NSSC 8
NUCLEAR SCIENCE and SECURITY CONSORTIUM

Nuclear Science and Security Consortium

September Workshop and Advisory Board Meeting

Heavy-Ion Collision Processes & Symmetry Energy:

Measuring Neutrons in Coincidence with Fragments

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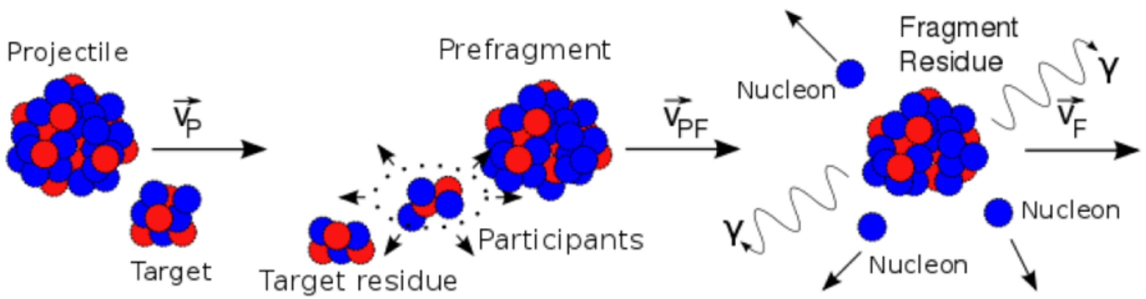
Projectile Fragmentation Process

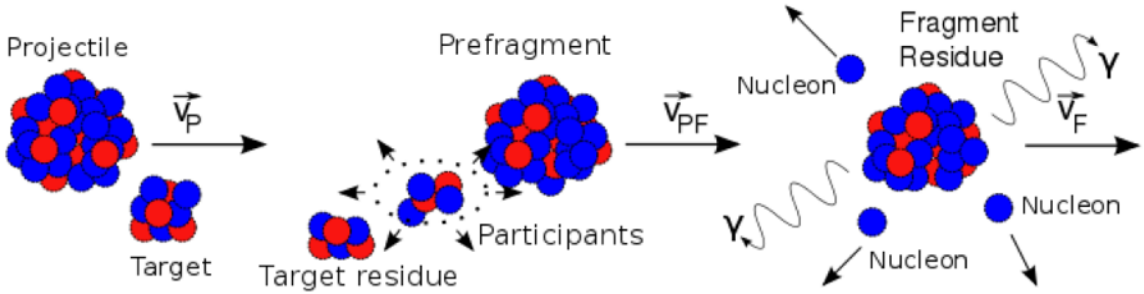


Two-step abrasion/ablation projectile fragmentation reaction

M.A. Mosby, *Measurement of Excitation Energy of Neutron-Rich Precursor Fragments* (2013)

- **Projectile fragmentation reactions described as a two-step process**
  1) **Fast collision creates an excited precursor fragment**
  2) **Precursor fragment undergoes a slower de-excitation process**
- **Reactions used at the NSCL**

Projectile Fragmentation Process



Two-step abrasion/ablation projectile fragmentation reaction

M.A. Mosby, *Measurement of Excitation Energy of Neutron-Rich Precursor Fragments* (2013)

- **The specifics in the intermediate prefragment are not well understood**
- **Fragment and neutron coincidence experimental data can provide insight into the projectile fragmentation process**
  - Compare experimental data to outcomes from Liège Intranuclear Cascade model (INCL++) coupled with a de-excitation code
    - INCL++ is a recently developed model of collisions
    - S. Leray, D. Mancusi, P. Kaitaniemi, J.C. David, A. Boudard, B. Braunn, and J. Cugnon, J. Phys. Conf. Series **420**, 012065 (2013)

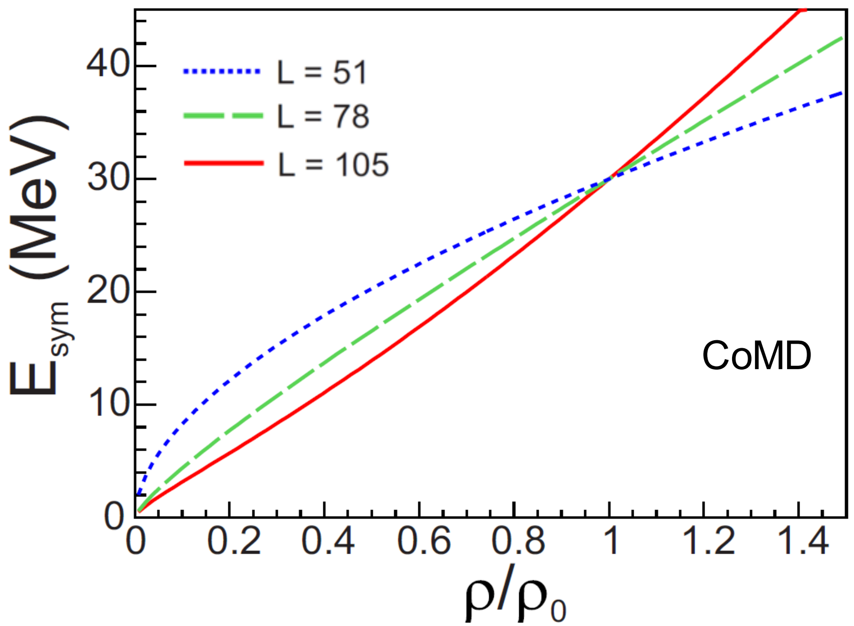
Nuclear Equation of State and Symmetry Energy

The nuclear equation of state (EoS) is sometimes written as:

$$E(\rho, I) \approx E(\rho, 0) + E_{sym}(\rho) I^2$$

$$I = \frac{N - Z}{A}$$

- $E(\rho, I)$: binding energy
- $E(\rho, 0)$: binding energy for N = Z
- $E_{sym}(\rho)$: symmetry energy
- I: isospin asymmetry
- ρ: density



K. Stiefel et al., Phys. Rev. C **90**, 061605(R) (2014)

$$E_{sym}(\rho) \approx E_{sym}(\rho_0) + \frac{L_{sym}}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 \quad \ldots$$

