Probing the asymmetry dependence of the nuclear caloric curve in fusion-evaporation reactions

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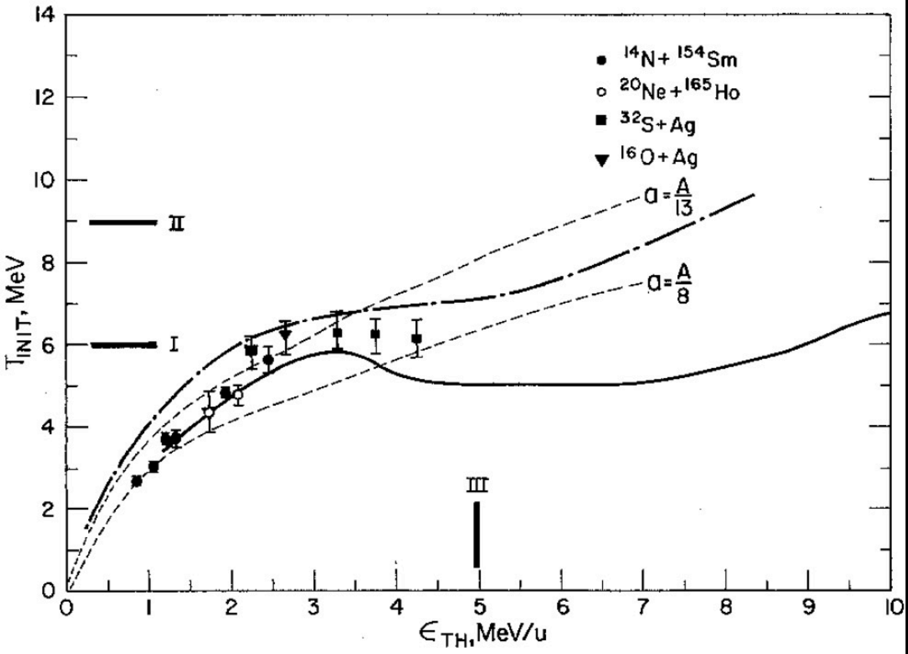
Nuclear Equation of State: T,μ,ρ,P,E*,I

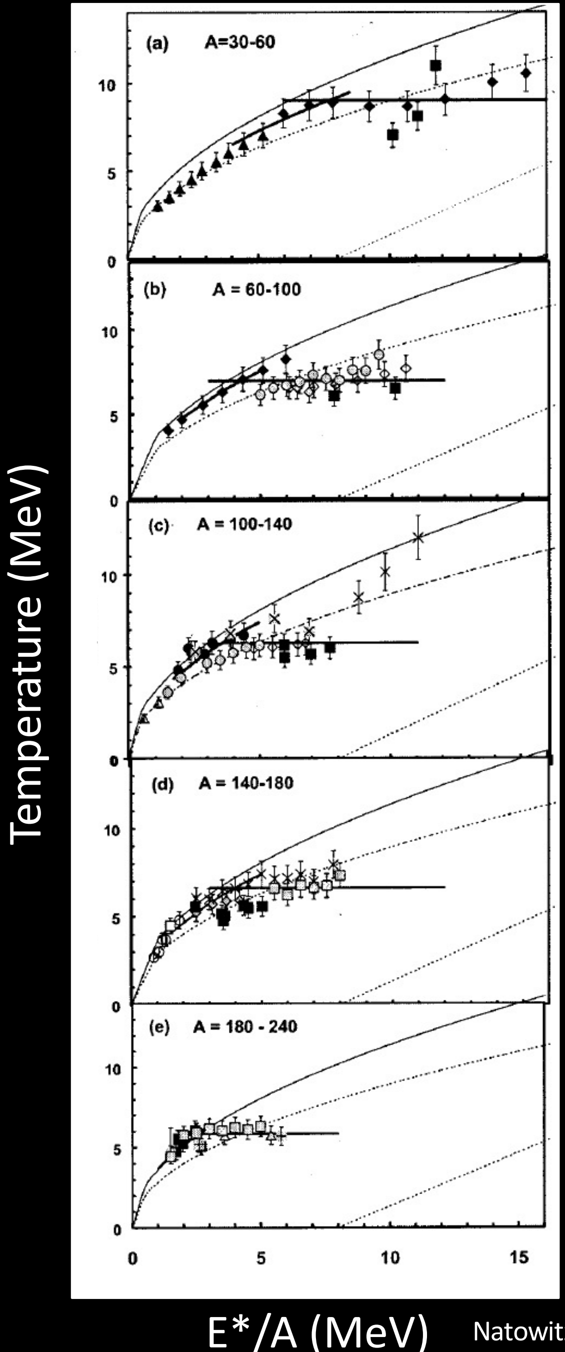
- ❖ Heavy Ion Collisions at All Energies
- ❖ Nuclear Structure (e.g. Resonances)
- ❖ Supernovae (nucleosynthesis)
- ❖ Neutron Stars (Crust to Core)
- ➢ n-p Asymmetry Crucial



D. Fabris et al., Phys. Lett. B 196 (1987) 429

- Essential Piece of Nuclear Equation of State: T vs E*/A
- Search for & Study of Phase Transition
  - Liquid to Vapor
  - Evaporation to Multifragmentation

Nuclear Caloric Curve



Natowitz et al. PRC65, 034618 (2002)

MASS DEPENDENCE!
With increasing mass:

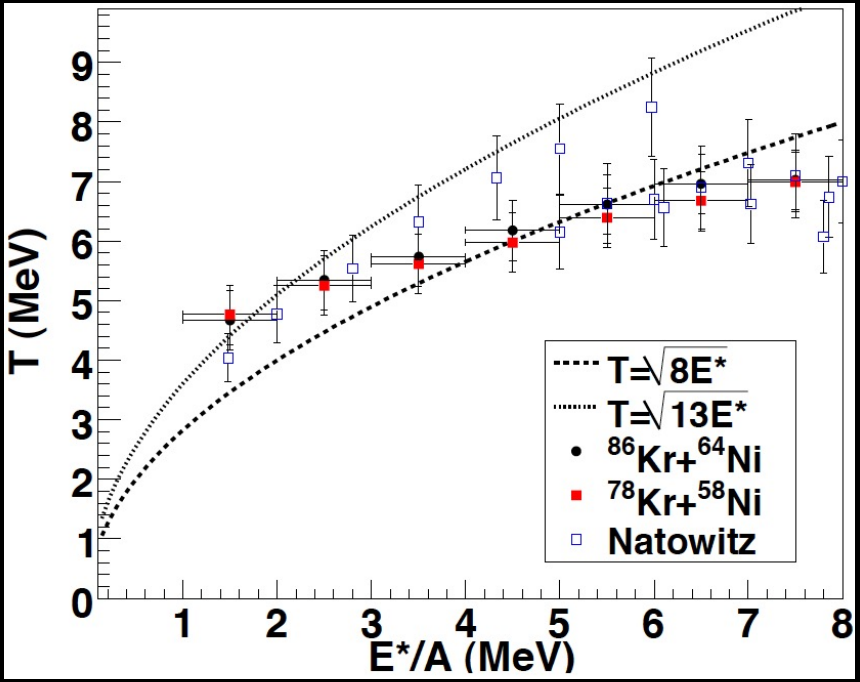
- Limiting Temperature decreases
- Onset of plateau at lower excitation

ASYMMETRY DEPENDENCE?

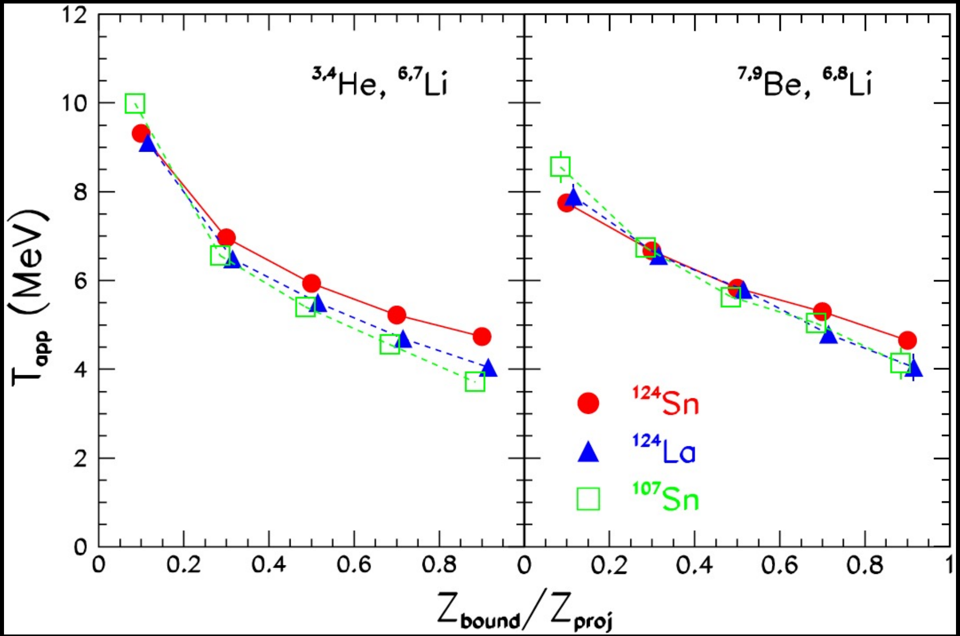
- Does an n-p Asymmetry Dependence Exist?
- Which way does it go?
- How strong is it?

