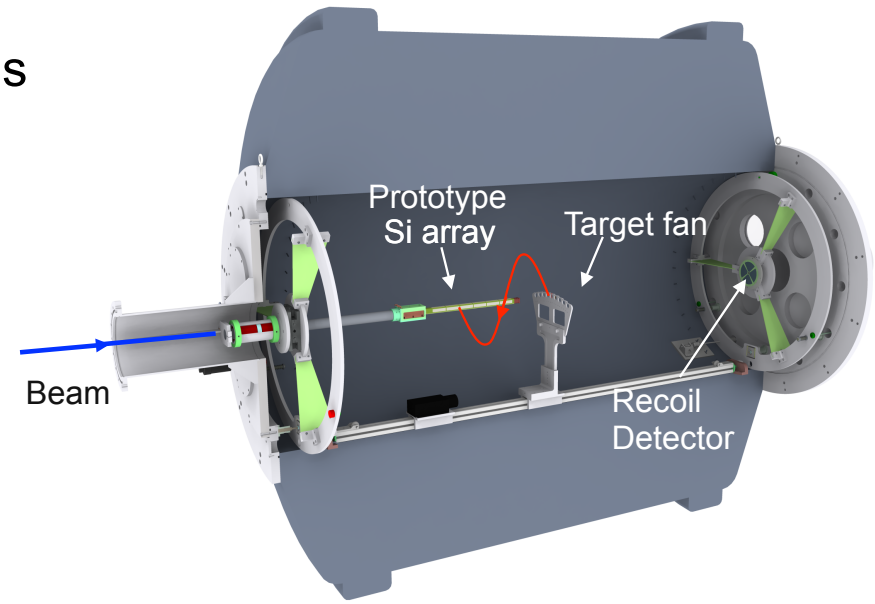
Direct (α,p) measurements with HELIOS at Argonne National Laboratory



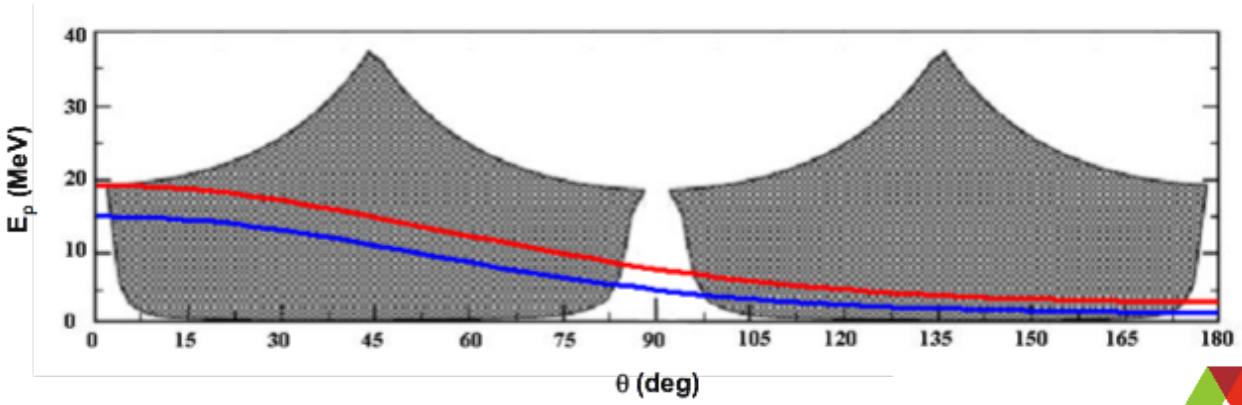
Direct (α,p) measurements with HELIOS

- HELIcal Orbit Spectrometer (HELIOS)
  - repurposed MRI magnet
  - magnetic field aligned with beam axis
  - commissioned 2008

- Ideal for studying reactions with radioactive ion beams
  - unique particle identification from time-of-flight
  - high geometrical efficiency
  - improve resolution (avoid kinematic compression)



Particle	p	^{3}He	d,^{4}He	t
TOF(ns)	21.9	32.8	43.7	65.6



Direct (α,p) measurements with HELIOS

- Direct (α,p) measurement needs:
  - ^{4}He gas target
    - cryogenically cooled
    - commissioned with ^{14}C(d,p)^{15}C, ^{14}C(^{3}He,d)^{15}N Spring 2013