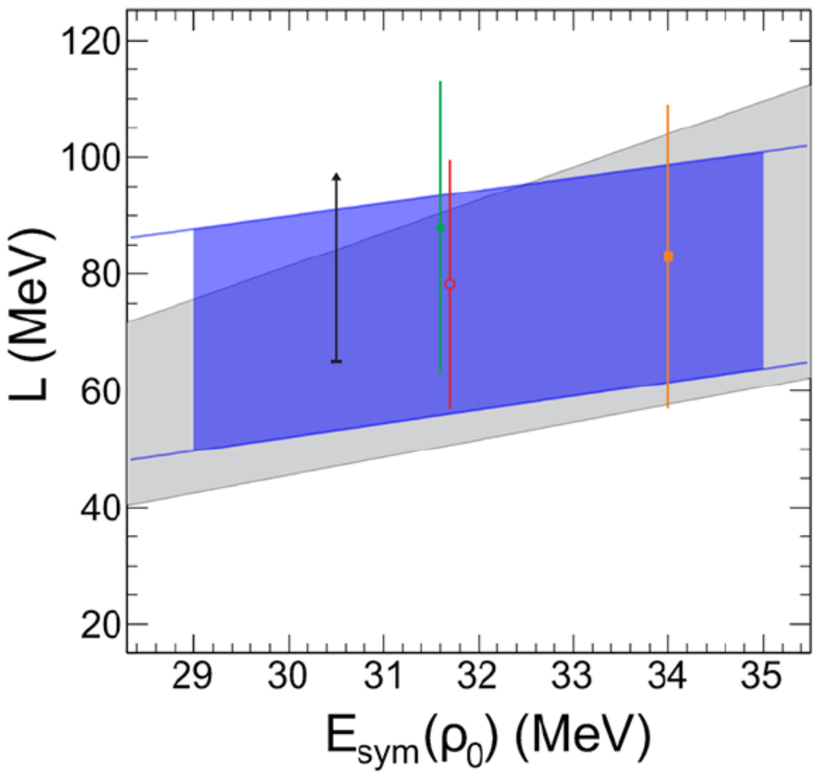
E_{sym} is magnitude, L_{sym} is slope, K_{sym} is curvature

CoMD Reference

M. Papa, T. Maruyama, and A. Bonasera, Phys. Rev. C **64**, 024612 (2001)

M. Papa, G. Giuliani, and A. Bonasera, J. Comput. Phys. **208**, 403 (2005)

Constraints on Symmetry Energy with Heavy Ion Collisions (HICs)

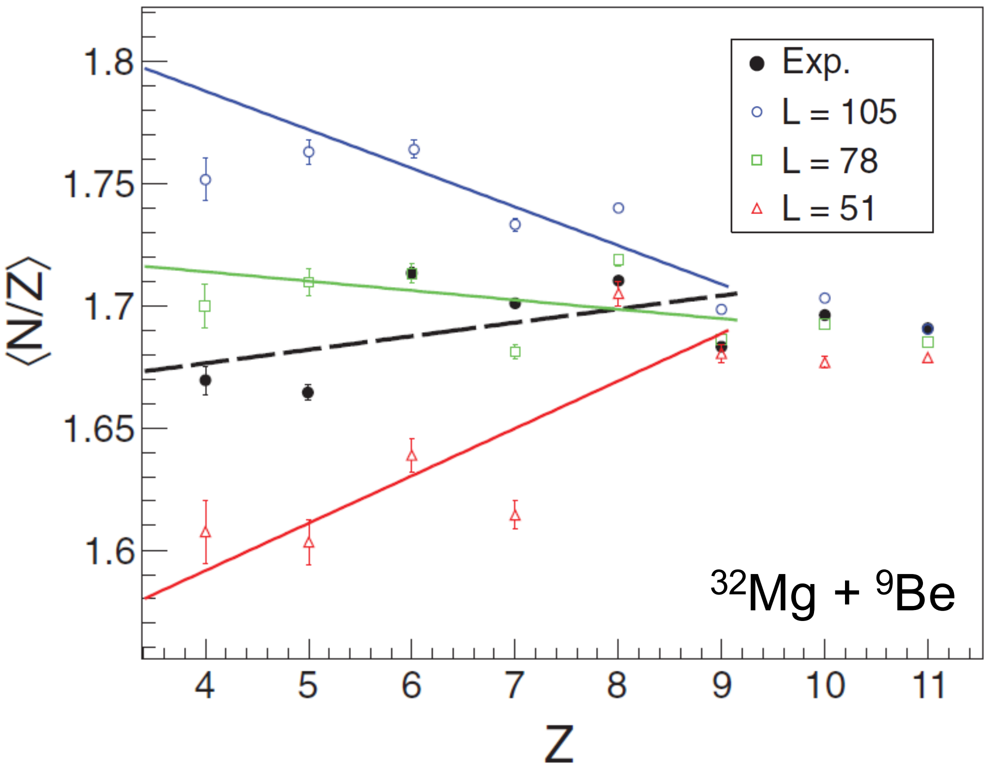


- **Use HICs to probe nuclear matter away from stable nuclei**
  - Compare to models containing E_{sym} term
- **Use RIBs for better constraints**
  - Larger asymmetries
  - Larger I^2
  - Enhanced sensitivity to symmetry energy

Z. Kohley and S.J. Yennello, Eur. Phys. J. A **50**, 31 (2014)

Gray box: M.B. Tsang *et. al.*, Phys. Rev. Lett. **102**, 122701 (2009)
Purple box: Z. Kohley *et. al.*, Phys. Rev. C **88**, 041601(R) (2013)
Black line: Z. Kohley *et. al.*, Phys. Rev. C **82**, 064601 (2010)
Solid green circle: B.A. Li, *et. al.*, Phys. Rep. **464**, 113 (2008)
Open red circle: D.V. Shetty, *et. al.*, Phys. Rev. C **76**, 024606 (2007)
Solid orange square: P. Russotto *et. al.*, Phys. Lett. B **697**, 471 (2011)

HIC Previous Measurement



- **Inclusive fragment production measurement with Sweeper**
  - Fragments produced from the collision of contaminant ^{32}Mg on ^{9}Be
  - Indicates average N/Z as function of produced fragments Z is sensitive to form of symmetry energy
- **Neutrons emitted may be a potential observable**

