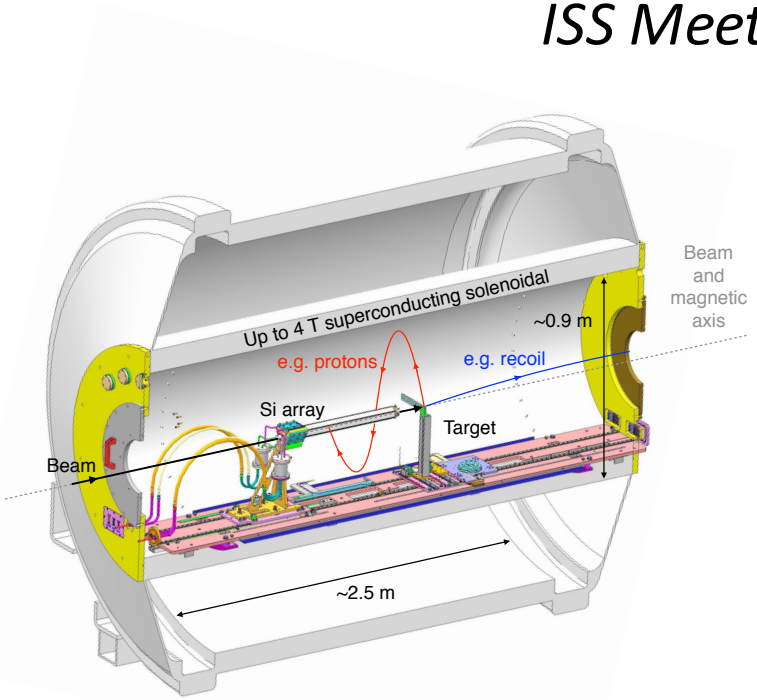
The ^{61}Zn(d,p)^{62}Zn transfer reaction and other nuclear astrophysics opportunities with the ISS

Daniel Doherty
University of Surrey

ISS Meeting, August 2019



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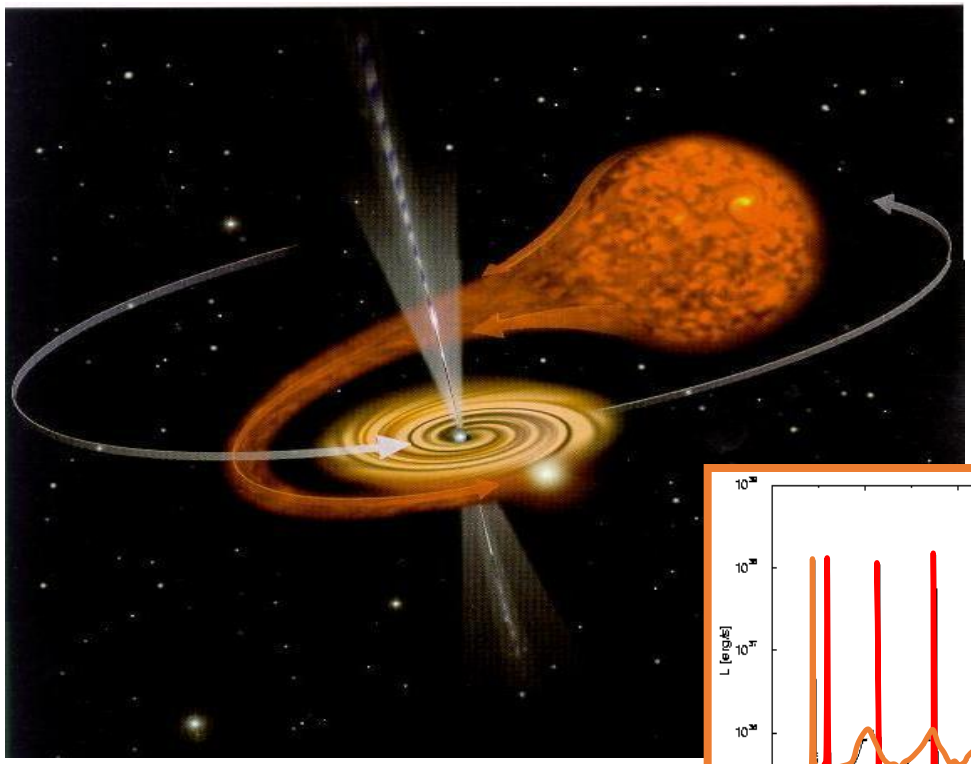
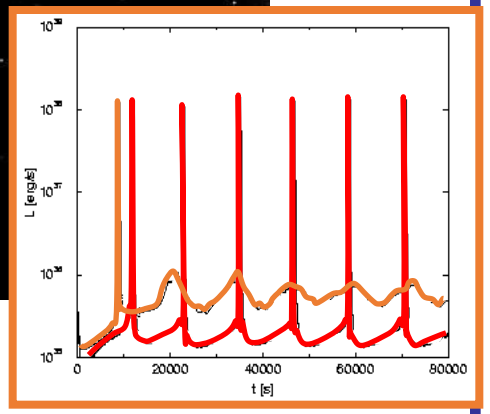
Motivation

The observation of X-ray bursts is interpreted as thermonuclear explosions in the atmosphere of a neutron star in a close binary system.

As temperature and density at the surface of the neutron star increase, the CNO cycles breakout into the *rp* process.