Caloric Curve: Asymmetry Dependence?

Experiment



S. Wuenschel, Ph.D. Thesis, 2009



Sfienti et al., PRL 102, 152701 (2009)

Slight offset of neutron-rich system, but not statistically significant

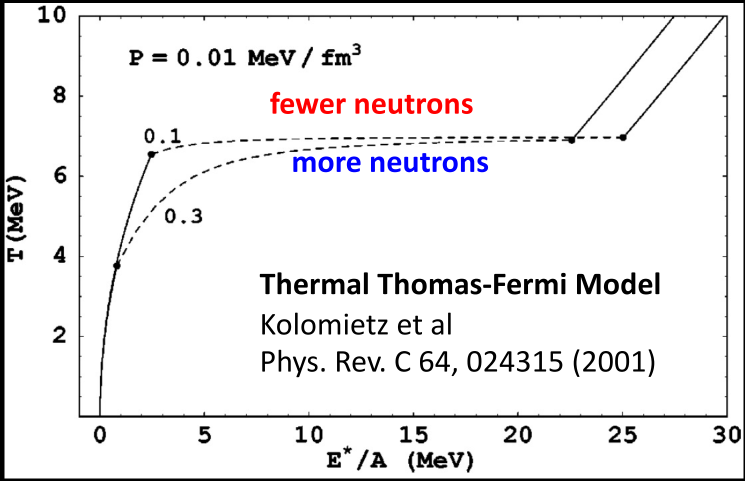
Possible dependence on asymmetry, but not for all impact parameters.

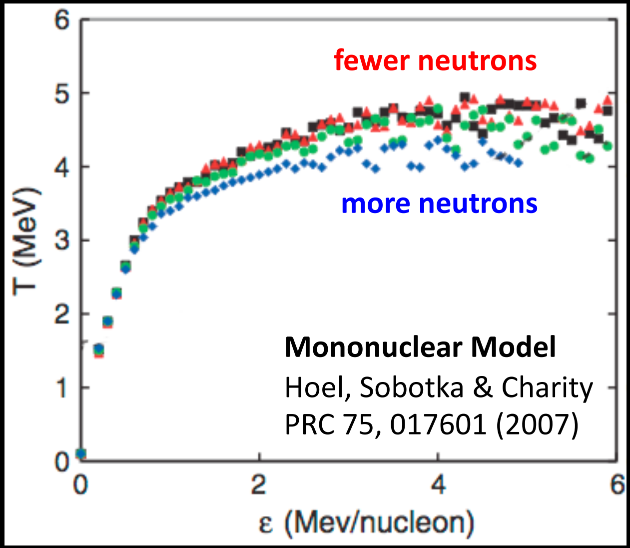
Non-observation.
Selection was on the system composition.

Theory

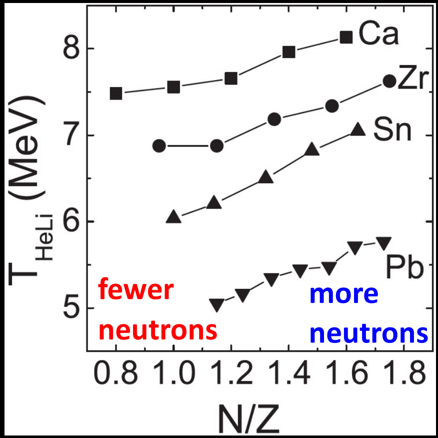
Different models make very different predictions about how the caloric curve may depend on n-p asymmetry.

Neutron Rich → Lower T

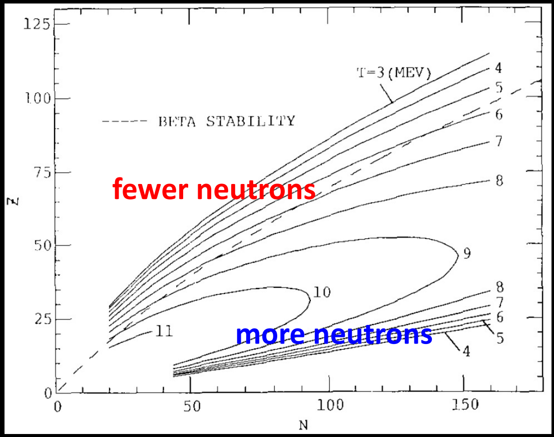




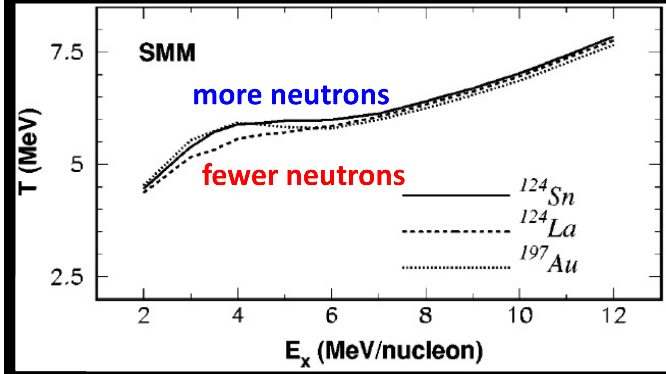
Neutron Rich → Higher T



Isospin-Dependent Quantum Molecular Dynamics
Su & Zhang
Phys. Rev. C 84, 037601 (2011)

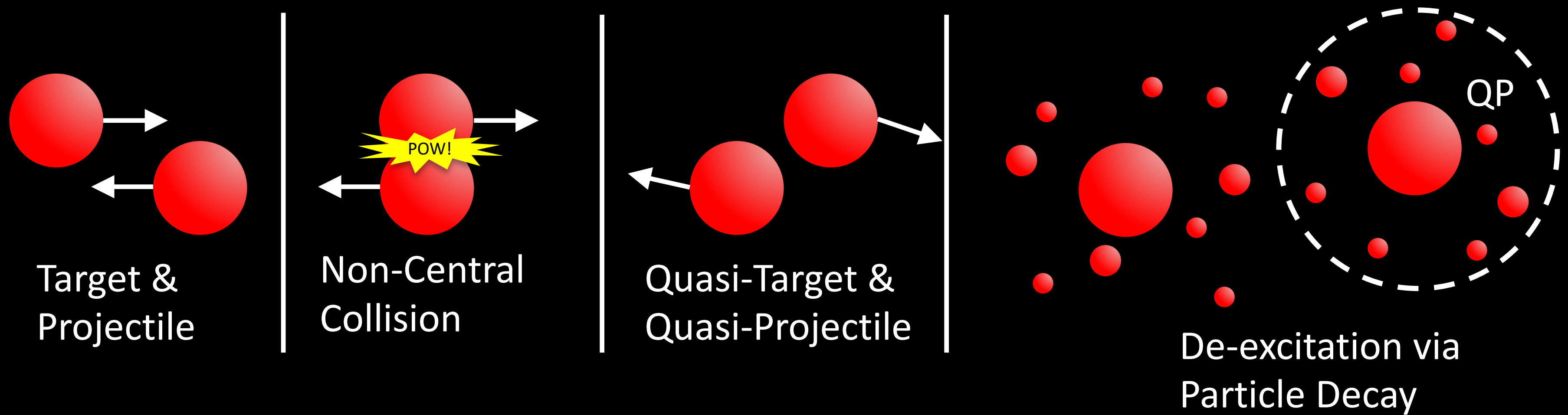


Hot Liquid Drop Model
Besprosvany & Levit
Phys. Lett B 217, 1 (1989)



Statistical Multifragmentation Model
Ogul & Botvina
Phys. Rev. C 66, 051601 (2002)

The Multifragmentation Reactions



$^{70}Zn + ^{70}Zn$

$^{64}Zn + ^{64}Zn$

$^{64}Ni + ^{64}Ni$

E = 35A MeV

QP Reconstruction

Goal: select events with an equilibrated source

Select particles that may comprise the QP

Velocity selection

Charged particles & free neutrons

Calculate Z, A, p, E* & asymmetry

Select mass (range) of QP

Select on-average spherical events

MQF Thermometer

Momentum Quadrupole Fluctuation

The quadrupole momentum distribution

$$Q_{xy} = p_x^2 - p_y^2$$

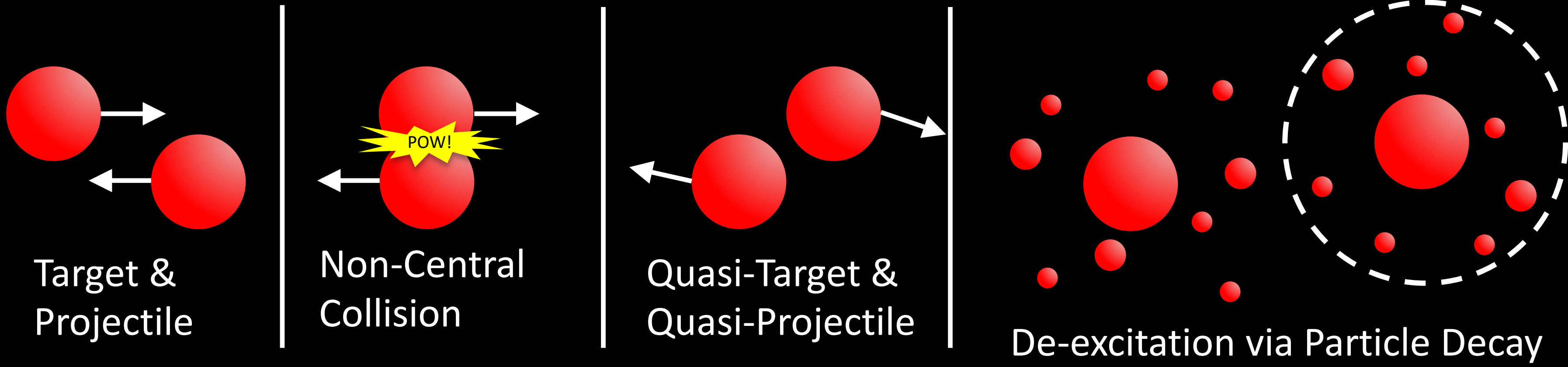
Contains information on the temperature through its fluctuations