Open symbols come from CoMD model calculations

Z. Kohley *et. al.*, Phys. Rev. C **88**, 041601(R) (2013)

Experiment 12011

- **Use MoNA LISA and the Sweeper magnet to measure neutrons and fragments in coincidence from two RIB reactions**
  - $^{30}S + ^{9}Be$, a proton-rich projectile reaction
  - $^{40}S + ^{9}Be$, a neutron-rich projectile reaction

^{30}Cl	^{31}Cl	^{32}Cl	^{33}Cl	^{34}Cl	^{35}Cl	^{36}Cl	^{37}Cl	^{38}Cl	^{39}Cl	^{40}Cl	^{41}Cl	^{42}Cl
^{29}S	^{30}S	^{31}S	^{32}S	^{33}S	^{34}S	^{35}S	^{36}S	^{37}S	^{38}S	^{39}S	^{40}S	^{41}S
^{28}P	^{29}P	^{30}P	^{31}P	^{32}P	^{33}P	^{34}P	^{35}P	^{36}P	^{37}P	^{38}P	^{39}P	^{40}P

Z

N

stable

EC+, β+

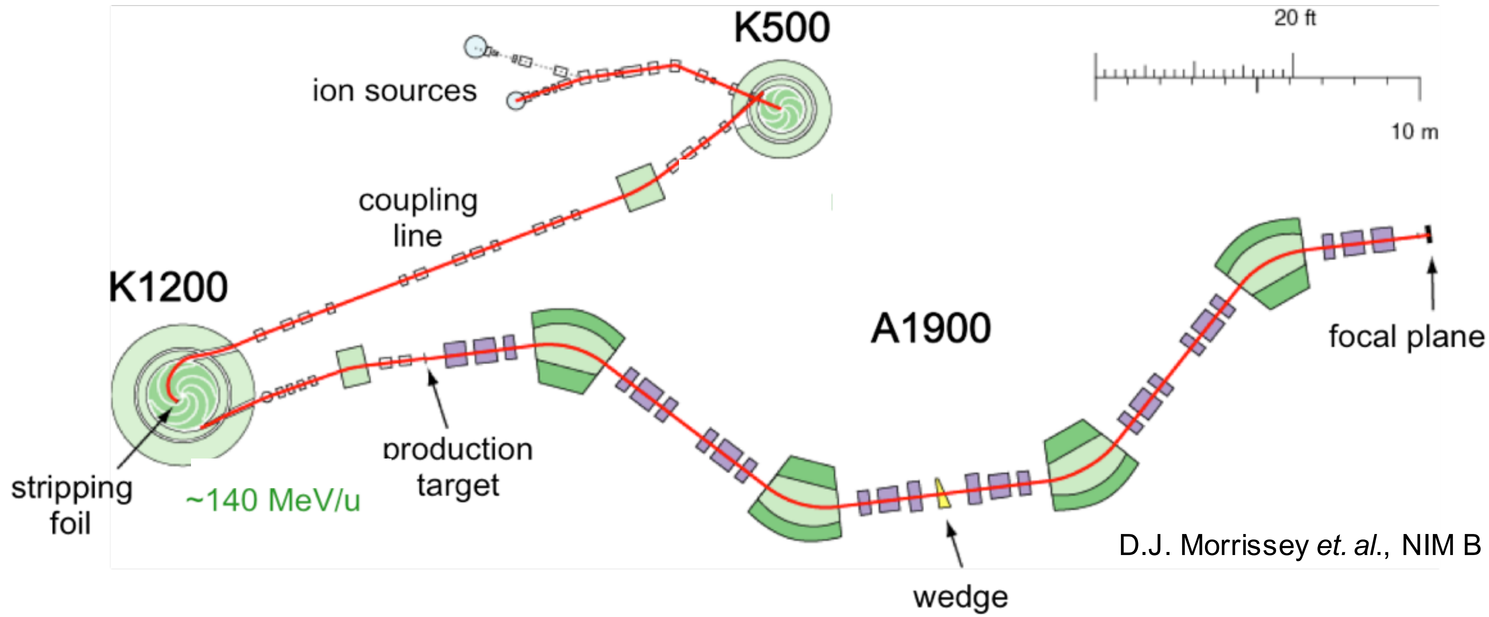
proton emission

β-

IAEA Nuclear Data Section
https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

- **Compare data to model predictions**
  - Study the precursors of final fragments in a reaction with INCL++
  - Constrain the density dependence of symmetry energy with CoMD