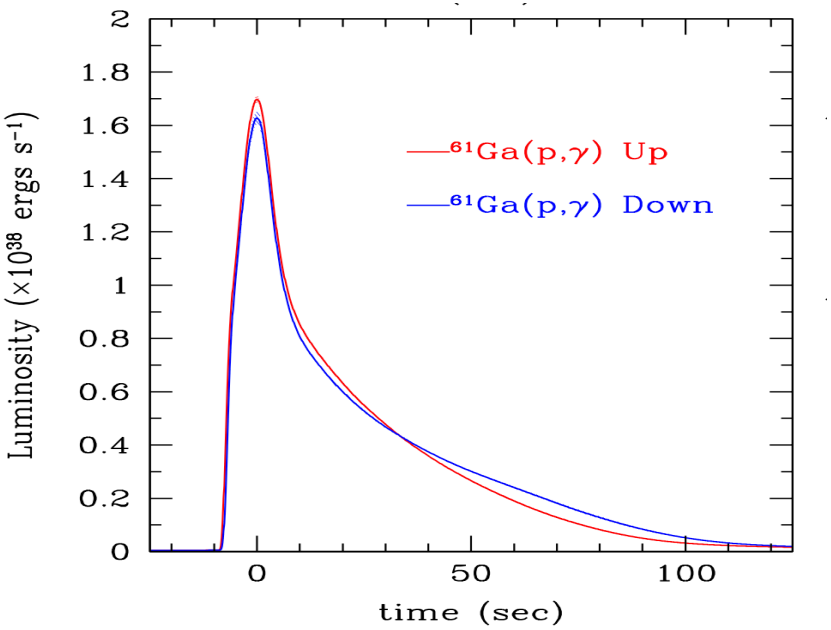




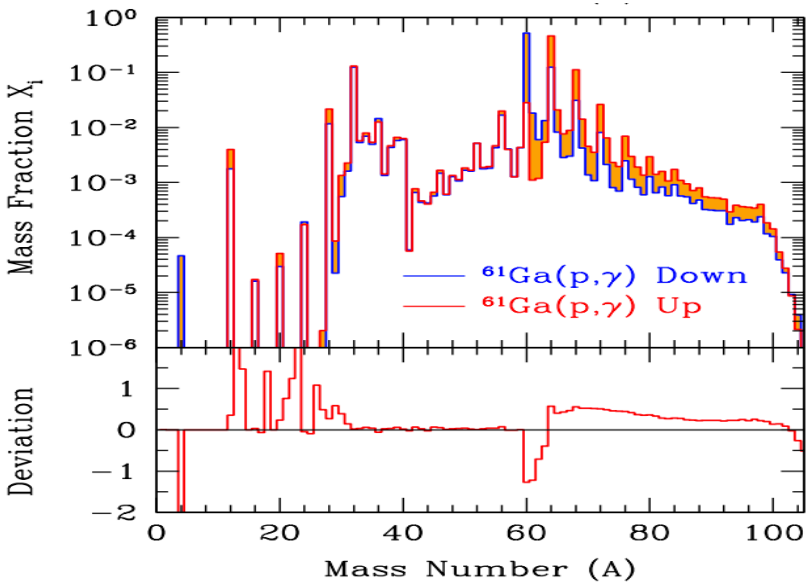
Sensitivity studies highlight the key reactions for understanding these bursts

→ ^{61}Ga(p,γ)^{62}Ge suggested as being particularly important

Motivation



Effect on the X-ray burst light curve from varying the $^{61}Ga(p,\gamma)^{62}Ge$ reaction rate within its associated uncertainties.



Effect on the final abundances from varying the $^{61}Ga(p,\gamma)^{62}Ge$ reaction rate within its associated uncertainties.

R.H. Cyburt *et al.*, Astrophys. J. **830**, 2 (2016).

Motivation

TABLE 19

SUMMARY OF THE MOST INFLUENTIAL NUCLEAR PROCESSES, AS COLLECTED FROM TABLES 1–10

Reaction	Models Affected
$^{12}C(\alpha, \gamma)^{16}O$[a]	F08, K04-B2, K04-B4, K04-B5
$^{18}Ne(\alpha, p)^{21}Na$[a]	K04-B1[b]
$^{25}Si(\alpha, p)^{28}P$	K04-B5
$^{26g}Al(\alpha, p)^{29}Si$	F08
$^{29}S(\alpha, p)^{32}Cl$	K04-B5
$^{30}P(\alpha, p)^{33}S$	K04-B4
$^{30}S(\alpha, p)^{33}Cl$	K04-B4,[b] K04-B5[b]
$^{31}Cl(p, \gamma)^{32}Ar$	K04-B1
$^{32}S(\alpha, \gamma)^{36}Ar$	K04-B2
$^{56}Ni(\alpha, p)^{59}Cu$	S01,[b] K04-B5
$^{57}Cu(p, \gamma)^{58}Zn$	F08
$^{59}Cu(p, \gamma)^{60}Zn$	S01,[b] K04-B5
$^{61}Ga(p, \gamma)^{62}Ge$	F08, K04-B1, K04-B2, K04-B5, K04-B6
$^{65}As(p, \gamma)^{66}Se$	K04,[b] K04-B1, K04-B2,[b] K04-B3,[b] K04-B4, K04-B5, K04-B6
$^{69}Br(p, \gamma)^{70}Kr$	K04-B7
$^{75}Rb(p, \gamma)^{76}Sr$	K04-B2
$^{82}Zr(p, \gamma)^{83}Nb$	K04-B6
$^{84}Zr(p, \gamma)^{85}Nb$	K04-B2
$^{84}Nb(p, \gamma)^{85}Mo$	K04-B6
$^{85}Mo(p, \gamma)^{86}Tc$	F08
$^{86}Mo(p, \gamma)^{87}Tc$	F08, K04-B6
$^{87}Mo(p, \gamma)^{88}Tc$	K04-B6
$^{92}Ru(p, \gamma)^{93}Rh$	K04-B2, K04-B6
$^{93}Rh(p, \gamma)^{94}Pd$	K04-B2
$^{96}Ag(p, \gamma)^{97}Cd$	K04, K04-B2, K04-B3, K04-B7
$^{102}In(p, \gamma)^{103}Sn$	K04, K04-B3
$^{103}In(p, \gamma)^{104}Sn$	K04-B3, K04-B7
$^{103}Sn(\alpha, p)^{106}Sb$	S01[b]