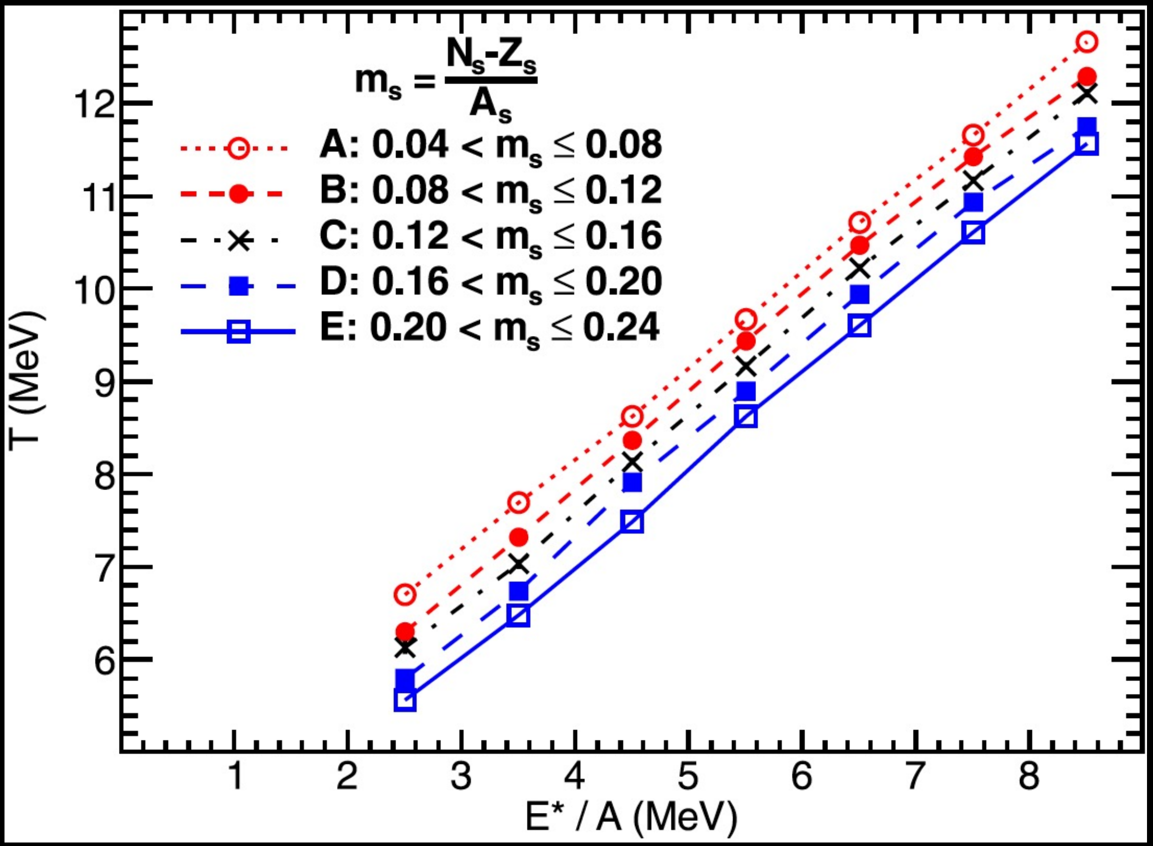
$$\sigma_{xy}^2 = \int d^3p \left(p_x^2 - p_y^2\right)^2 f(p)$$

If f(p) is a Maxwell-Boltzmann distribution

$$\sigma_{xy}^2 = 4m^2T^2$$

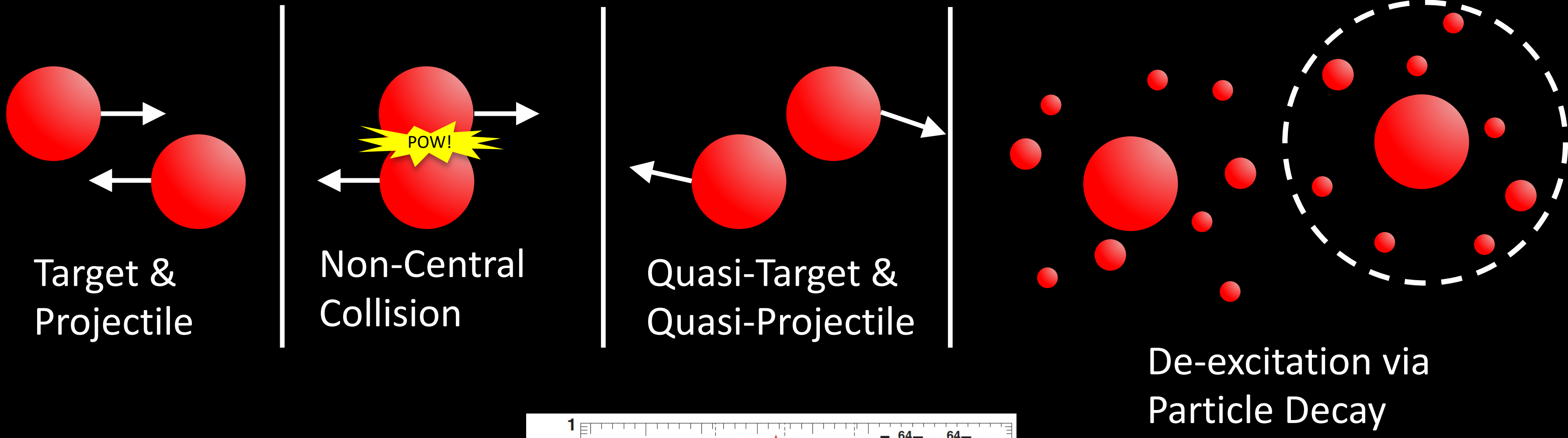
H. Zheng & A. Bonasera, PLB **696**, 178 (2011)
S. Wuenschel, NPA 843, 1 (2010)
S. Wuenschel Ph.D. Thesis, TAMU (2009)



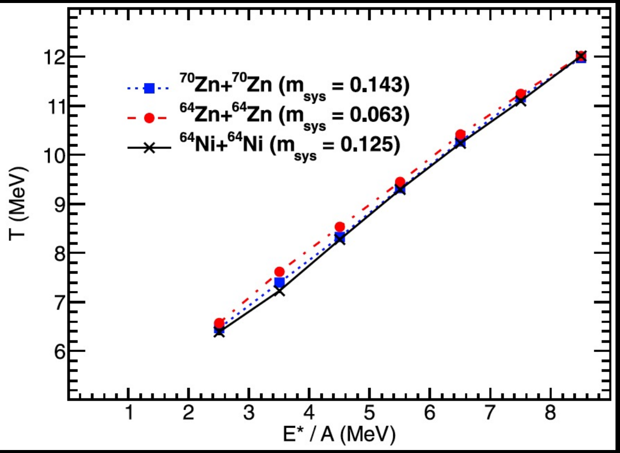


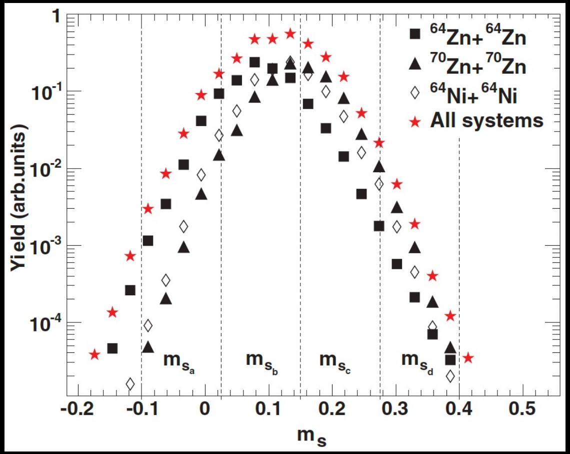
Decrease of ~ 1 MeV for changing four protons into neutrons

McIntosh et al
PLB 719 (2013) 337
PRC 87 (2013) 034617
EPJA 50 (2014) 35
Marini et al
PRC 85 (2012) 034617



System composition

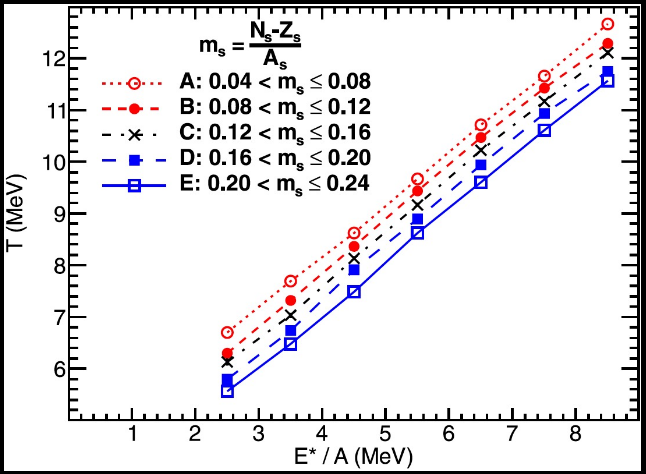




McIntosh et al
PLB 719 (2013) 337
PRC 87 (2013) 034617
EPJA 50 (2014) 35
Marini et al
PRC 85 (2012) 034617