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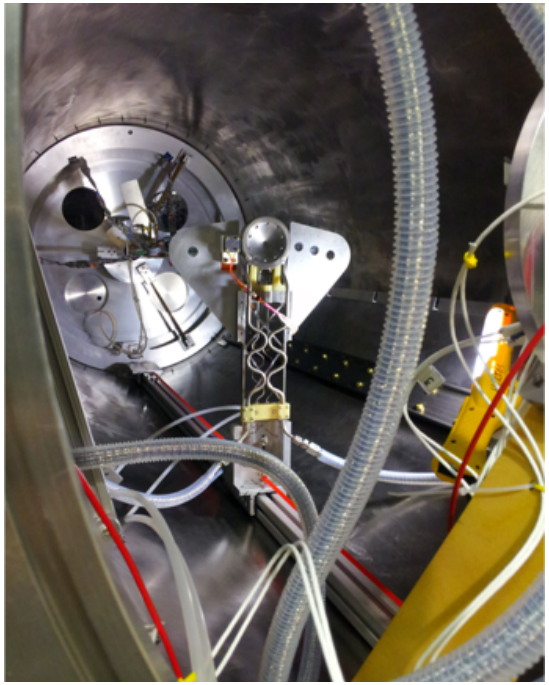

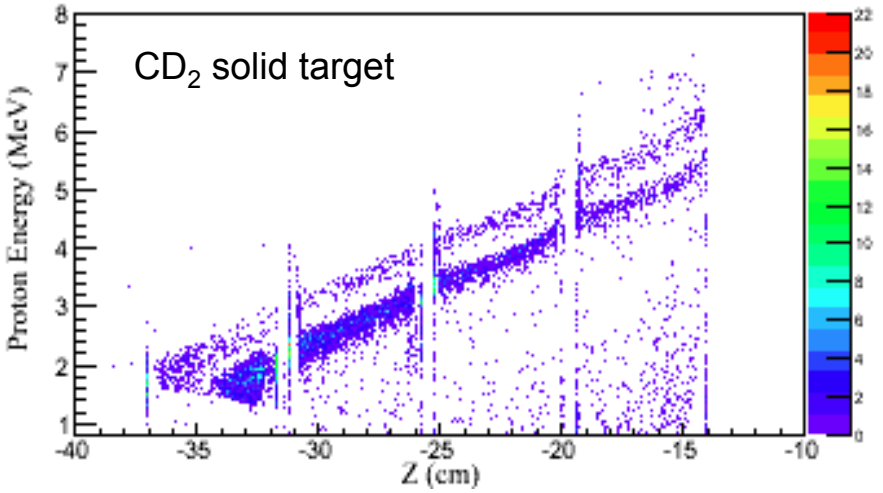

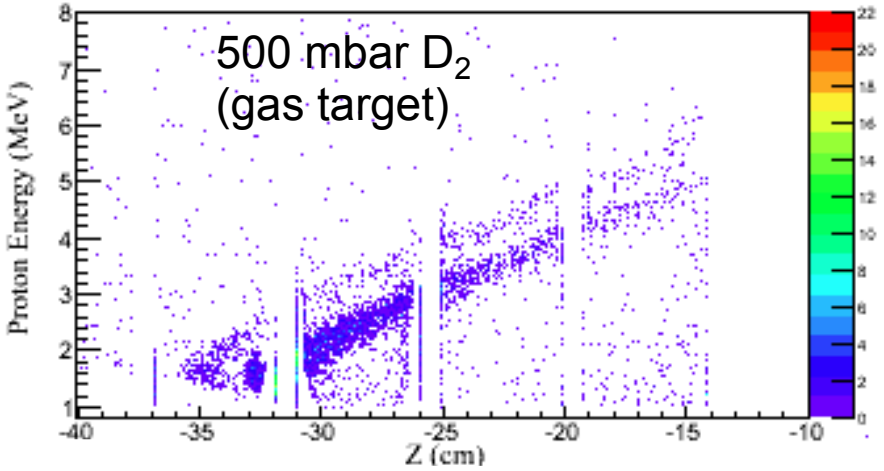

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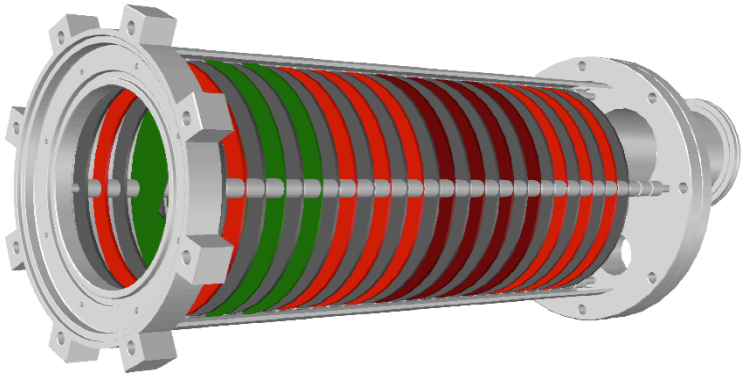
  - heavy-ion recoil detector
    - recoil identification
    - beam monitoring/normalization
    - position information