A. Parikh, J. Jose, F. Moreno and C. Iliadis, Astrophys. J. Suppl. Ser. **178**, 110 (2008).

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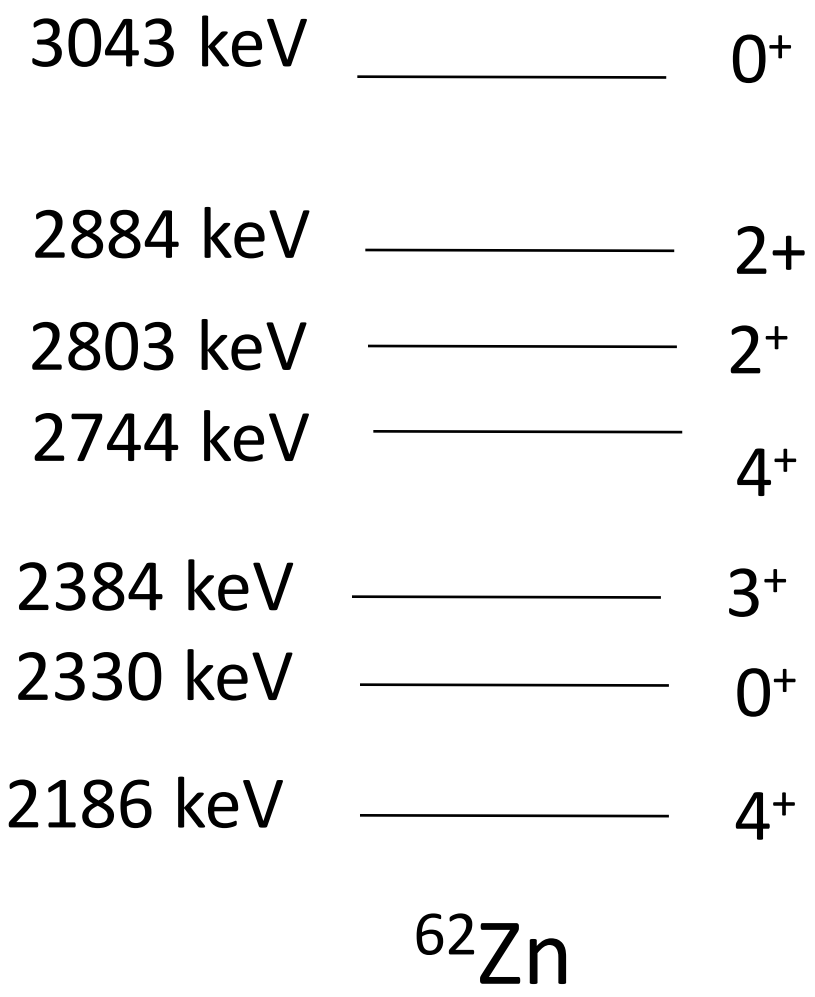
States of Interest in ^{62}Zn

Proton separation energy in ^{62}Ge is 2053(145) keV

- uncertainty from mass data

Mirror energy differences from theory

Rate expected to be dominated by low-spin states



States of Interest in ^{62}Zn

The Spectroscopic factor (C^2S) is directly related to the proton widths and, hence, the resonance strengths.

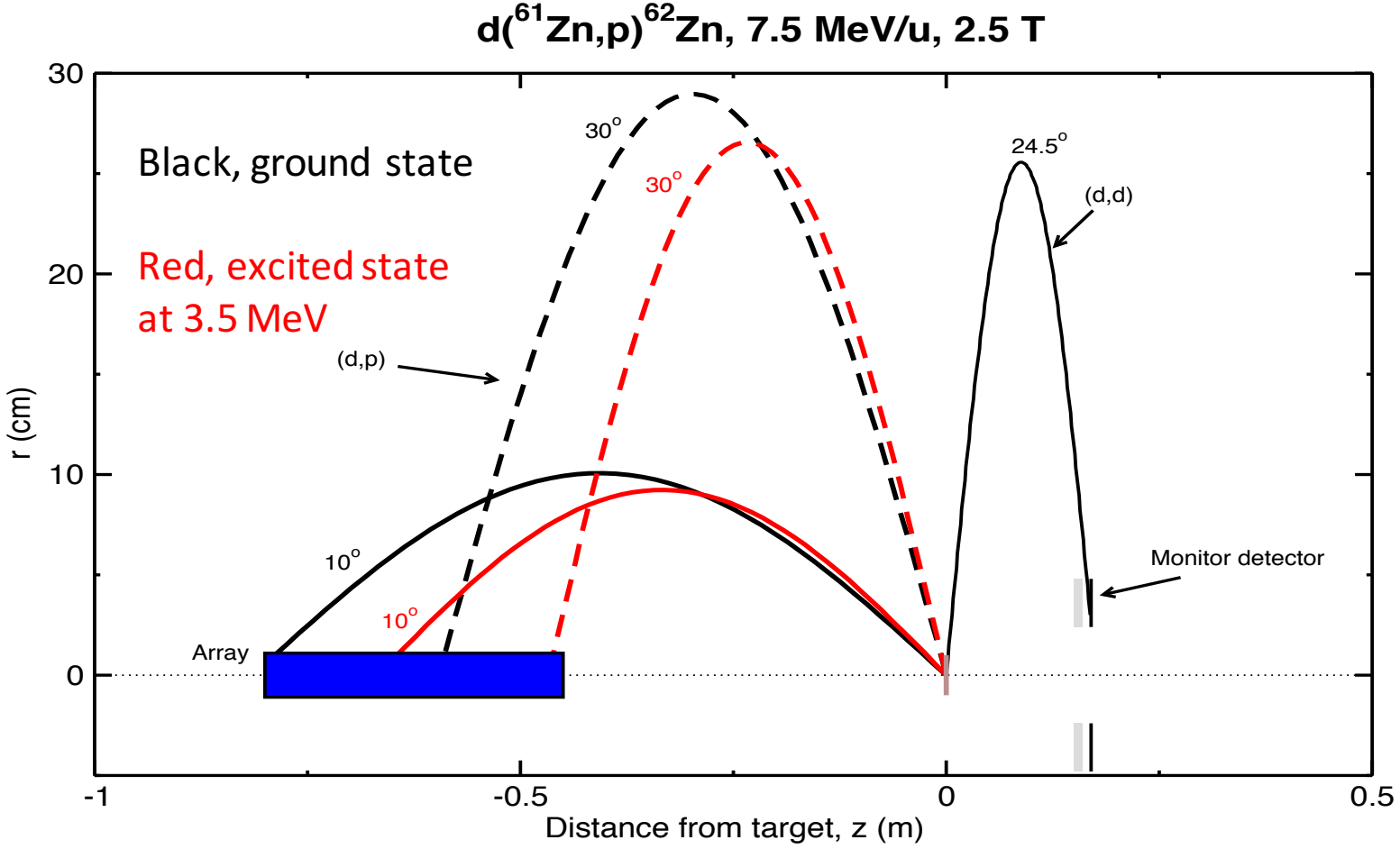
$$\omega\gamma = \omega\frac{\Gamma_p\Gamma_\gamma}{\Gamma_p+\Gamma\gamma} \approx \omega\frac{\Gamma_p\Gamma\gamma}{\Gamma_\gamma} \approx \omega\Gamma_p. \qquad \Gamma_p = C^2S\Gamma_{sp}$$