Either way:
neutron rich -> lower T

Composition of reconstructed source

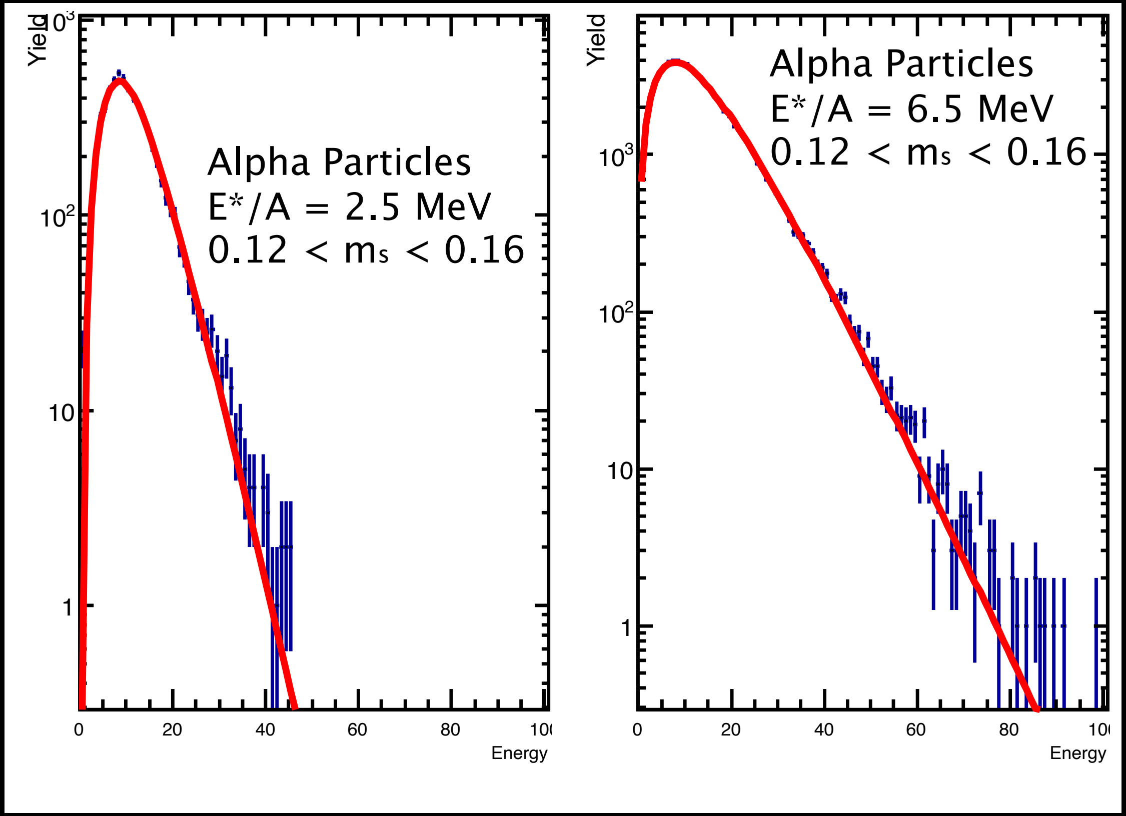


Albergo Chemical Thermometer

	H/He	Li/He
Double yield ratio	$R = \frac{Y(d)/Y(t)}{Y(h)/Y(\alpha)}$	$R = \frac{Y(6Li)/Y(7Li)}{Y(h)/Y(\alpha)}$
Account for binding energy differences and spin-degeneracies	$T_{raw} = \frac{14.3MeV}{\ln(1.59R)}$	$T_{raw} = \frac{13.3MeV}{\ln(2.18R)}$
~3% correction for secondary decay	$T = \frac{1}{\frac{1}{T_{raw}} - 0.0097}$	$T = \frac{1}{\frac{1}{T_{raw}} + 0.0051}$

Albergo et al., Il Nuovo Cimento **89**, 1 (1985)
Xi et al. PRC **59**, 1567 (1999)

Slope Temperatures



Maxwell-Boltzmann with
Diffuse Barrier

Form: Yanez, Phys. Rev. C 68, 011602(R) (2003)

Asymmetry Dependent Temperature

Physics Letters B 719 (2013) 337–340
Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Asymmetry dependence of the nuclear caloric curve

A.B. McIntosh[a,*], A. Bonasera[a,b], P. Cammarata[a,c], K. Hagel[a], L. Heilborn[a,c], Z. Kohley[a,c,1], J. Mabiala[a], L.W. May[a,c], P. Marini[a,2], A. Raphelt[a,c], G.A. Souliotis[a,d], S. Wuenschel[a,c], A. Zarrella[a,c], S.J. Yennello[a,c]

PHYSICAL REVIEW C **87**, 034617 (2013)

Using light charged particles to probe the asymmetry dependence of the nuclear caloric curve

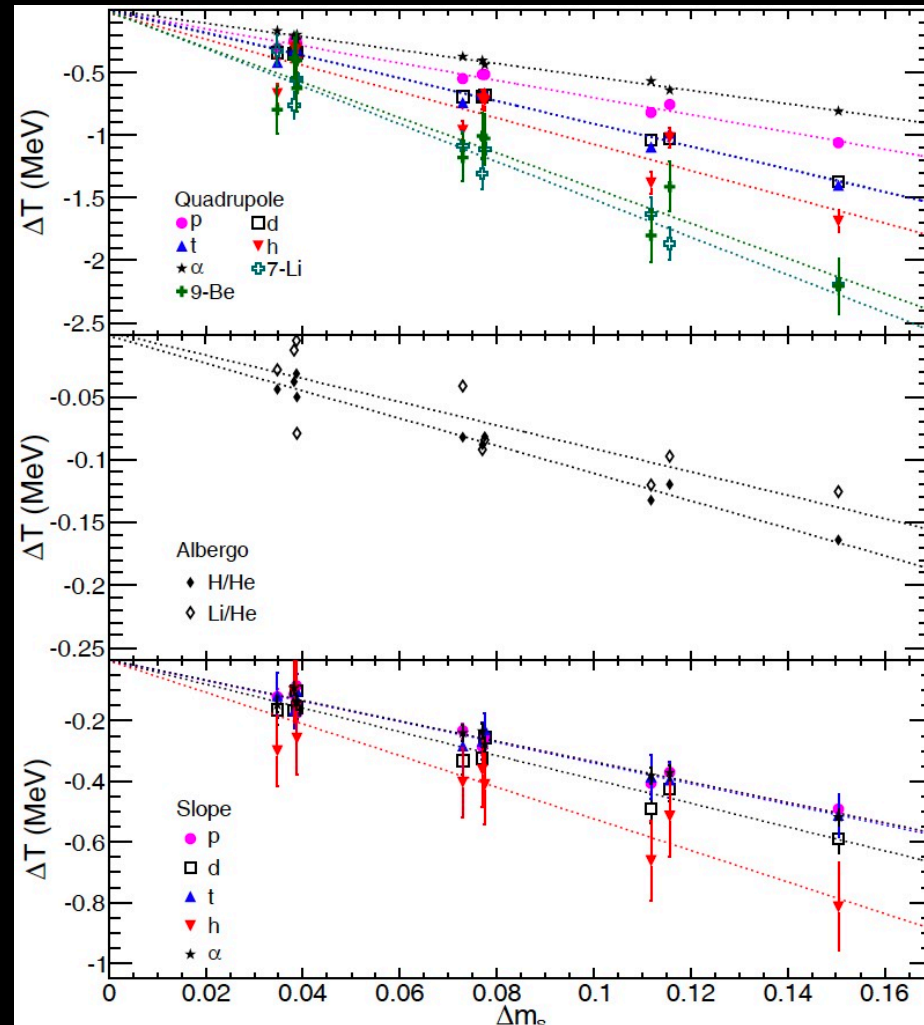
A. B. McIntosh,[1,*] A. Bonasera,[1,2] Z. Kohley,[1,3,†] P. J. Cammarata,[1,3] K. Hagel,[1] L. Heilborn,[1,3] J. Mabiala,[1] L. W. May,[1,3] P. Marini,[1,‡] A. Raphelt,[1,3] G. A. Souliotis,[1,4] S. Wuenschel,[1,3] A. Zarrella,[1,3] and S. J. Yennello[1,3]

Eur. Phys. J. A (2014) **50**: 35
DOI 10.1140/epja/i2014-14035-8
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article – Experimental Physics

How much cooler would it be with some more neutrons?*

Exploring the asymmetry dependence of the nuclear caloric curve and the liquid-gas phase transition

A.B. McIntosh[1,a], J. Mabiala[1], A. Bonasera[1,2], P. Cammarata[1,3], K. Hagel[1], Z. Kohley[1,3,4], L. Heilborn[1,3], L.W. May[1,3], P. Marini[1,5], A. Raphelt[1,3], G.A. Souliotis[1,6], S. Wuenschel[1,3], A. Zarrella[1,3], H. Zheng[1,7], and S.J. Yennello[1,3]