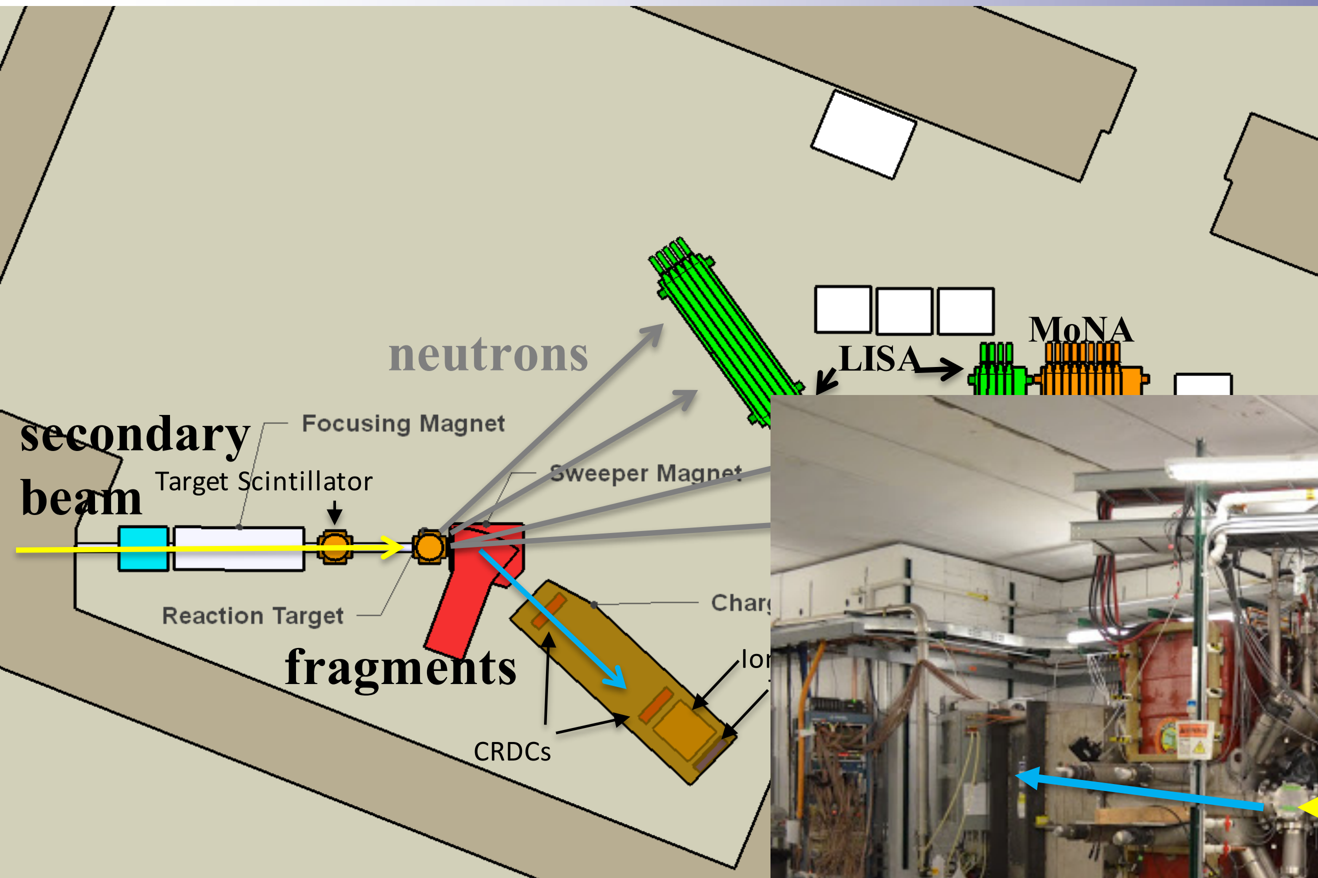
Beam Production

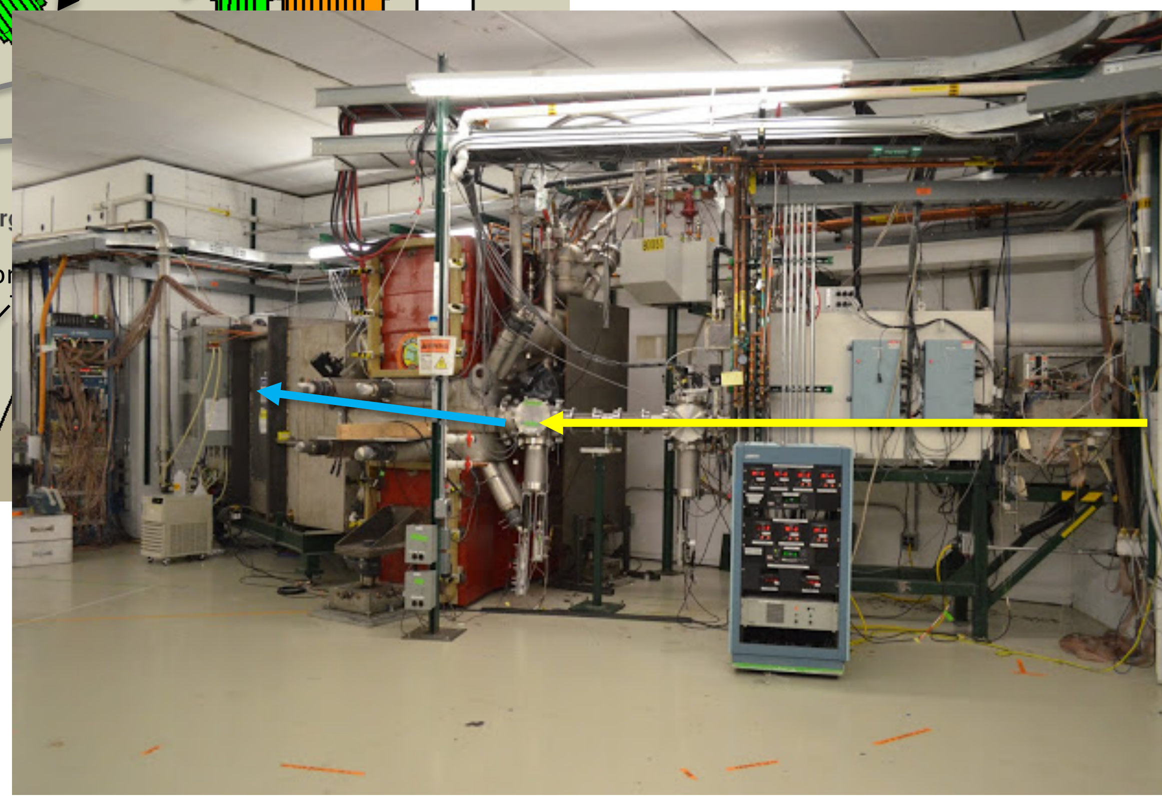


D.J. Morrissey *et. al.*, NIM B **204**, 90 (2013)

Secondary Beam	Primary Beam	Production Target	RIB Rate (pps)
55 MeV/u ^{30}S	150 MeV/u ^{36}Ar (75 pnA)	Be 940 mg/cm^2	250,000
55 MeV/u ^{40}S	140 MeV/u ^{48}Ca (80 pnA)	Be 1151 mg/cm^2	185,000

Experiment 12011 Set-Up
MoNA LISA – Sweeper Magnet





Reactions:

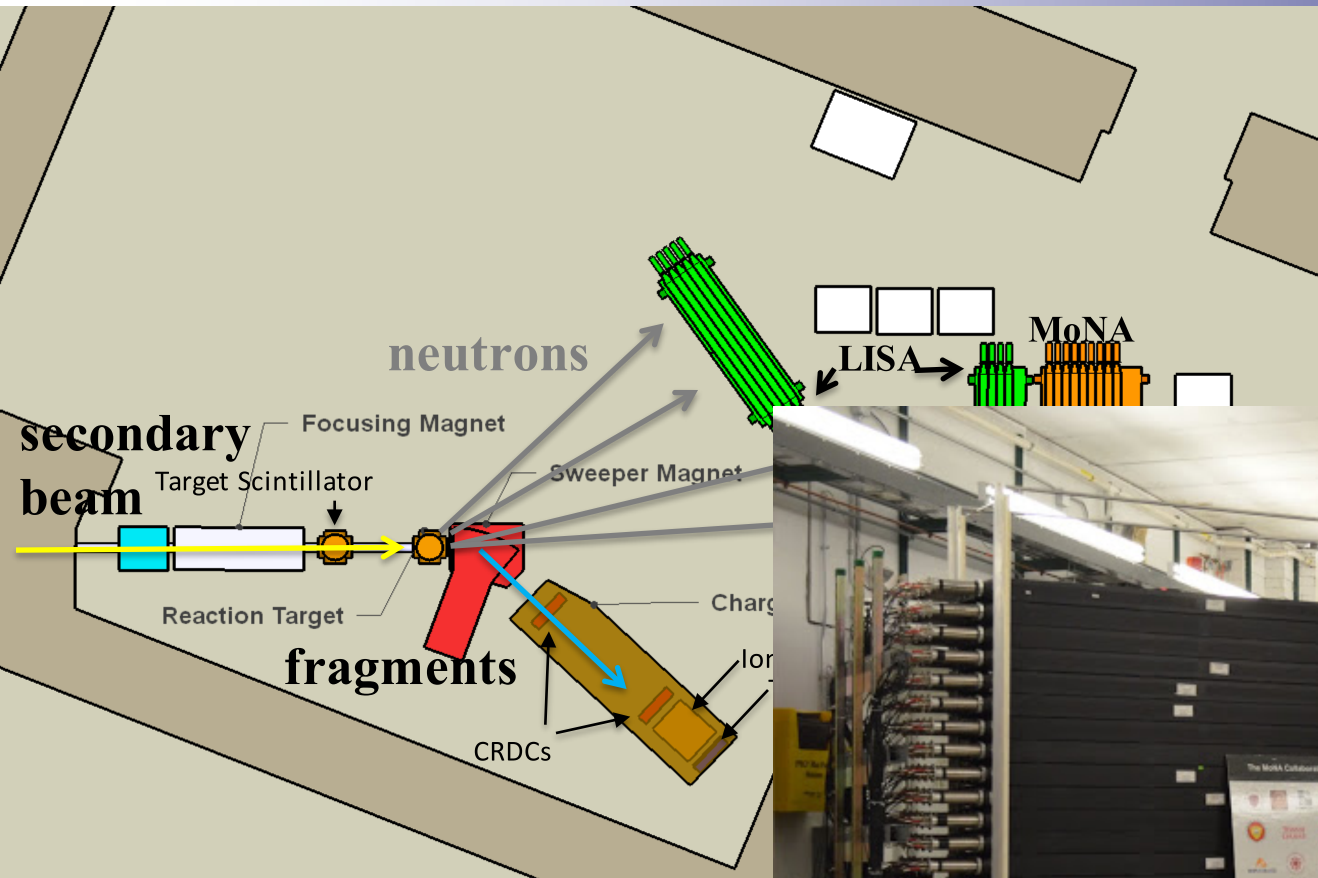
$^{30}S + ^{9}Be$

$^{40}S + ^{9}Be$

55 MeV/u

Two magnet settings per beam gives range of produced fragments.

Experiment 12011 Set-Up
MoNA LISA – Sweeper Magnet



Reactions:

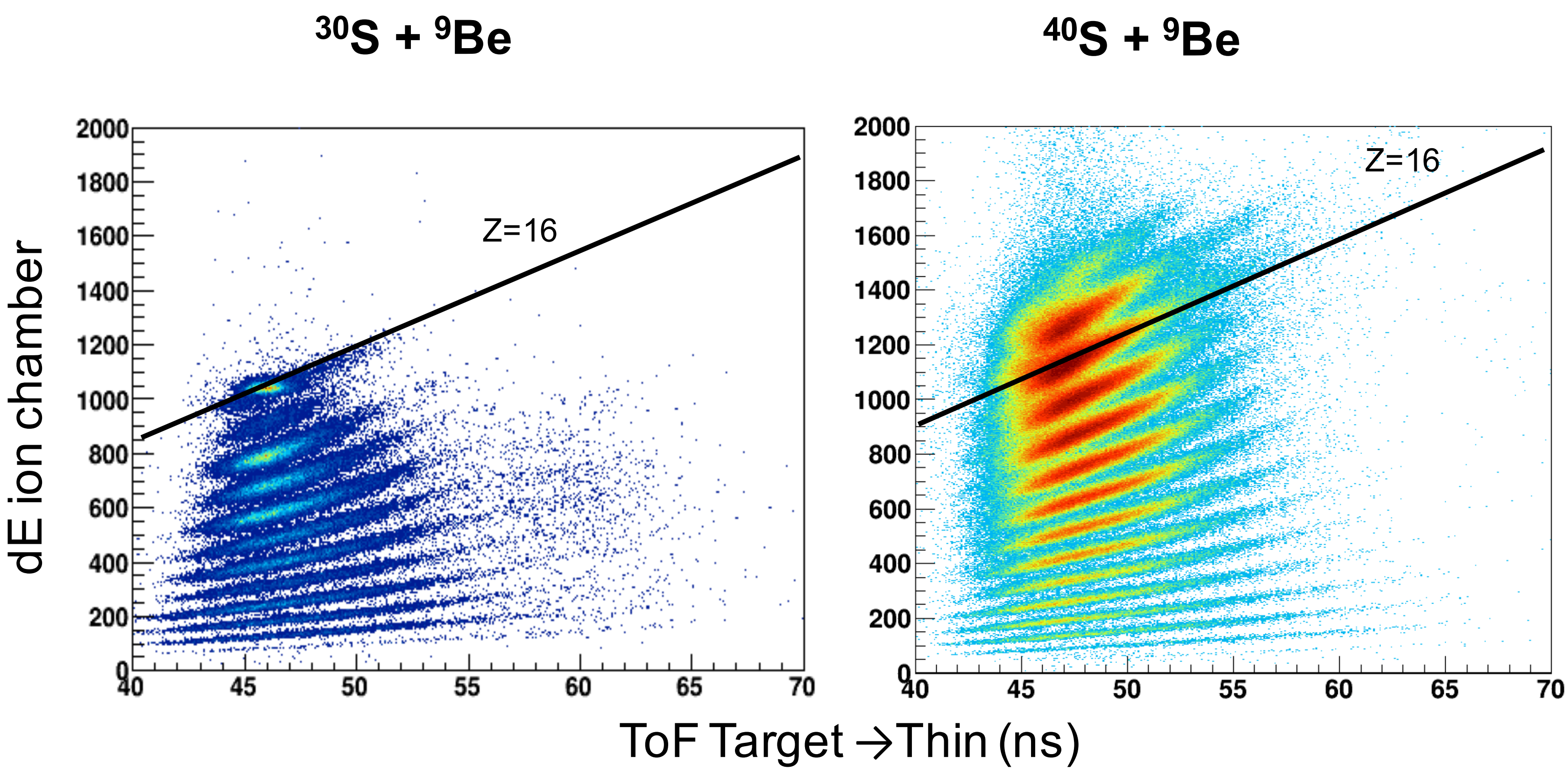
$^{30}S + {}^{9}Be$

$^{40}S + {}^{9}Be$

55 MeV/u

Bars provide angular coverage up to about 40 degrees

Element Identification



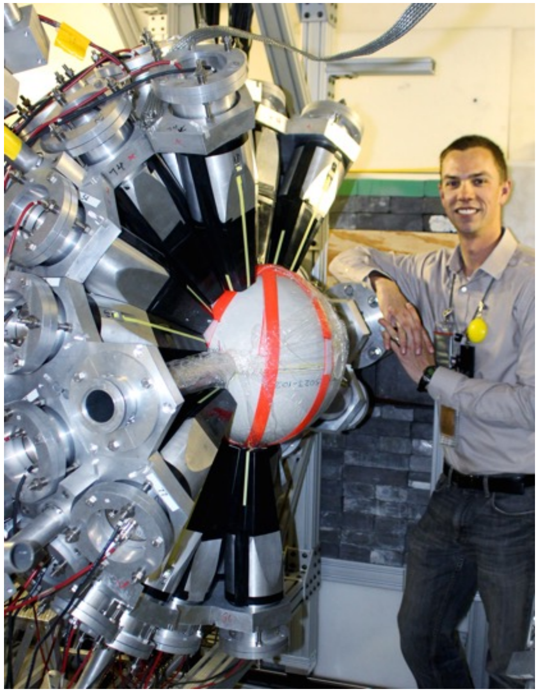
Sweeper setting: 2.25 Tm

Sweeper setting: 2.01 Tm

Particle Identification Process

3D correlations between angle, position, and time of flight need to be considered to separate isotopes with the Sweeper magnet.

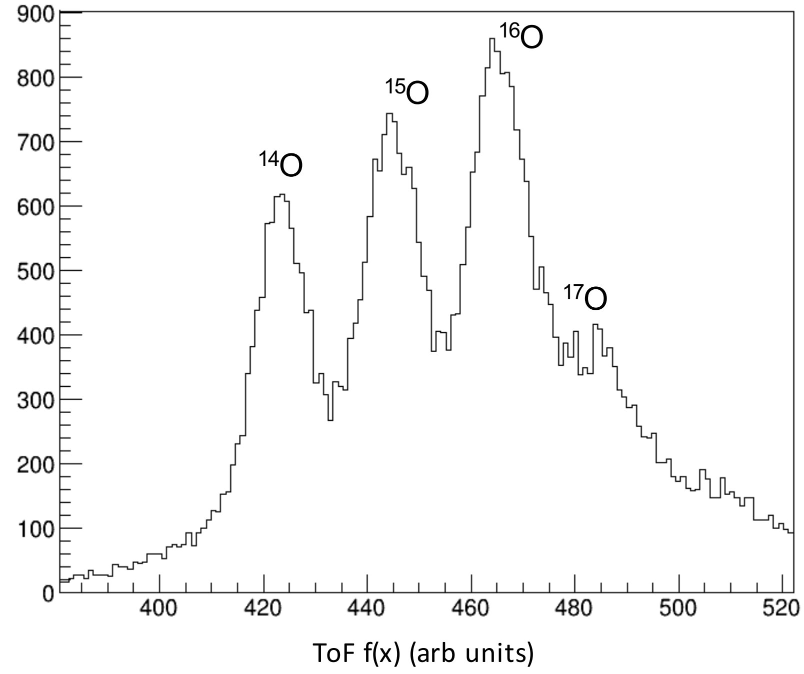
Applying corrections gives more definable isotope bands.