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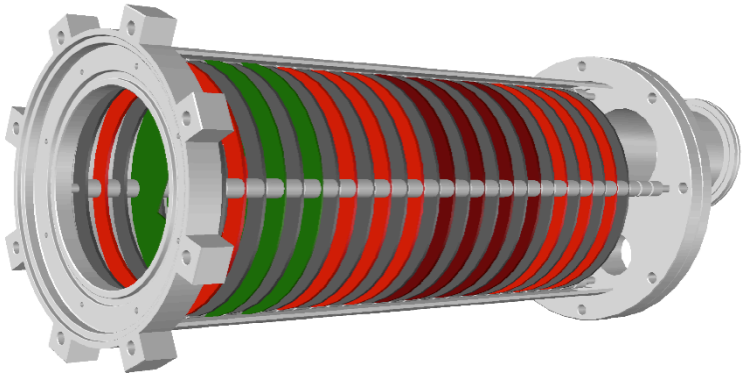
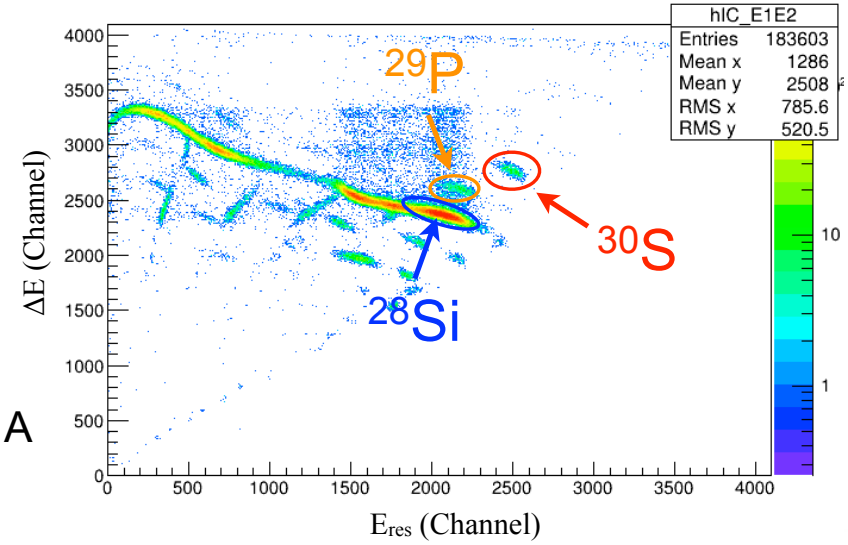