Will be extracted from the proton yields with the ADWA code TWOFNR. Recent success for the astrophysically important ^{27}Al-^{27}Si system. V. Margerin et al., PRL **115** 062701 (2015)

C^2S of mirror analog states are expected to agree within 20%

N. K. Timofeyuk, R. C. Johnson, and A. M. Mukhamedzhanov, PRL **91**, 232501 (2003)
N. K. Timofeyuk, P. Descouvemont, and R. C. Johnson, Eur. Phys. J. A **27**, 269 (2006).

ISS – ISOLDE Solenoid Spectrometer

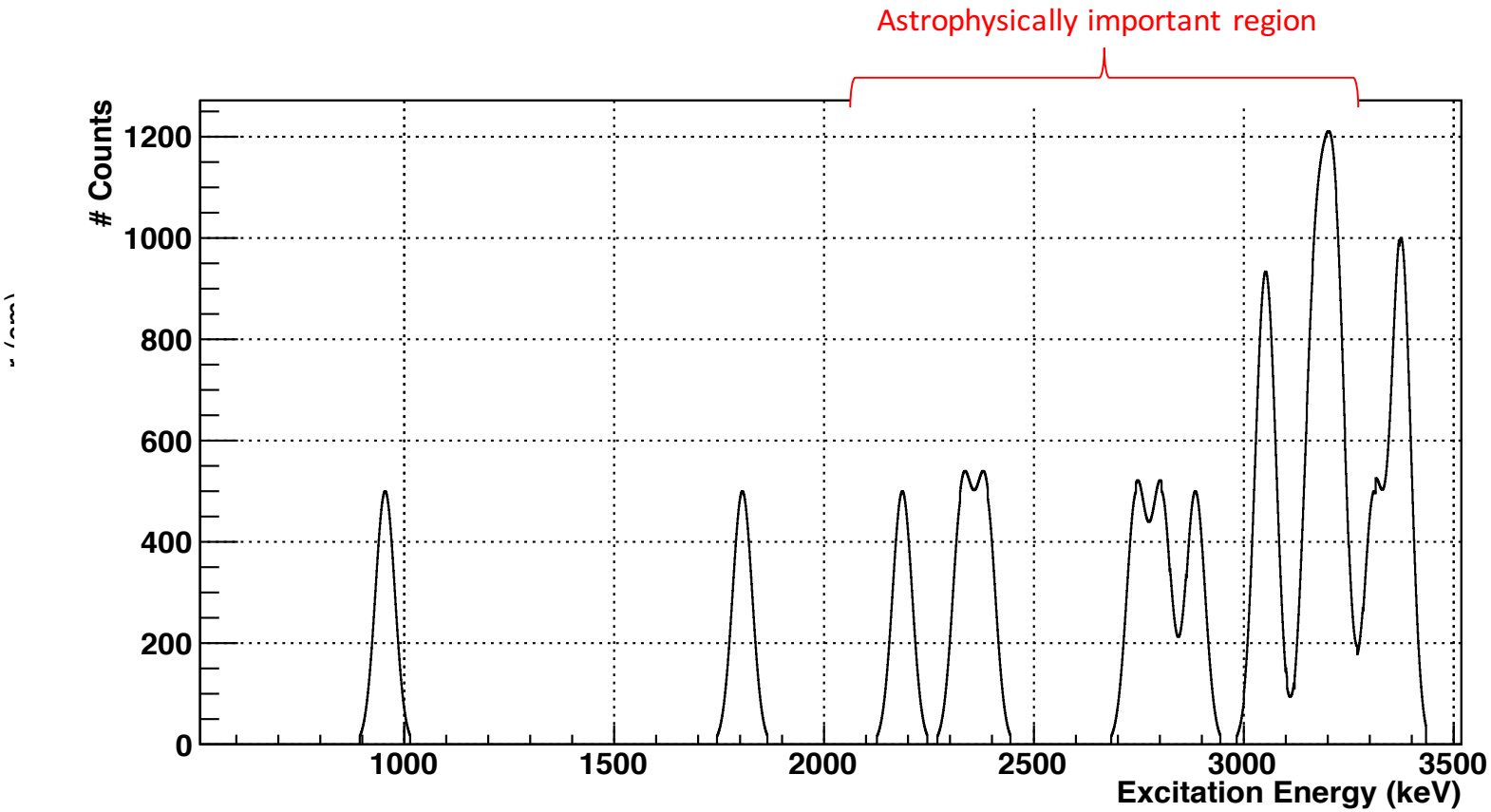


$10° < \theta_{CM} < 30°$ => protons emitted at backward lab angles

Proton energies ~10 MeV

ISS – ISOLDE Solenoid Spectrometer

Know ^{62}Zn level scheme folded with 75-keV resolution obtained with HELIOS type device and detectors