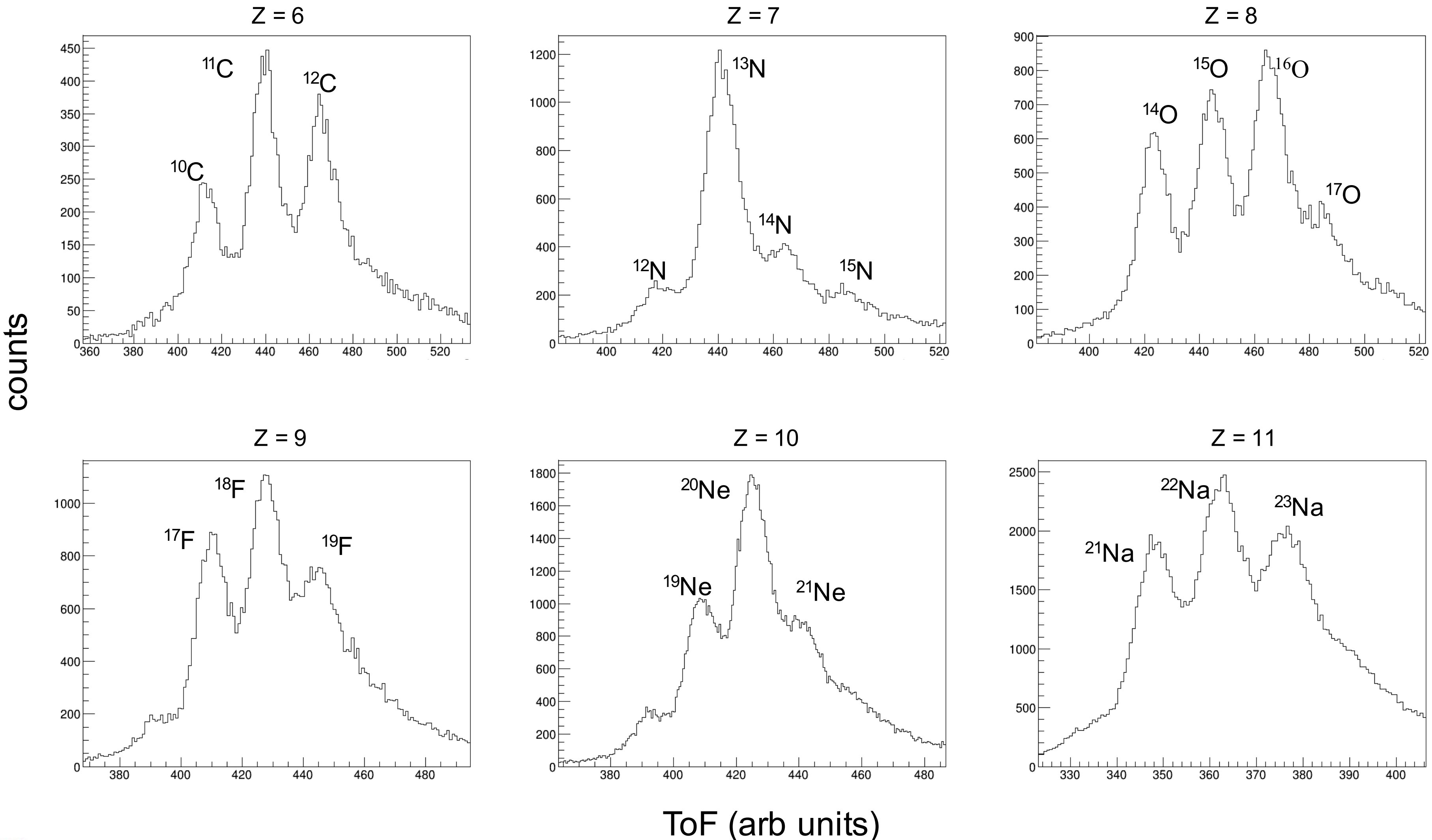
http://www.nscl.msu.edu/news/news-33.html