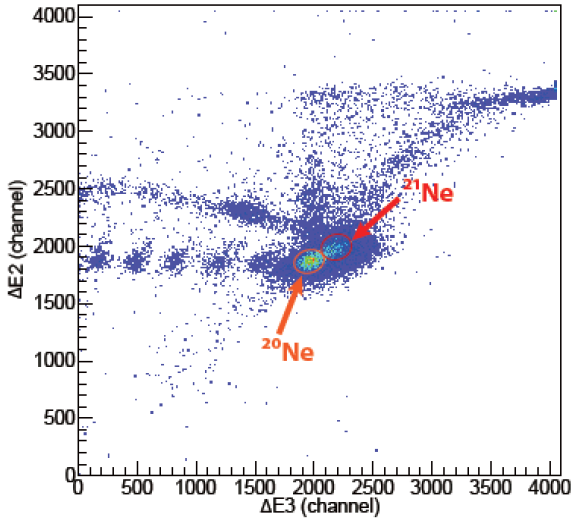
high rate: 500 kHz

energy resolution: <5%

position sensitivity

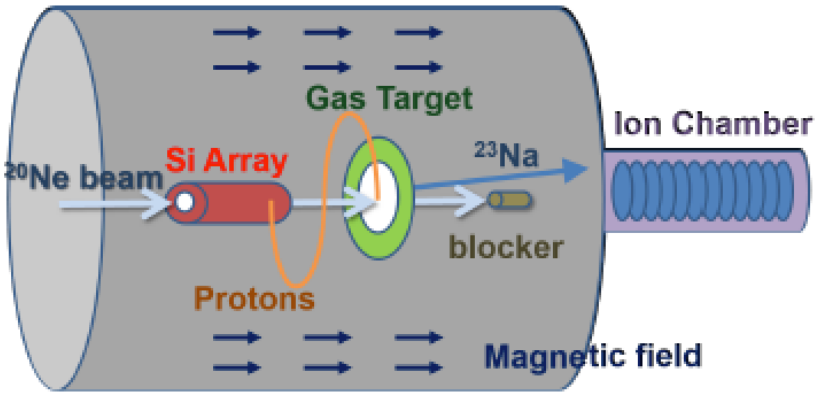
mass separation at low A

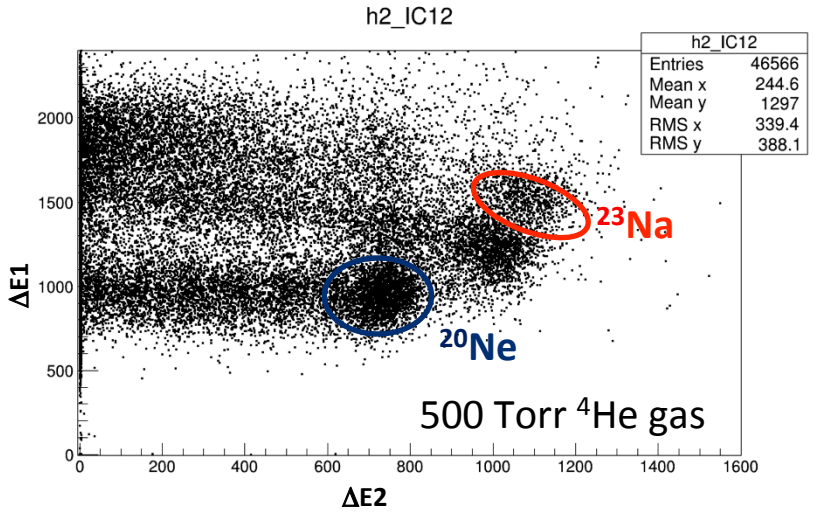


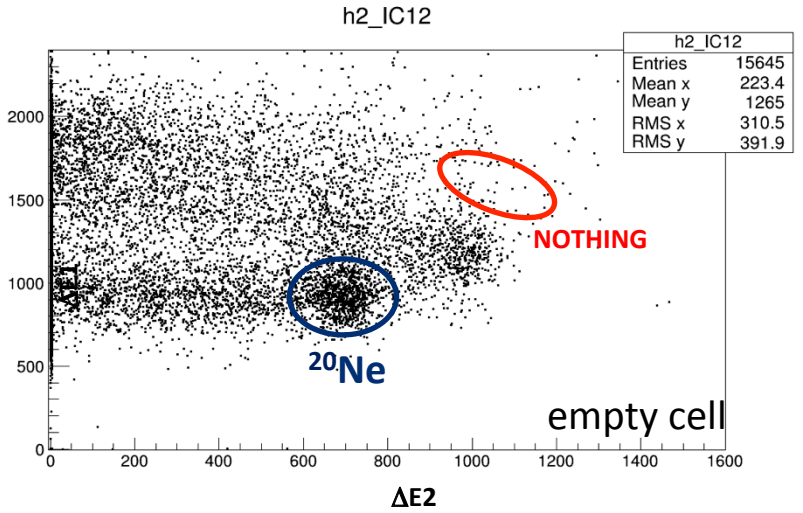


First Direct (α,p) Study with HELIOS: ^{20}Ne(α,p)^{23}Na

- Direct study of ^{20}Ne(α,p)^{23}Na
  - protons detected in HELIOS Si array
  - ^{23}Na detected in ionization chamber
  - normalized via known (d,p) reaction
- Part I completed December 2014
  - E_{beam} = 107, 100, 88 MeV