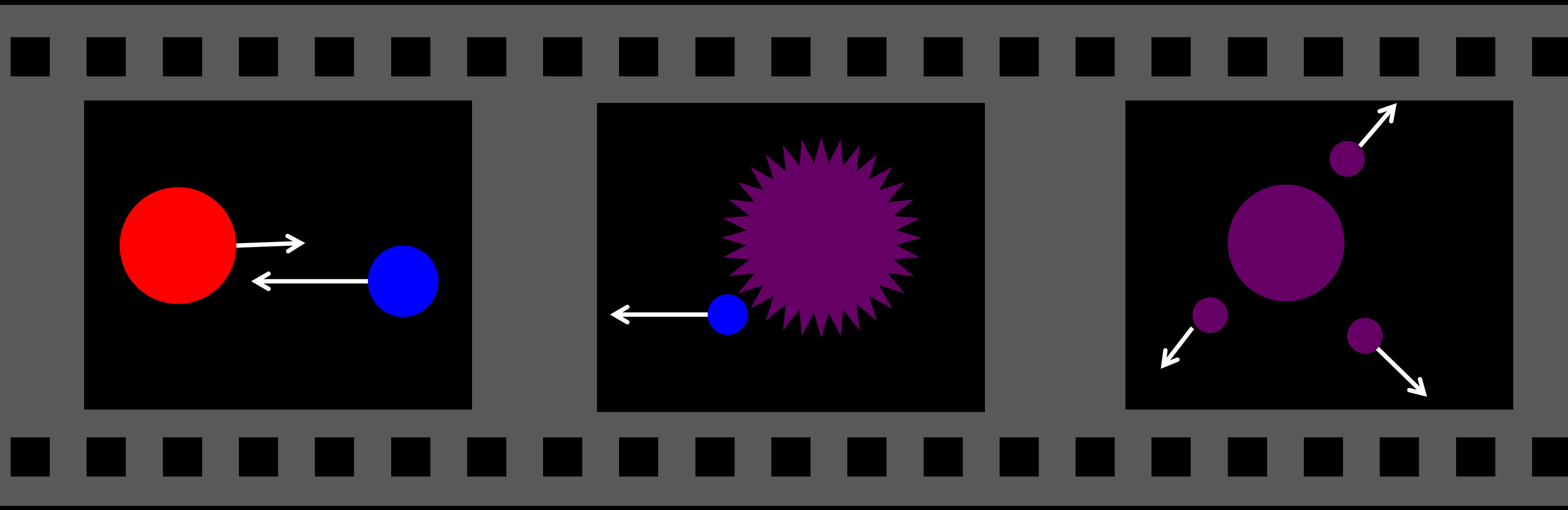


The Fusion-Evaporation Reactions

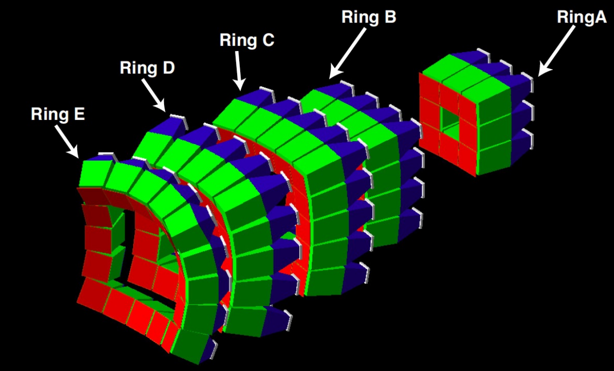
$^{78}Kr + {}^{12}C$

$^{86}Kr + {}^{12}C$

E/A = 15, 25, 35 MeV



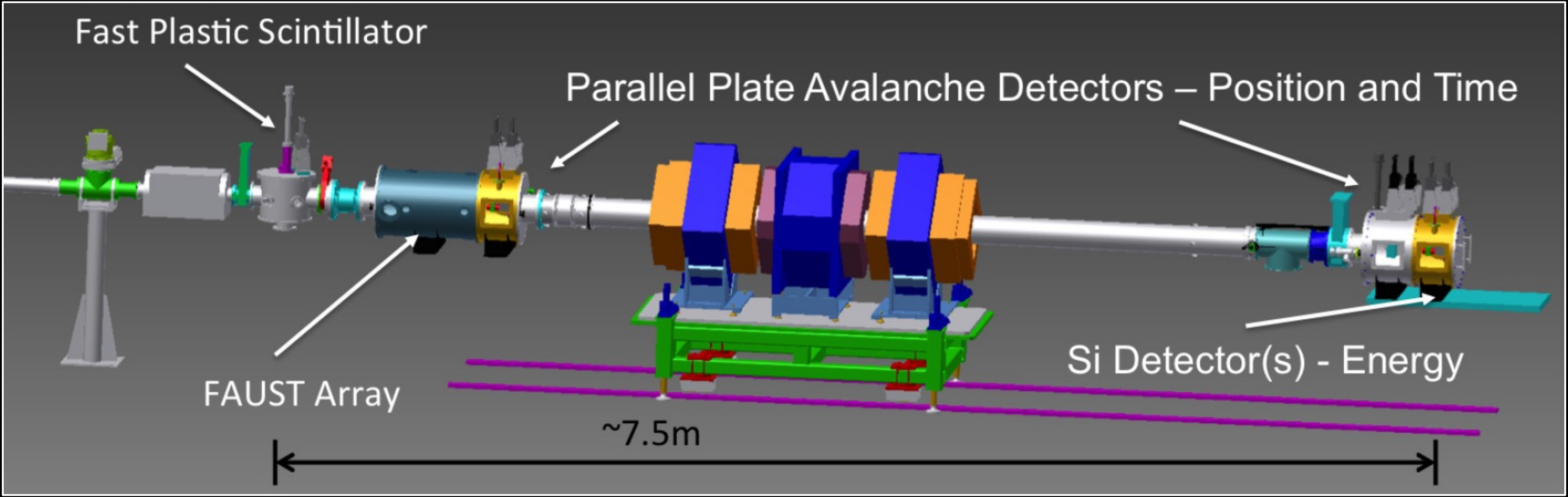
Experimental Configuration



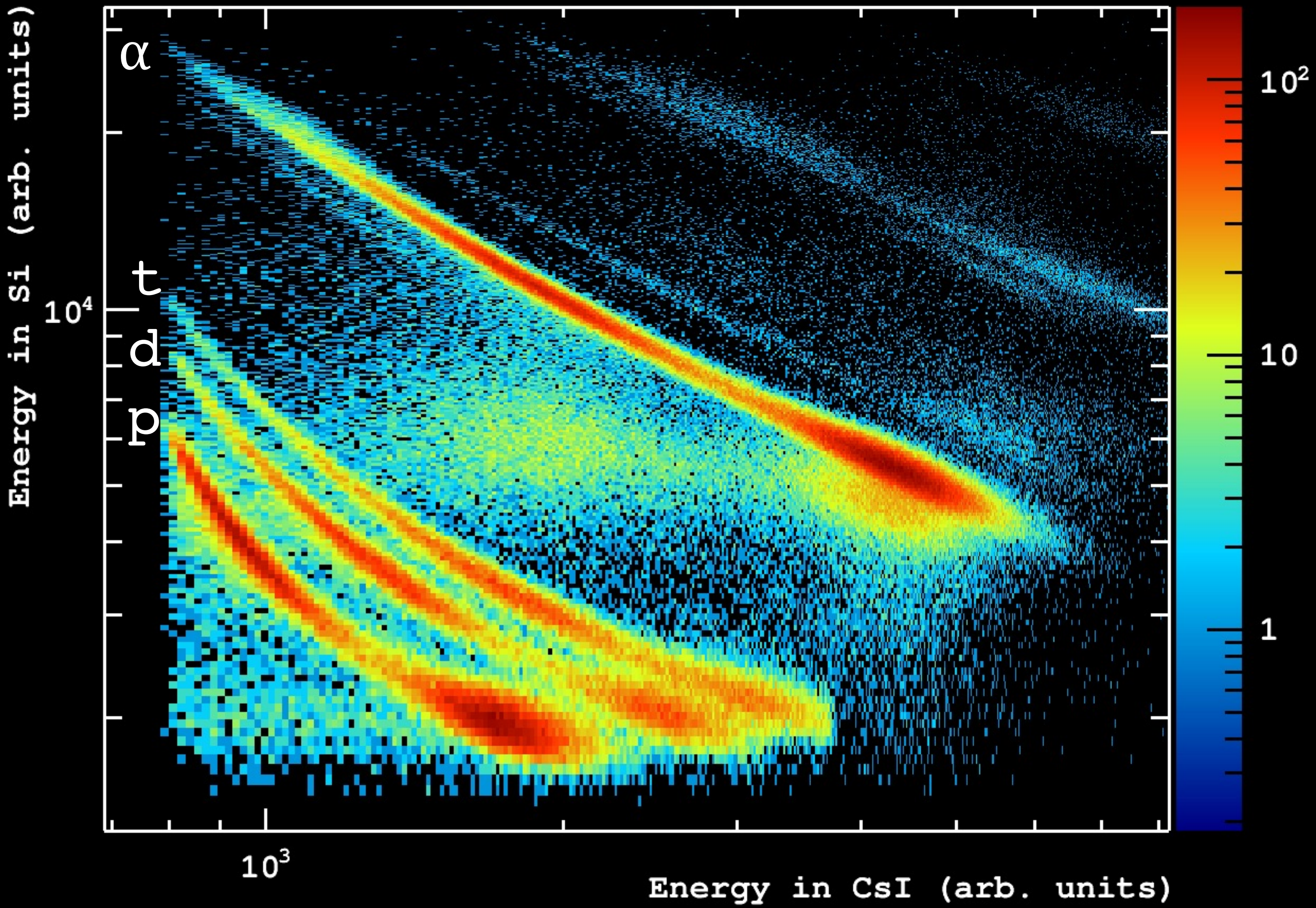
FAUST
Measure Light Charged Particles
Position-Sensitive
ΔE, E → Z, A, Energy
$1.6° \leq \theta \leq 45°$