$10° < \theta_{CM} < 30°$ => protons emitted at backward lab angles

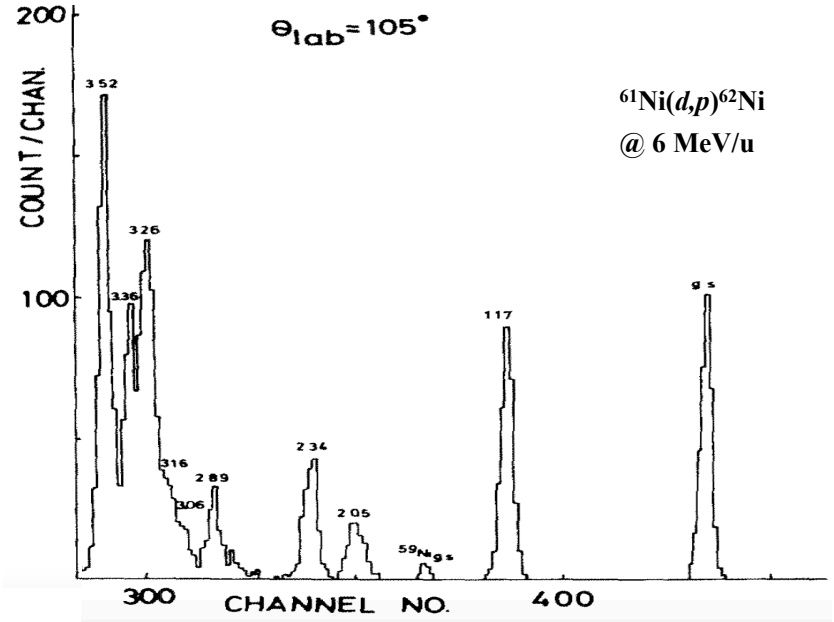
Proton energies ~10 MeV

ISS – ISOLDE Solenoid Spectrometer

7.5 MeV/u ^{61}Zn beam of minimum intensity 4 x 10^5 pps (ZrO_2 target)

Ga contamination to be suppressed with RILIS ionisation of Zn

Stable ^{61}Ni contaminant highlighted in TAC meeting, known spectrum. See below.



Problems from transfer on light elements from EBIS charge breeder?

O. Karban *et al.*, Nucl. Phys. **A366**, 68 (1981).

Energy Generation in X-ray Bursts (again)

The Astrophysical Journal, 872:84 (18pp), 2019 February 10

Influence of Nuclear Reaction Rate Uncertainties on Neutron Star Properties Extracted from X-Ray Burst Model–Observation Comparisons

Zach Meisel, Grant Merz, and Sophia Medvid

The Astrophysical Journal, 830:55 (20pp), 2016 October 20

DEPENDENCE OF X-RAY BURST MODELS ON NUCLEAR REACTION RATES

R. H. Cyburt[1,2], A. M. Amthor[3], A. Heger[2,4,5,6], E. Johnson[7], L. Keek[1,2,7,9], Z. Meisel[2,8], H. Schatz[1,2,7], and K. Smith[2,10]

Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha, \gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha, p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p, \gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p, \gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha, p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha, p)^{17}F$	D	5.8	1
7	$^{23}Al(p, \gamma)^{24}Si$	D	4.6	1
8	$^{18}Ne(\alpha, p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p, \gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p, \alpha)^{16}O$	U	1.3	2
11	$^{12}C(\alpha, \gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha, p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha, p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha, \gamma)^{28}Si$	U	1.2	2
15	$^{57}Cu(p, \gamma)^{58}Zn$	D	1.3	2
16	$^{60}Zn(\alpha, p)^{63}Ga$	U	1.1	2
17	$^{17}F(p, \gamma)^{18}Ne$	U	1.7	2
18	$^{40}Sc(p, \gamma)^{41}Ti$	D	1.1	2
19	$^{48}Cr(p, \gamma)^{49}Mn$	D	1.2	2

A variety of (p,γ) and (α,p) reactions have significant affect on the energy generated in X-ray bursts.

KEY REACTIONS

1. $^{61}Ga(p,\gamma)^{62}Ge$
2. $^{22}Mg(\alpha,p)^{25}Al$
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However, (α,p) reactions require a new development…