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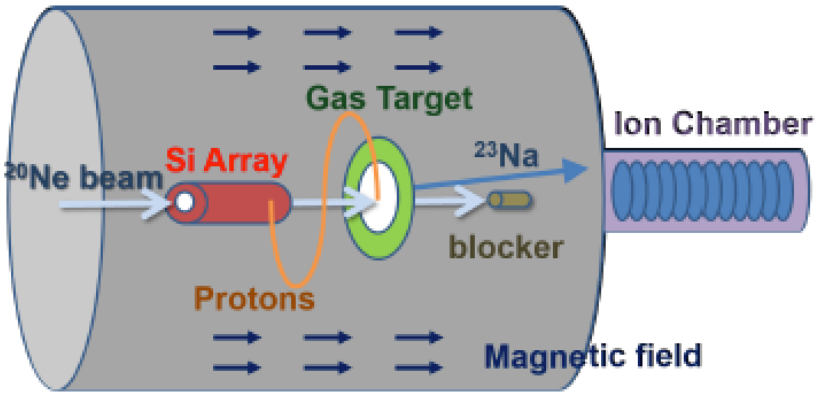
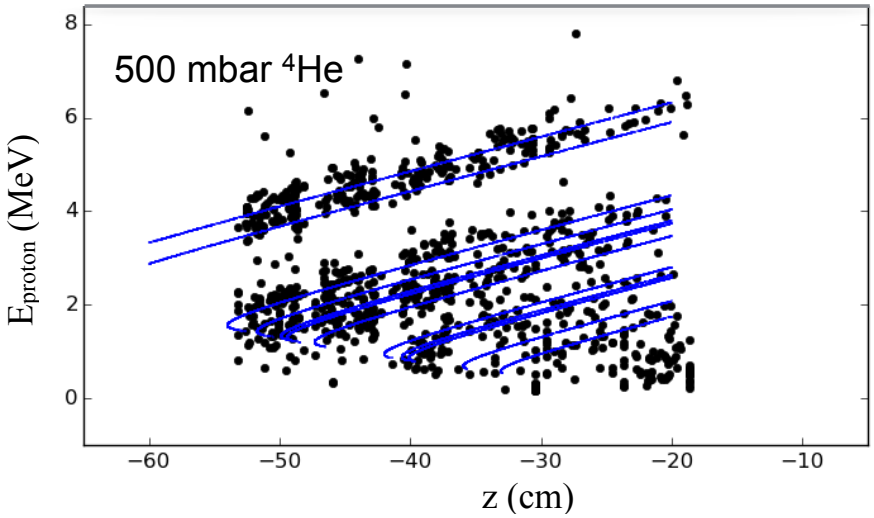
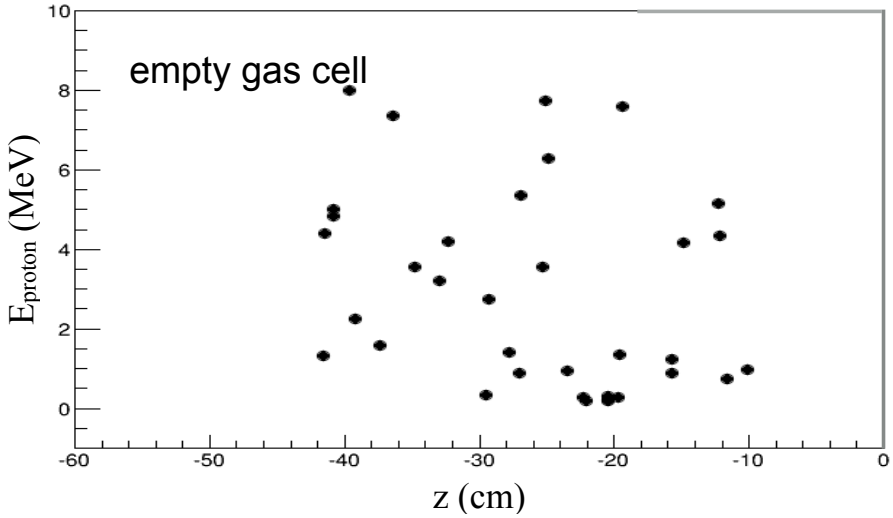
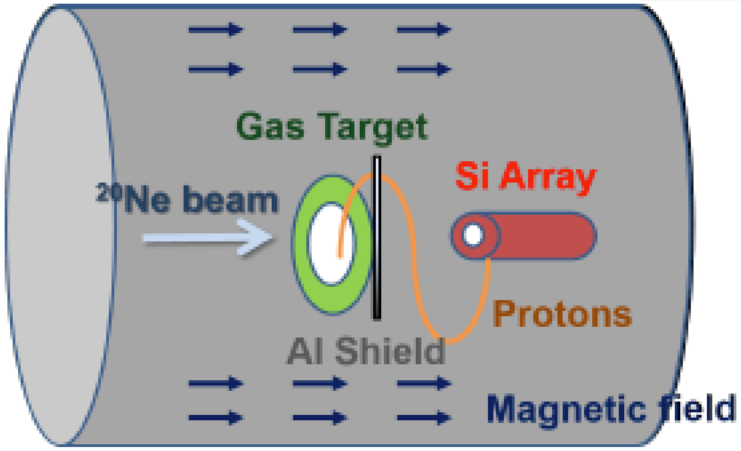