Quadrupole Triplet Spectrometer
Measure Fusion-Evaporation Residues
Time-Of-Flight → Velocity
$0.9° \leq \theta \leq 2.3°$

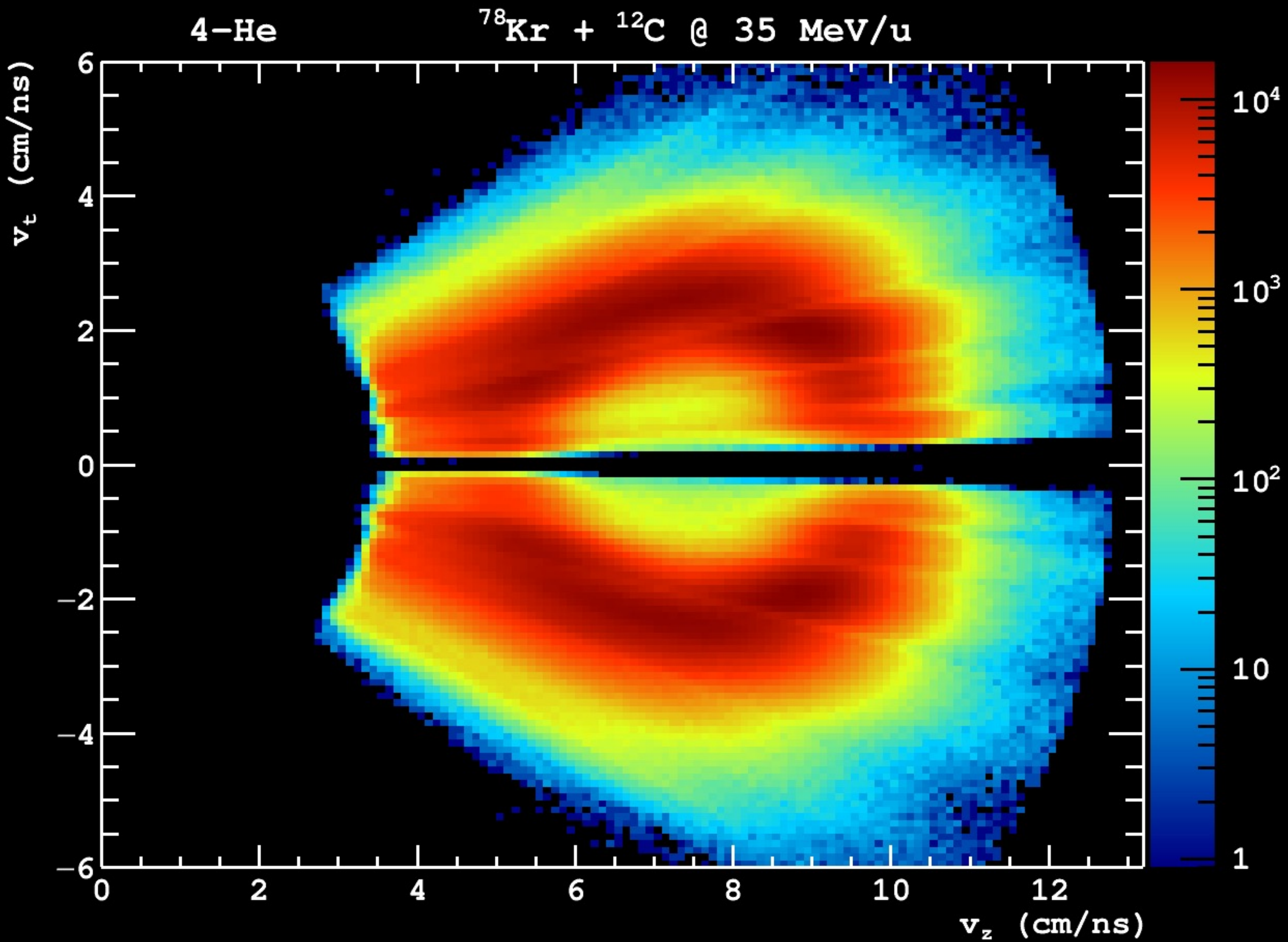
P. Cammarata et al., NIMA 792 (2015) 61
L.A. McIntosh et al., NIMA 985 (2020) 164642