in the Multi-zone X-ray Burst Model

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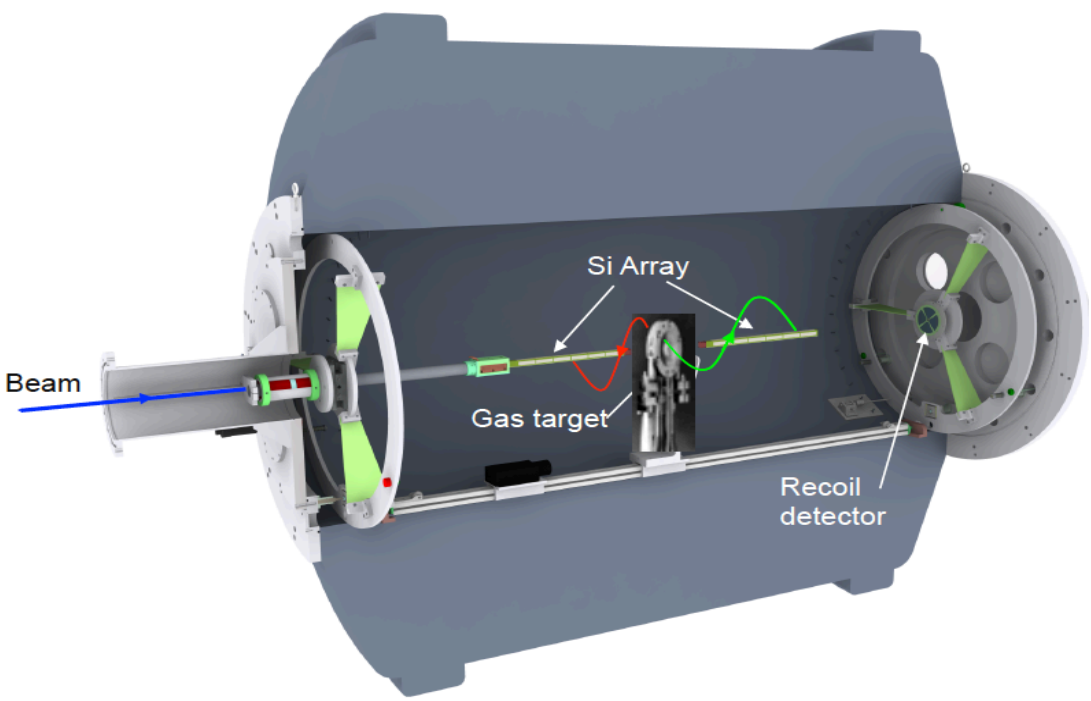
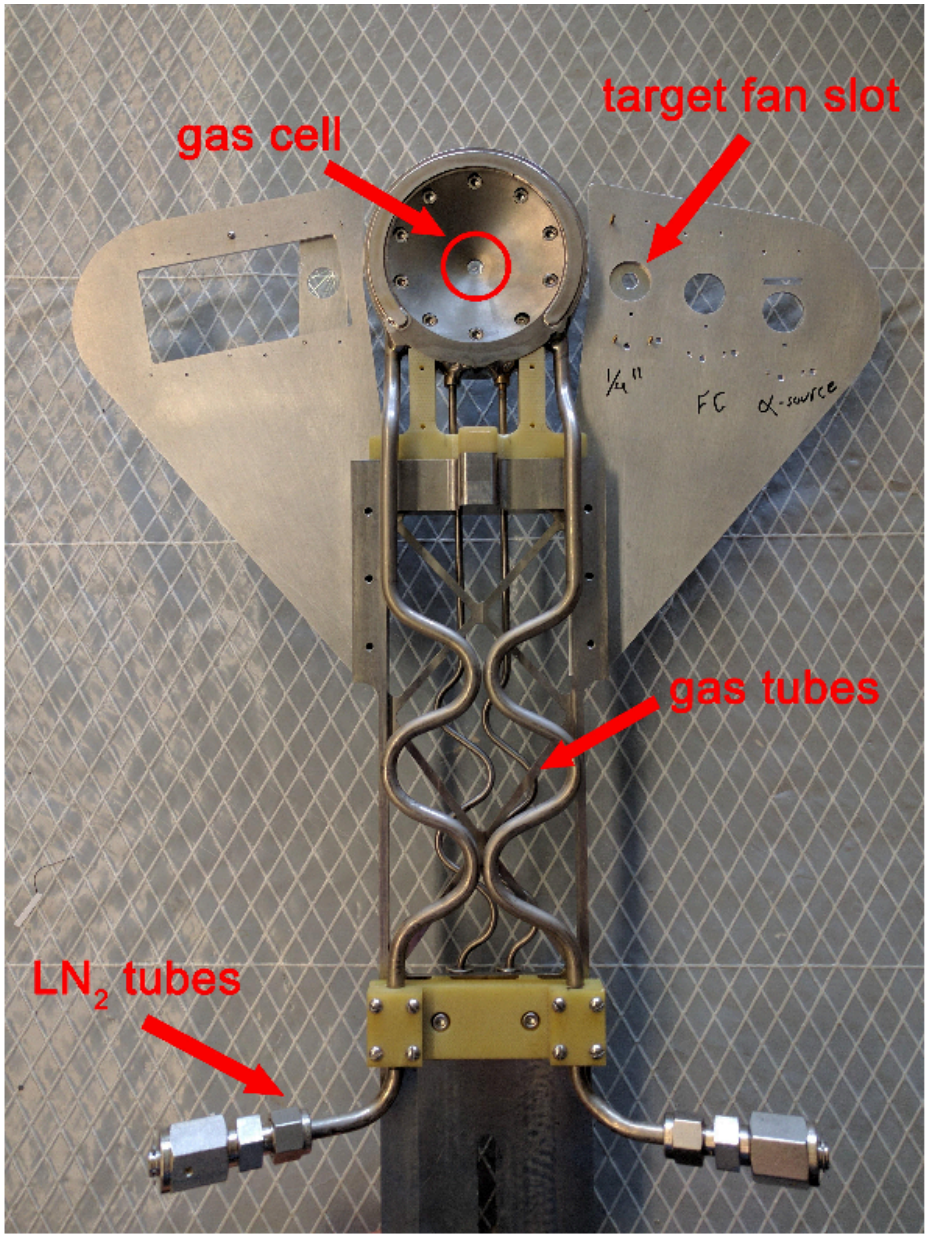
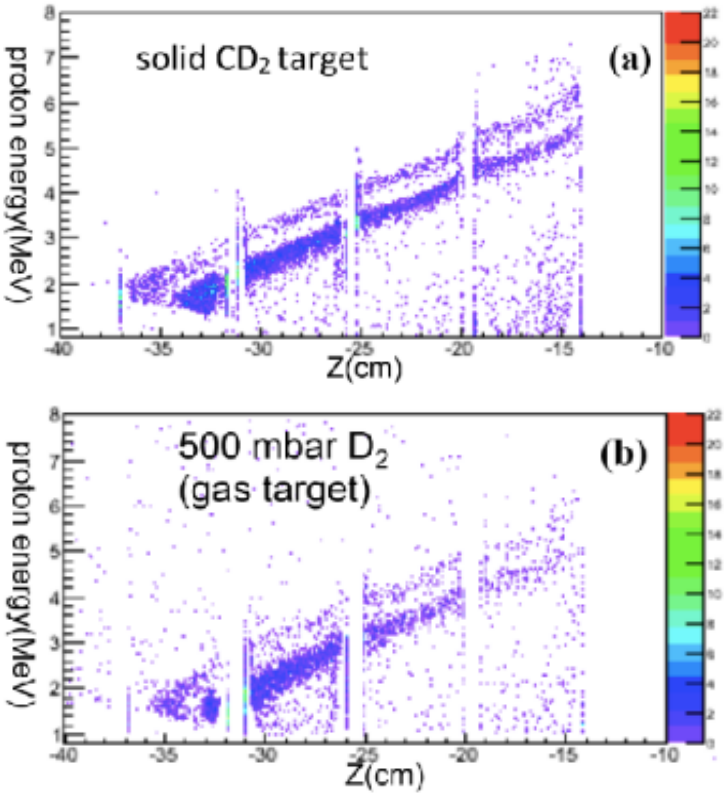
Development of Cryogenic Target for ISS