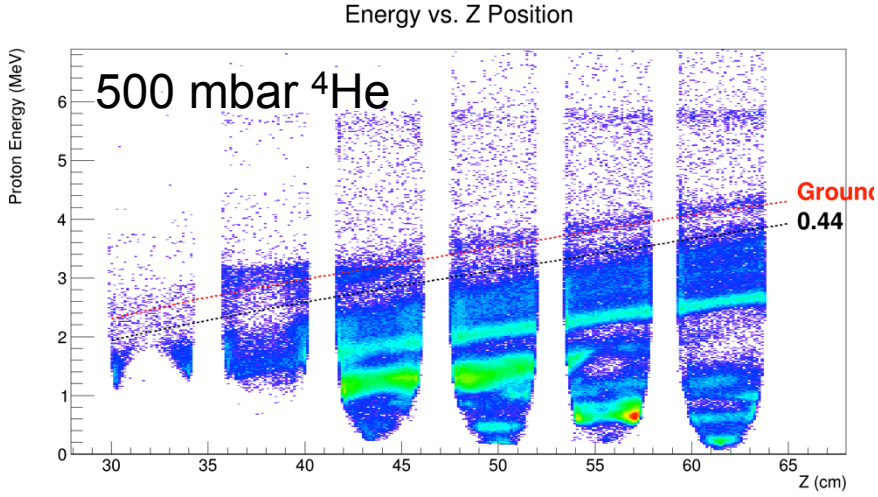


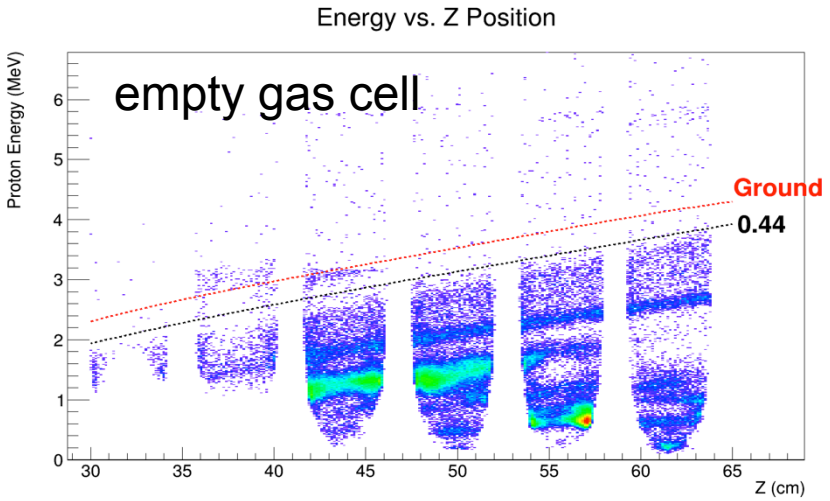


First Direct (α,p) Study with HELIOS: ^{20}Ne(α,p)^{23}Na

- Part II completed July 2015
- Normalization via (α,α) scattering and (d,p) on solid target
- Dissertation of Jianping Lai (LSU) – August 2016