FAUST Particle ID

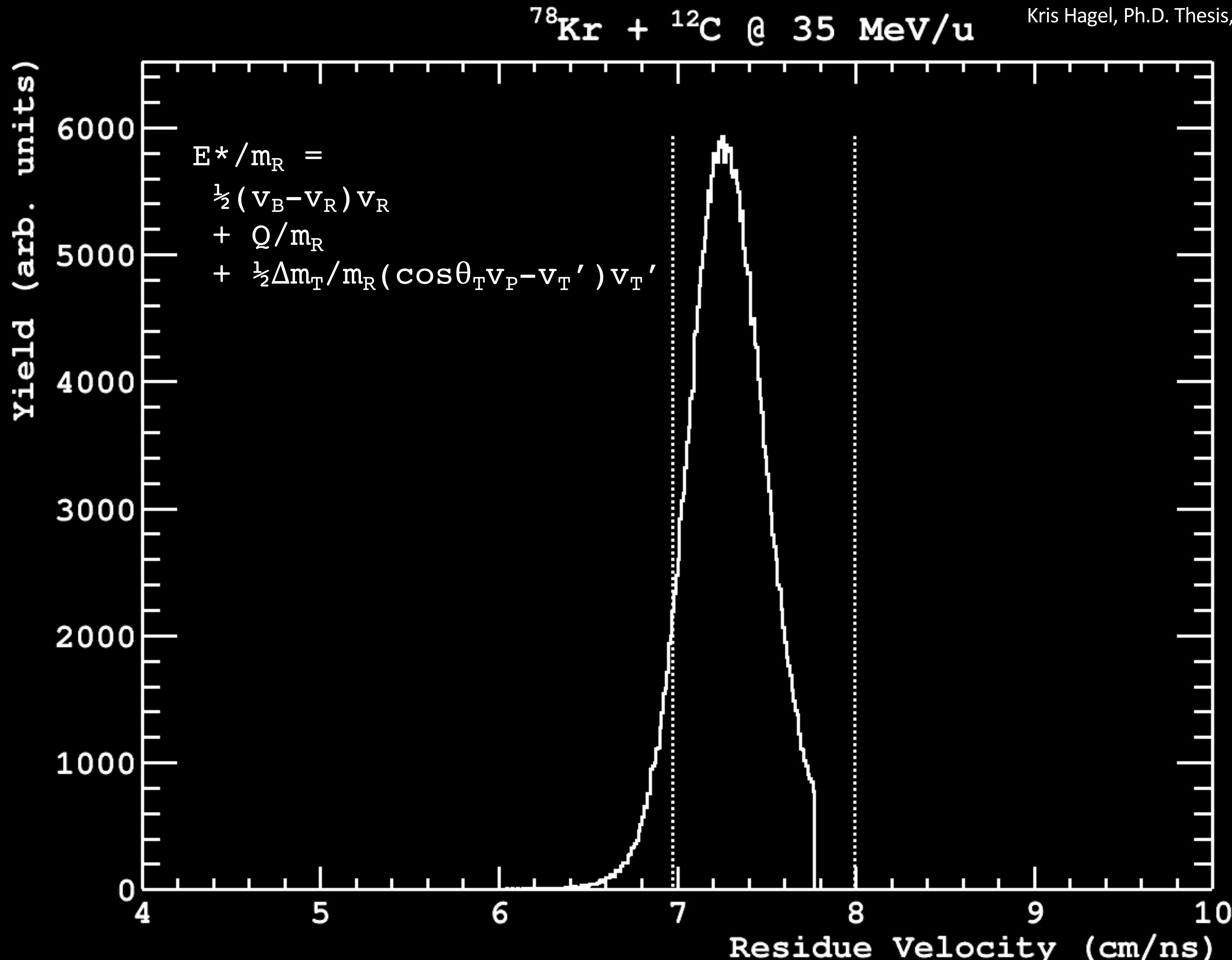


Measured Alpha-Particle Velocity

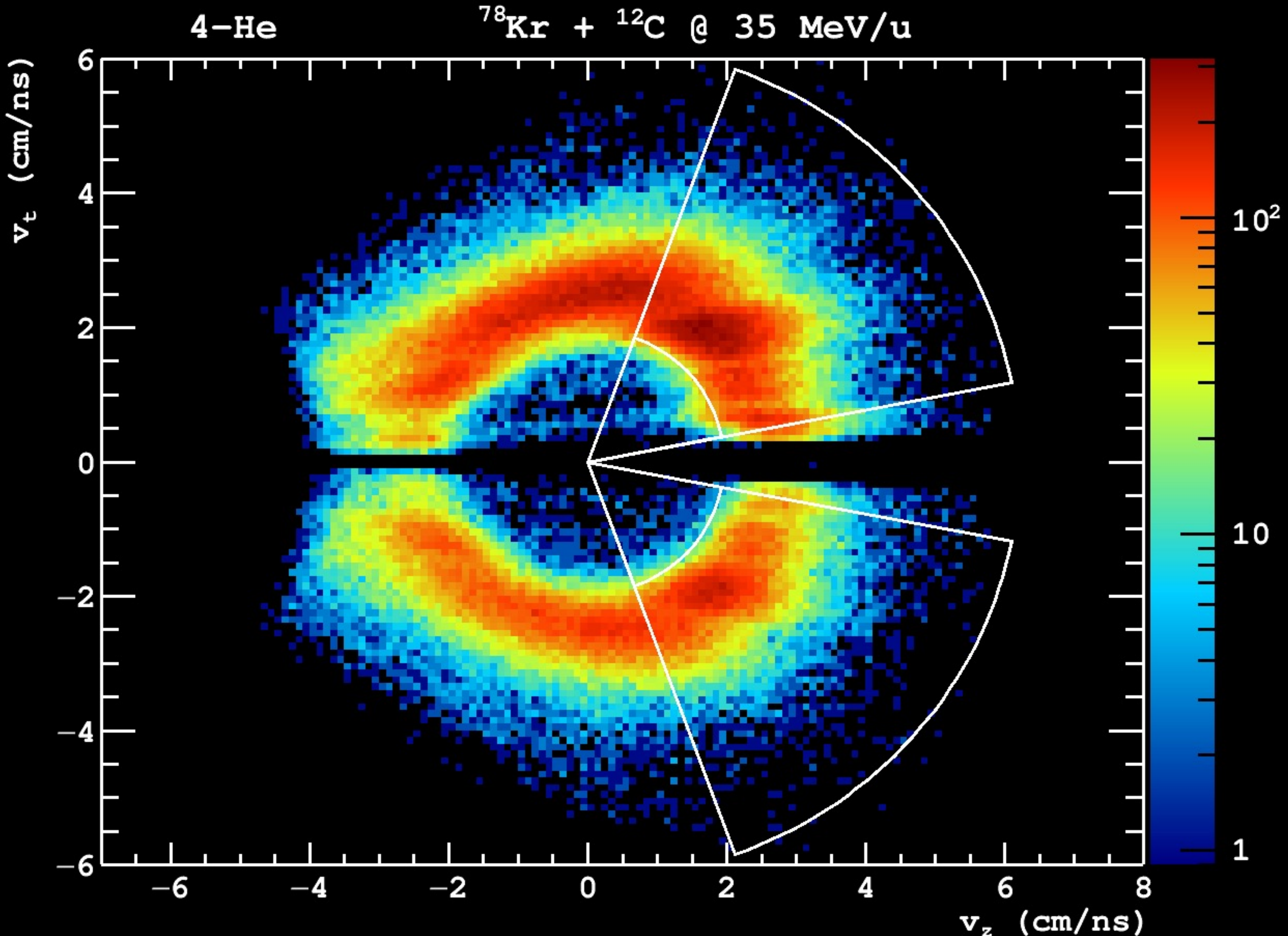


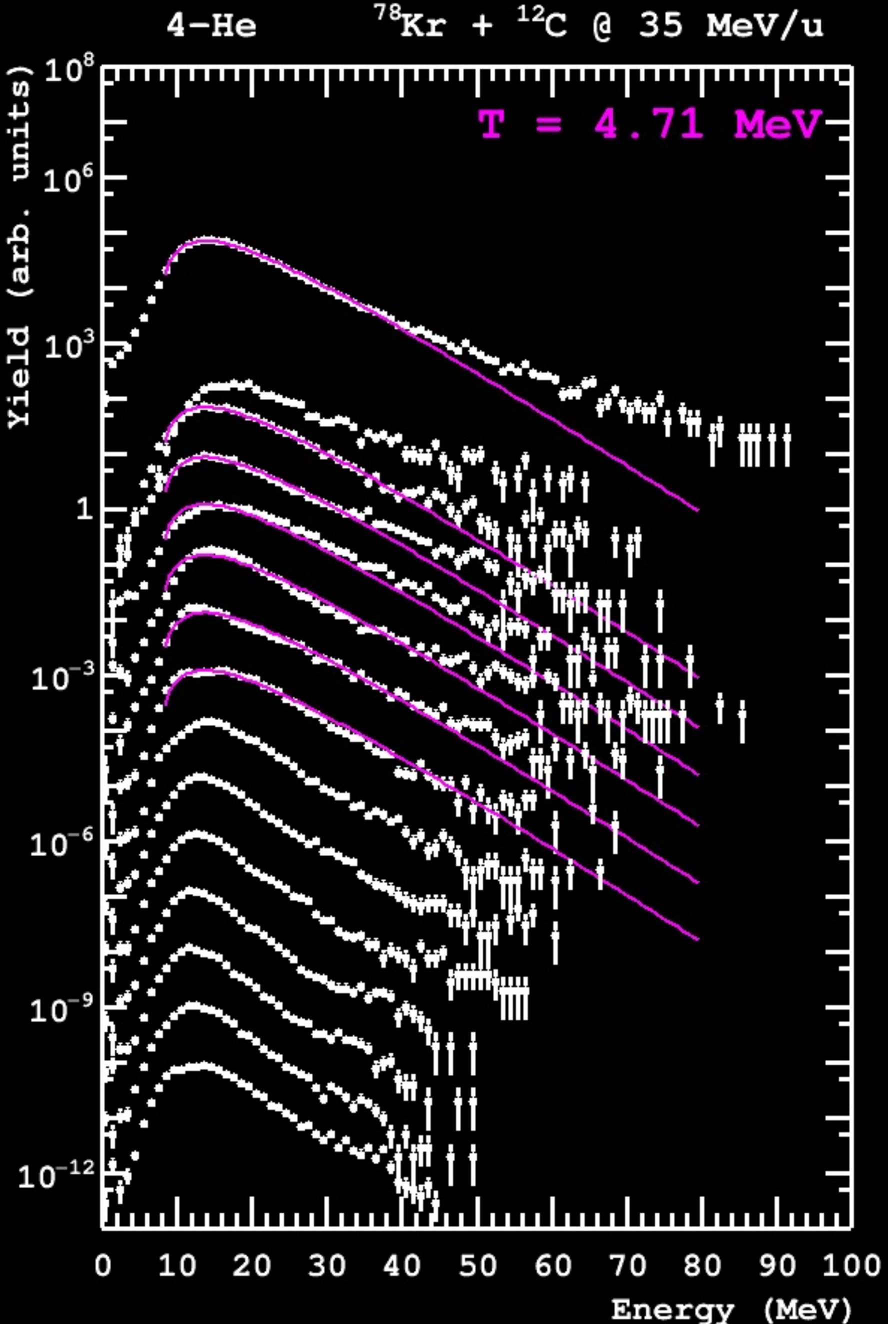
Excitation Energy

E* Formula:
W. Bohne et al. Phys. Rev. C 41 (1990) R41
D. Fabris et al. Phys. Lett. B 196 (1987) 429
Kris Hagel, Ph.D. Thesis, TAMU



Alpha-Particle Velocity – Residue Frame





Alpha-Particle Energy

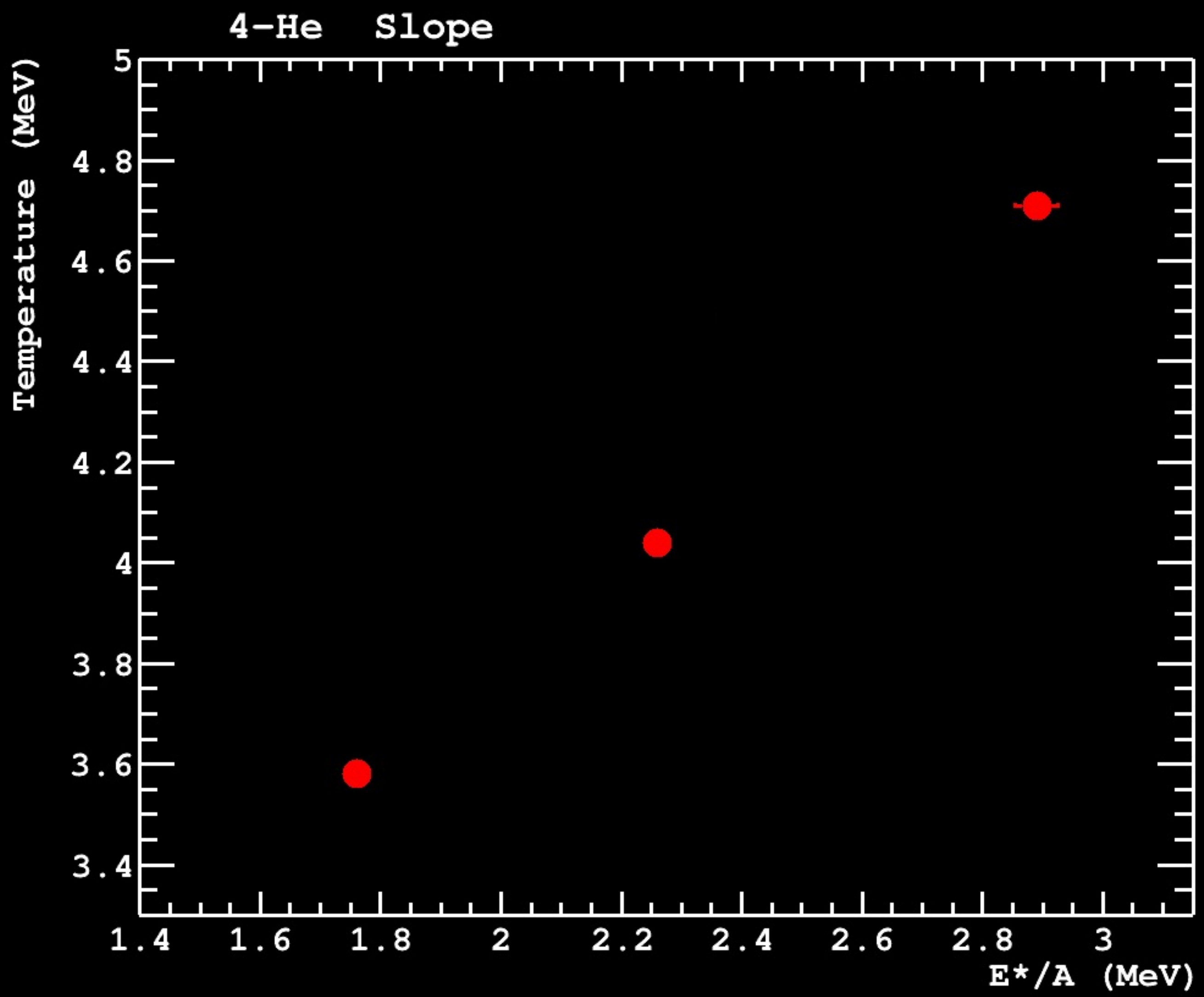
Boltzmann with Diffuse Barrier
8<E<80 MeV
10° < θ < 70°