Shea Mosby

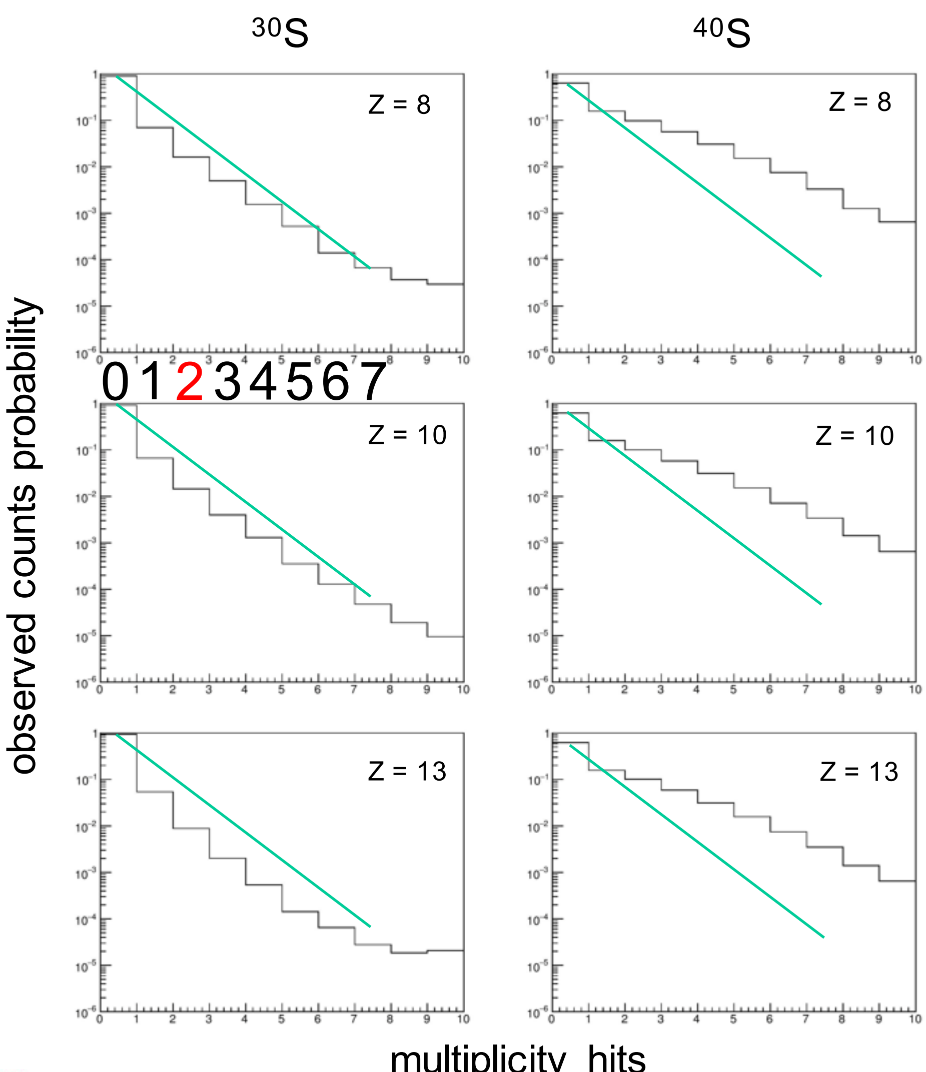
Staff Scientist



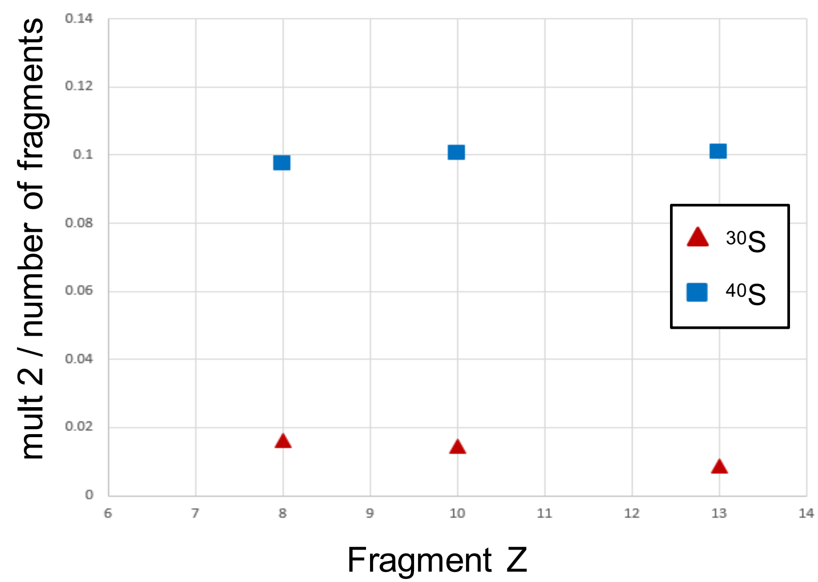
^{40}S beam, 2.01 Tm sweeper setting



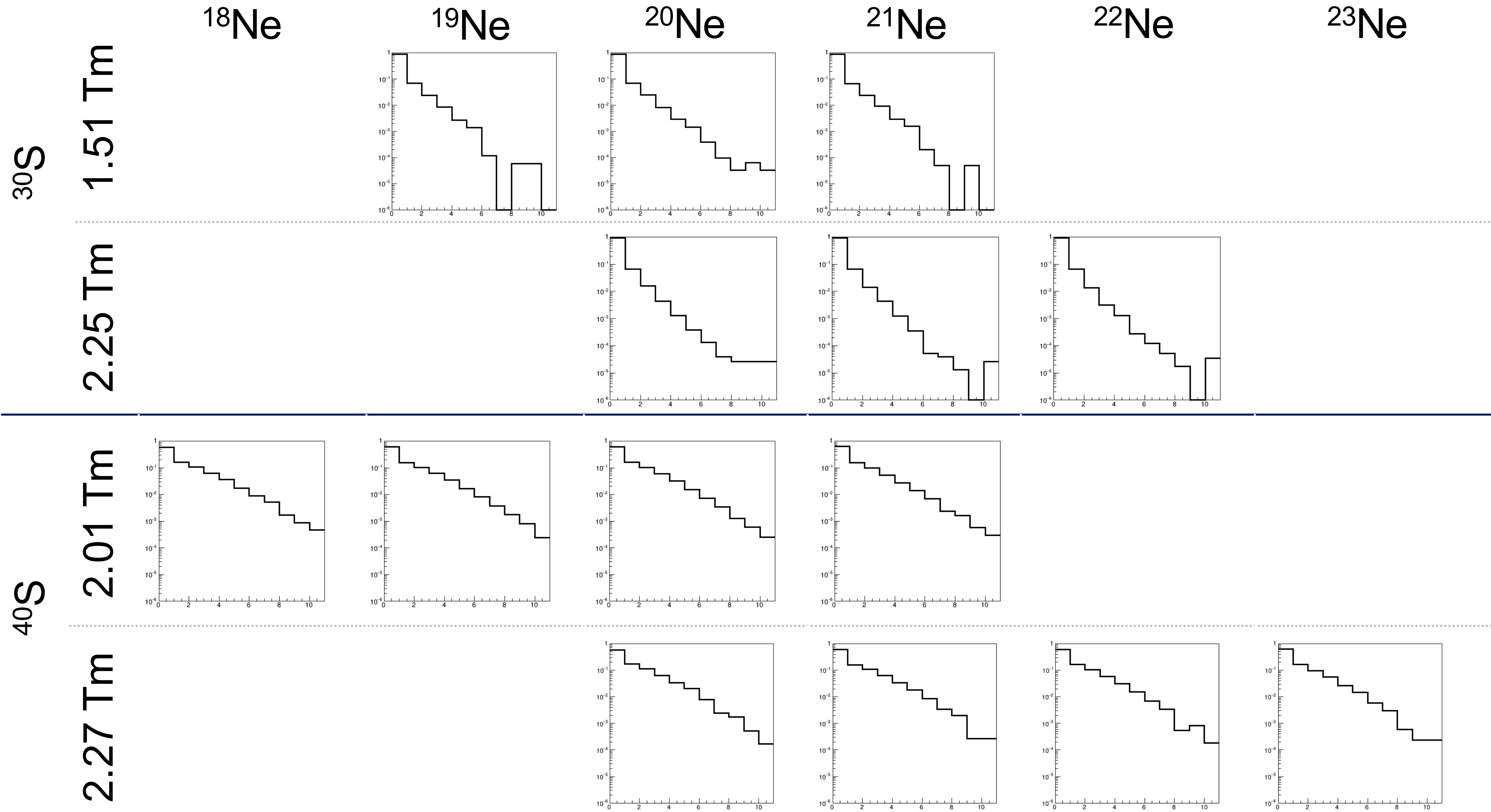
MoNA LISA Multiplicity-Detector Response



- Recorded number of “hits” in MoNA-LISA in coincidence with fragments
- Blue line was drawn by hand to follow the Z = 8 slope from ^{30}S



MoNA Response - Ne Isotopes



Modeling Fragmentation Process

Two different approaches to describe the fragment and neutron distributions which provide insight into the production mechanism.

- **Liege Intranuclear Cascade (INCL++) model**
  - Study the precursors of final fragments in a reaction with INCL++
- **Constrained Molecular Dynamics (CoMD) model**
  - Constrain the density dependence of symmetry energy with CoMD

Model predictions are passed through Geant4 to predict interactions with the MoNA LISA – Sweeper experimental set-up.

Isotope and neutron production predictions will be extracted from the models to compare to experimental data.

Summary

- **Reaction products from HICs may be used to study precursor fragments and constrain the symmetry energy term in the nuclear equation of state**

- **Continue and complete analysis for this experiment**
  - Fragment particle identification and neutron detector response achieved
  - Compare analyzed data to reactions model

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L. Heilborn, Texas A&M

S. Mosby, LANL

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Disclaimer

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