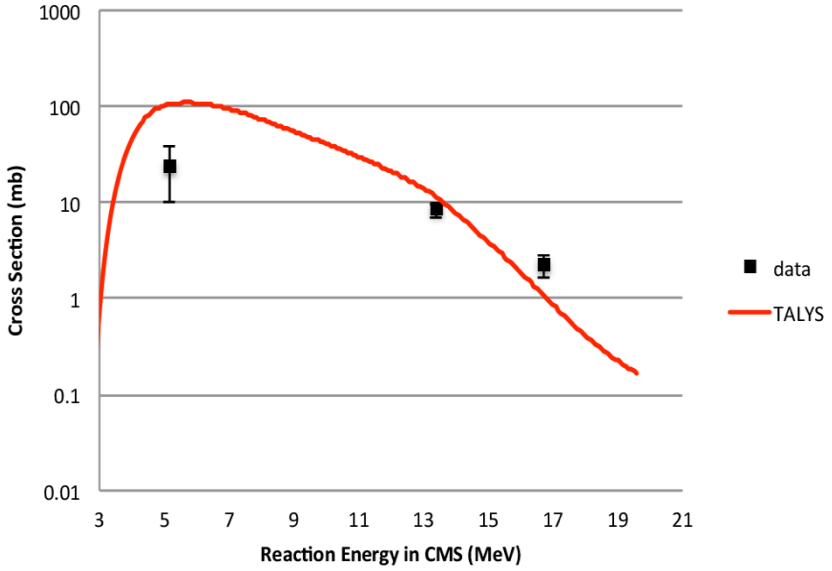




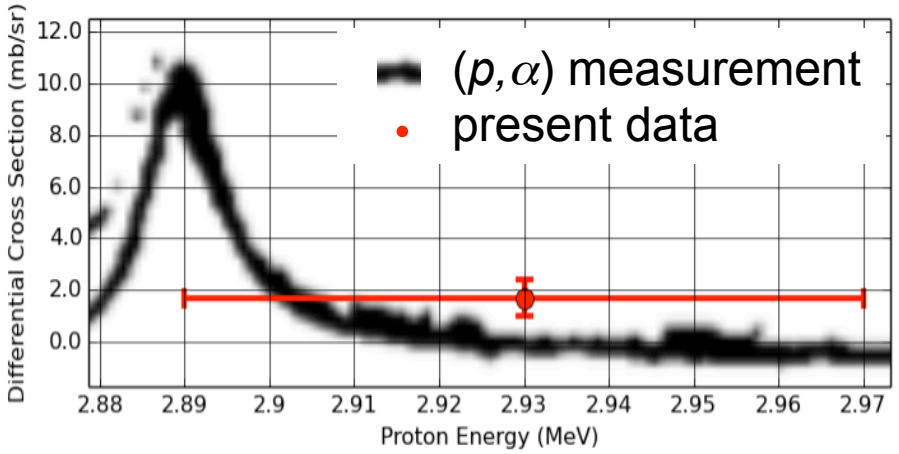


^{20}Ne(α,p)^{23}Na Cross Sections

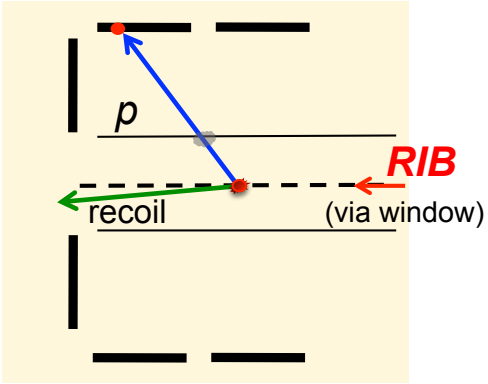
- Normalized cross section for ^{20}Ne(α,p)^{23}Na:
  - in agreement with Hauser-Feshbach calculations
  - in agreement with inverse reaction cross section



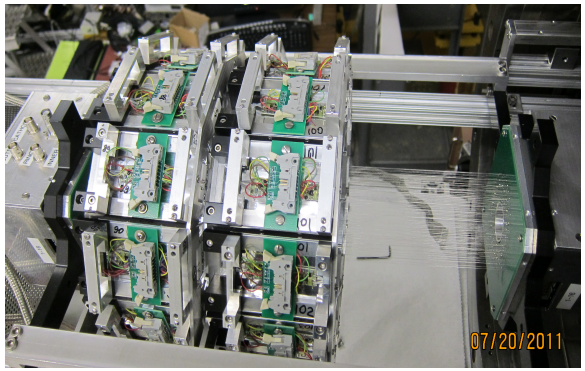
- Future plans:
  - determining contribution from excited states (present data)
  - measurements at more (and lower) energies
  - study affects on SNeIa models



Current Developments: ANASEN



- Array for Nuclear Astrophysics and Structure with Exotic Nuclei (ANASEN)
  - designed for direct (α,p) reaction studies
    - extended, active gas target
    - proportional counter
    - Si detector array



19 Anode PC

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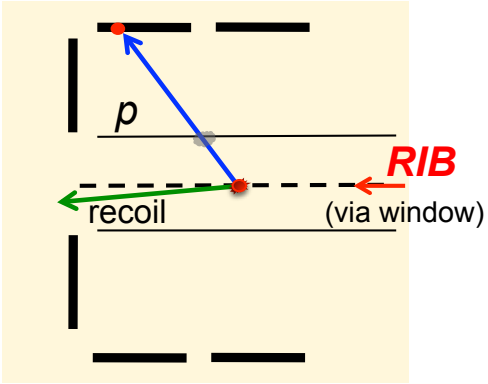