- Could improve upon HELIOS design shown above, although the option to change gas targets quickly is certainly useful.
- Currently uses Kapton windows
- Target thickness ~50 μg/cm^2
- Ability to accurately identify recoils is crucial (e.g. Ion Chamber)

HELIOS Cryogenic Target

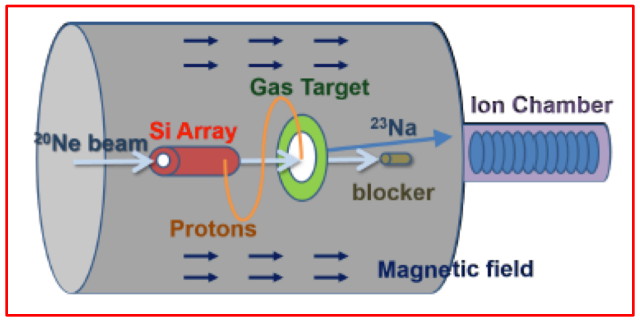


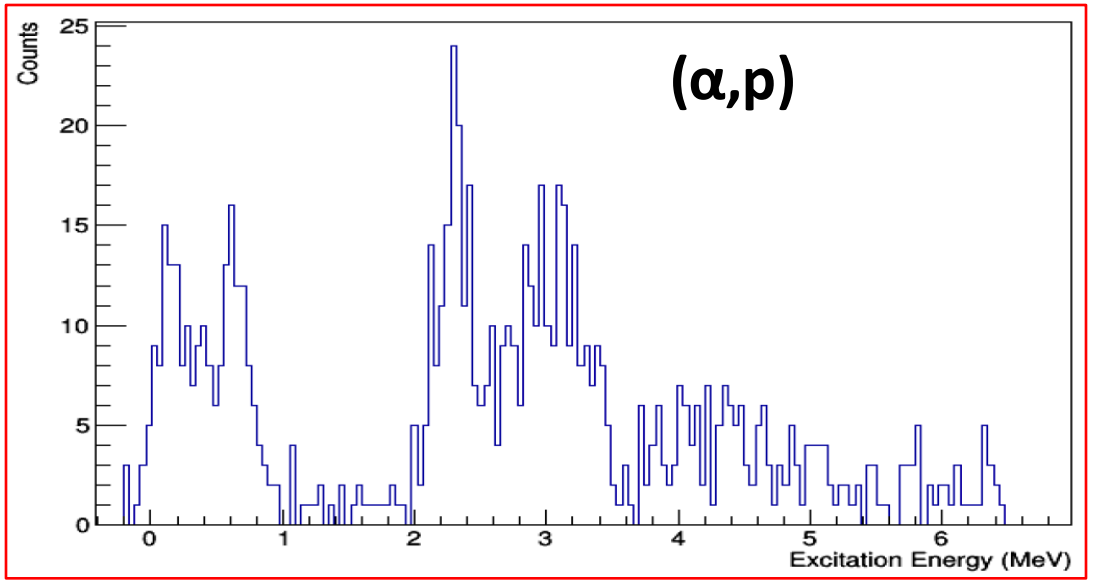


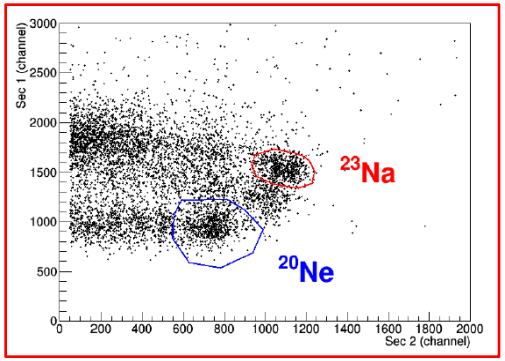
Proton spectra from d(^{14}C,p)^{15}C reaction

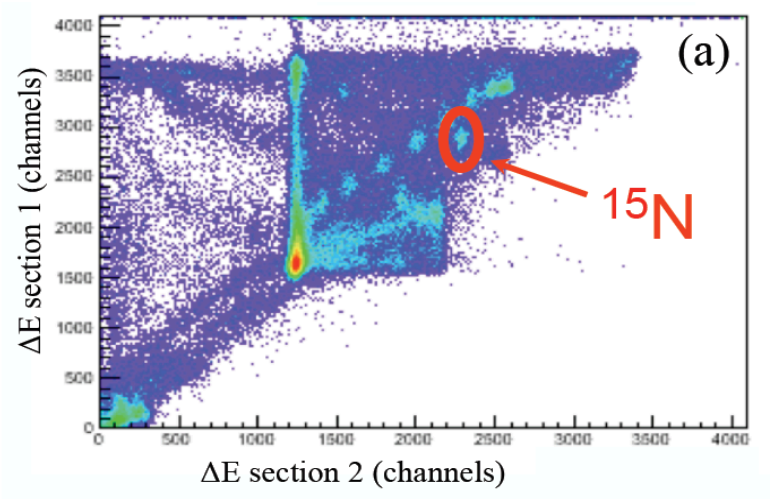
J. Lai, PhD Thesis, LSU (2016)