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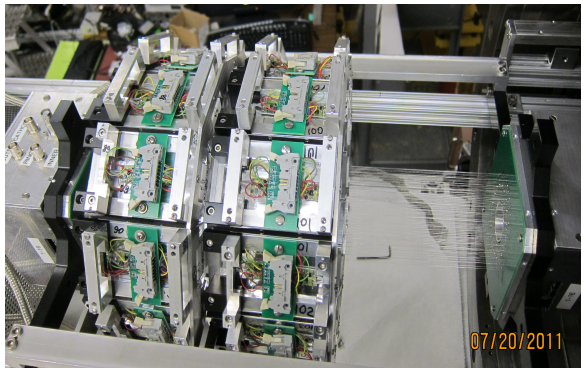
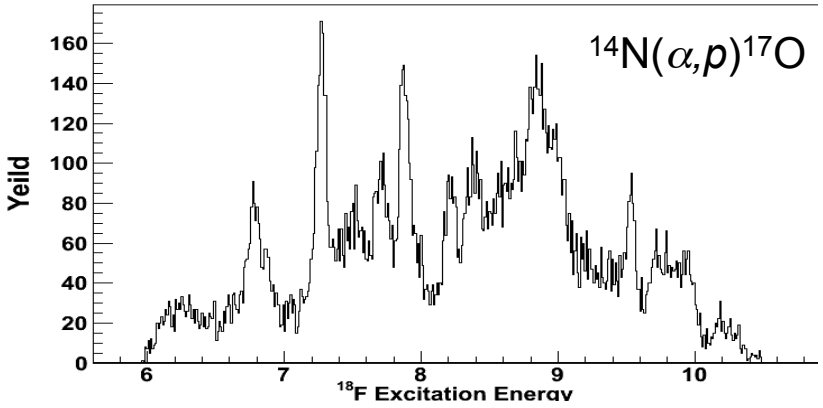
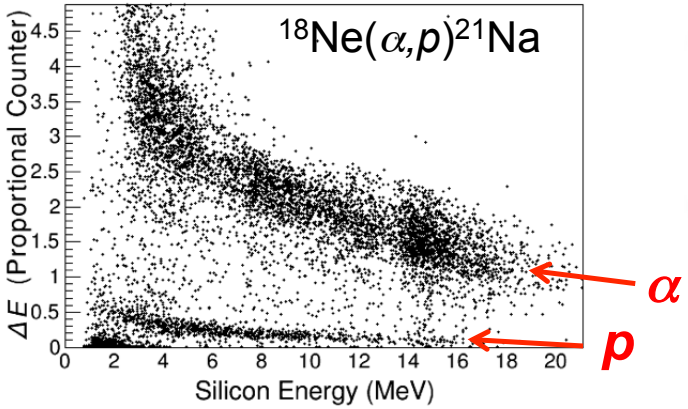
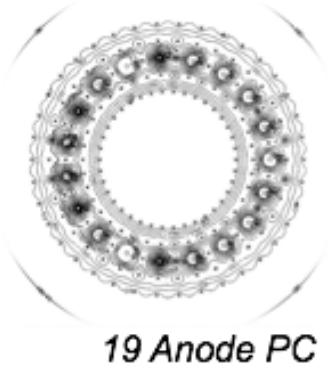


- Nuclear Astrophysics measurements:
  - ^{14}N(α,p)^{17}O (stable beam FSU)
  - ^{18}Ne(α,p)^{21}Na (RIB from RESOLUT @ FSU)
    - Kevin Macon, PhD Thesis (LSU)
  - ^{37}K(p,p)^{37}K (first RIB measurement @ ReA3)







Summary

- (α,p) reactions play a significant role in stellar explosive nucleosynthesis

- Direct measurements are challenging:
  - radioactive ion beams
  - gas targets
  - low cross sections

- Multiple methods underdevelopment for direct (α,p) measurements:
  - HELIcal Orbit Spectrometer (HELIOS) at ATLAS facility
  - ANASEN
  - JENSA gas-jet target with Si detector array

- First direct measurement of ^{20}Ne(α,p)^{23}Na:
  - proof-of-principle of HELIOS method
  - important for Type Ia Supernova nucleosynthesis

THANKS!

- ANL
  - Jason Clark
  - John Greene
  - Calem Hofman
  - Ben Kay
  - Richard Pardo
  - Ernst Rehm
  - Birger Back
  - Akaa Ayangeakaa
  - Melina Avila
- Louisiana State University
  - Jianping Lai
  - Jeff Blackmon
  - Daniel Santiago-Gonzalez
  - Kevin Macon (Postdoc – Notre Dame)
  - Amber Lauer (graduate student)
  - Liudmyla Afanasieva (Postdoc - WashU)
- Florida State University
  - Sergio Almaraz

ATLAS staff and operators

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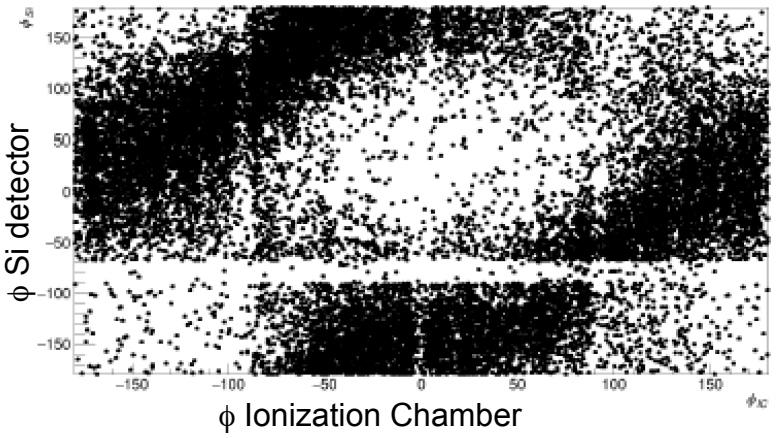

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