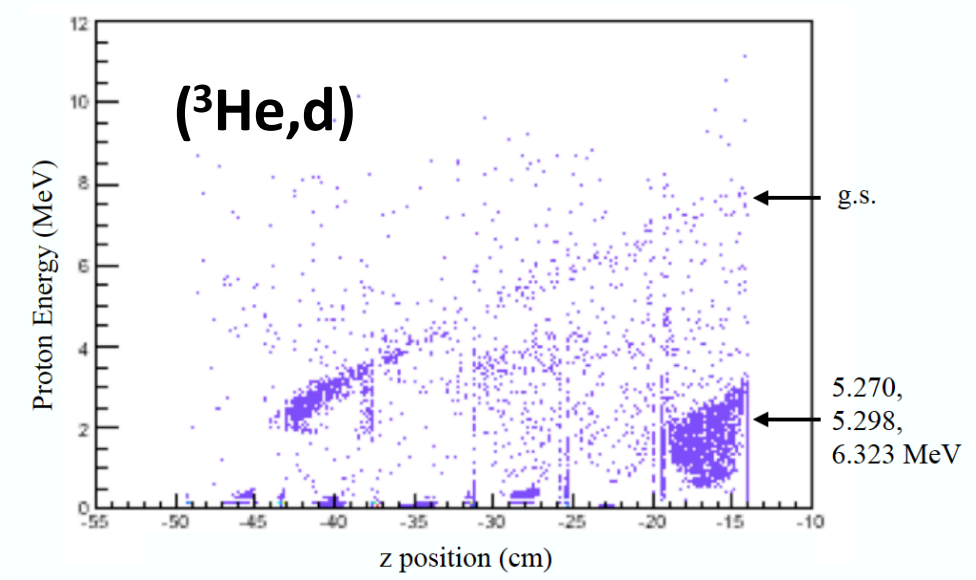
Previous Studies of ^{20}Ne(α,p) and ^{14}C(^{3}He,d)











Challenges and Discussion Points

- Gas targets are **extremely challenging** but the rewards are substantial and makes good use of the unique beam species available at HIE-ISOLDE.

- Work underway to look at new types of target, different windows etc (mentioned by Calem yesterday)

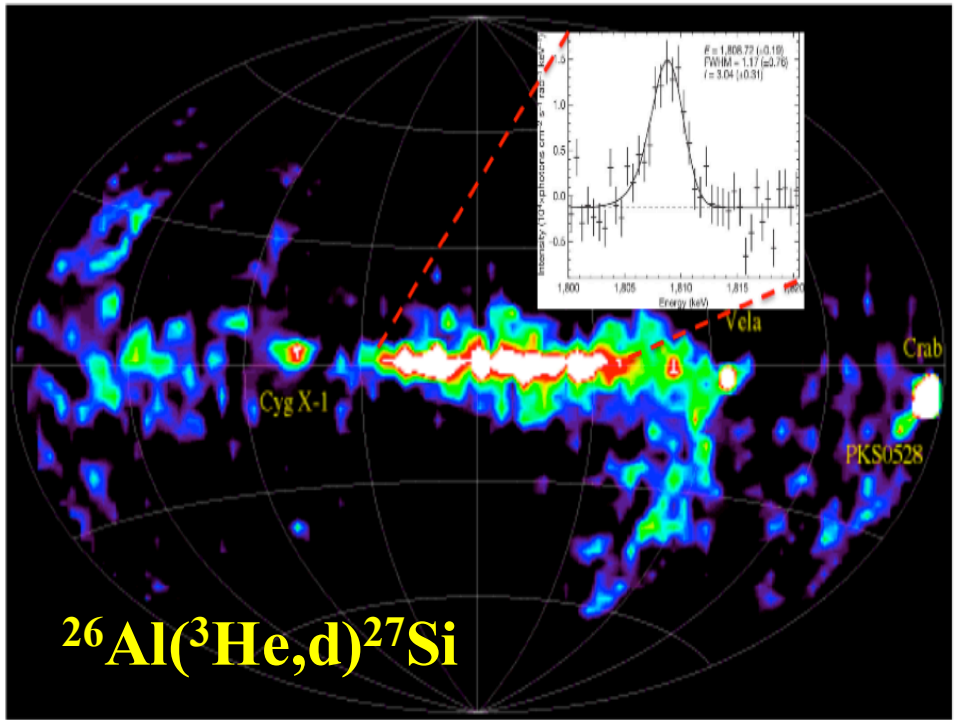
- Beam energies relatively low (< 2 Mev/u)

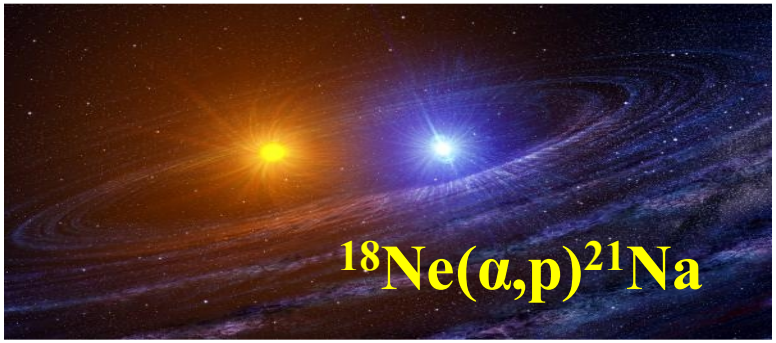
- Need normalization for (α,p) measurements
  $\Rightarrow (\alpha,\alpha')$

Summary

- A number of opportunities already exist for performing astrophysically important measurements using the ISS [e.g. $^{61}Zn(d,p)^{62}Zn$]

- However, the development of a cryogenic target would open up a whole host of possibilities in terms of nuclear astrophysics [e.g. some of the first direct measurements of (α,p) process reactions]





Thank you very much!

G. Lotay[1], **D.T. Doherty[1]**, W.N. Catford[1], Zs. Podolyak[1], P.A. Butler[2], R.D. Page[2], D.K. Sharp[3], S.J. Freeman[3], M. Labiche[4], B.P. Kay[5], C.R. Hoffman[5], R.V.F. Janssens[5], D.G. Jenkins[6], N. Orr[7], A. Matta[7], [8]L. P. Gaffney

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[8] *ISOLDE, CERN*

ISS meeting, Liverpool, 27th August, 2019

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ISS – ISOLDE Solenoid Spectrometer

- 4T superconducting solenoid.
- Obtained as MRI magnet from Brisbane.
  - Arrived @ CERN in April 2016.
- Dedicated to transfer reactions with HIE-ISOLDE.
- New Si array designed and under construction (ready after LS2).
  - First experiments with ANL array.