10° < θ < 70°

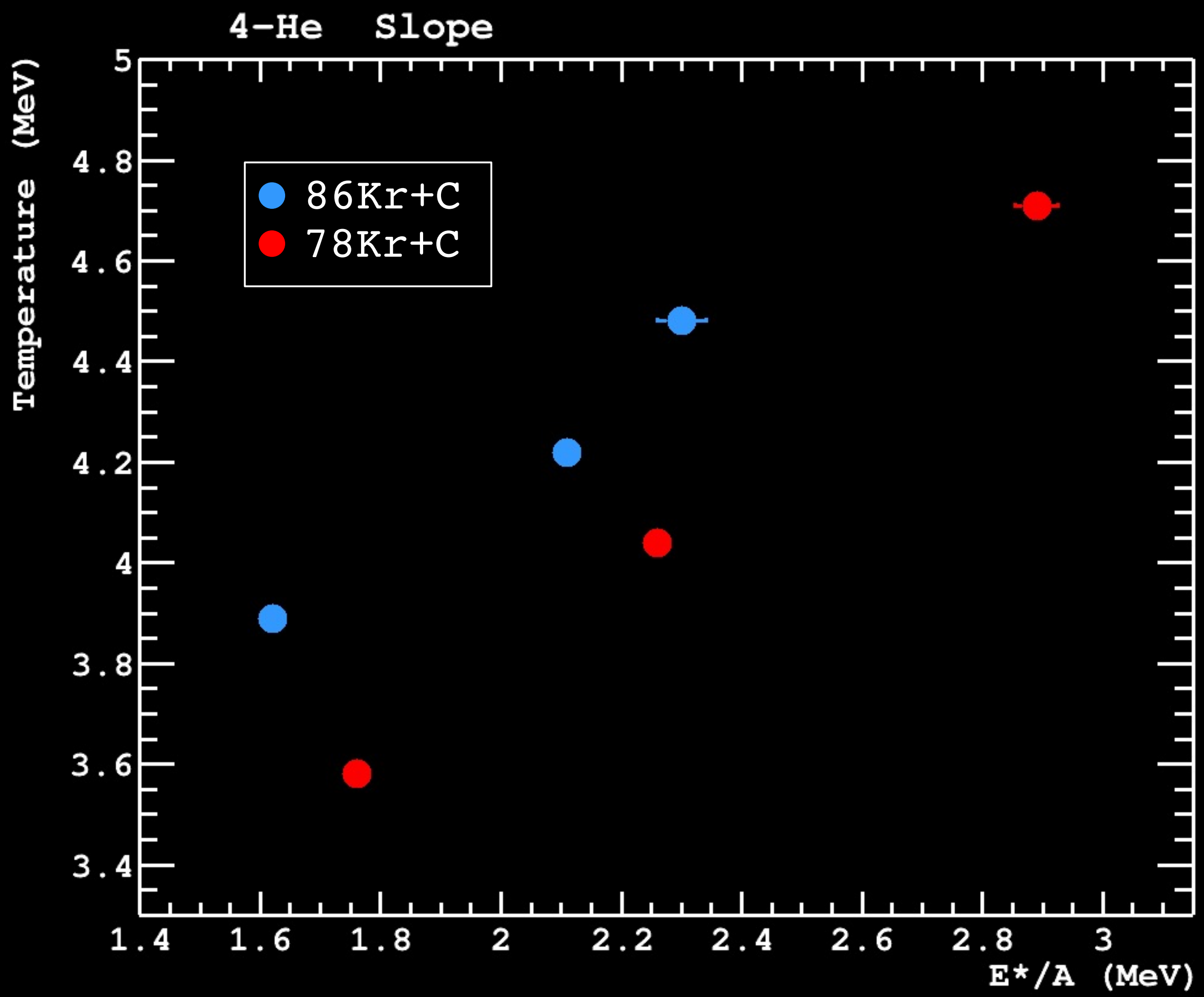
0° < θ < 10°
10° < θ < 20°
20° < θ < 30°
40° < θ < 50°
…

130° < θ < 140°

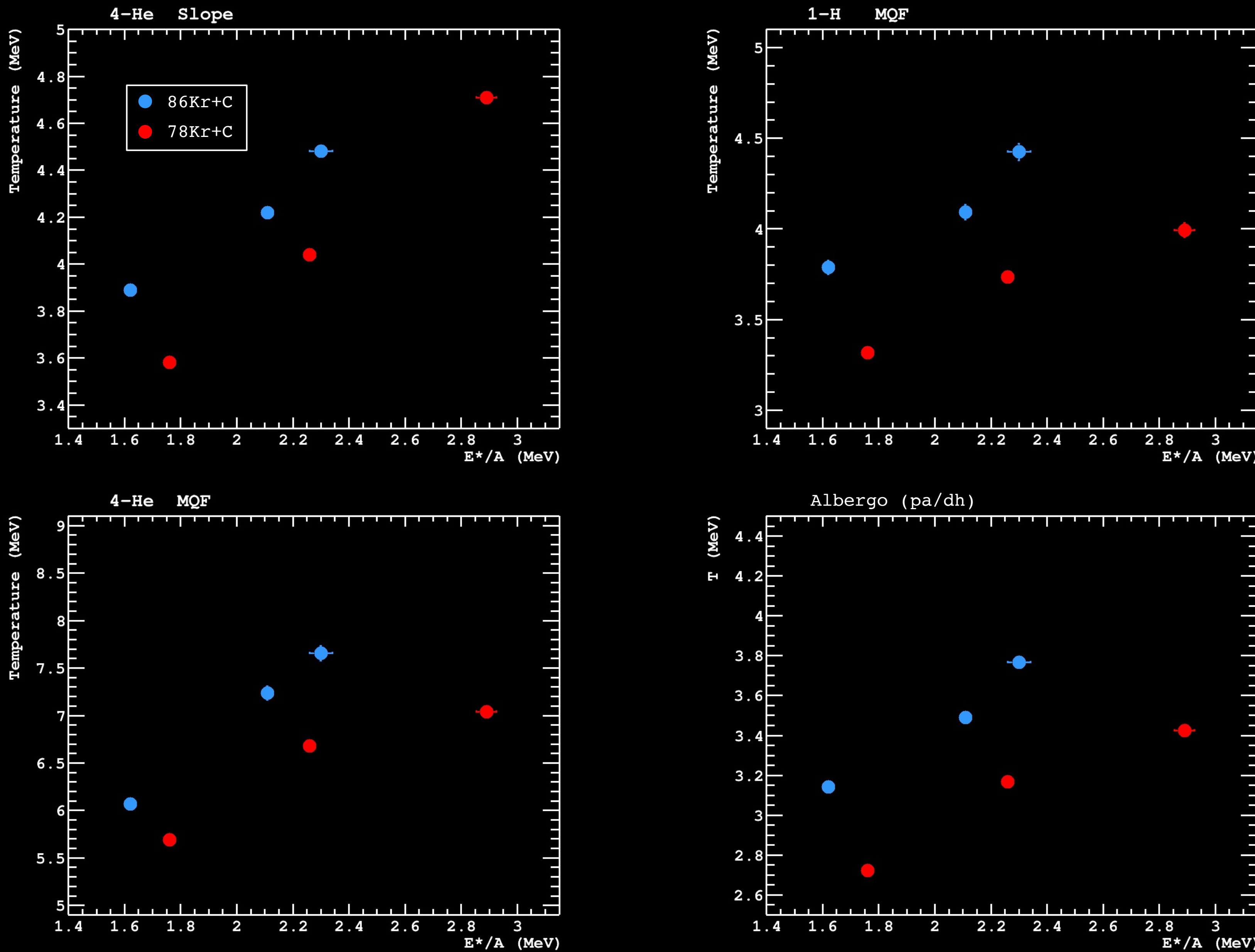
Temperature in Fusion-Evaporation Rxns

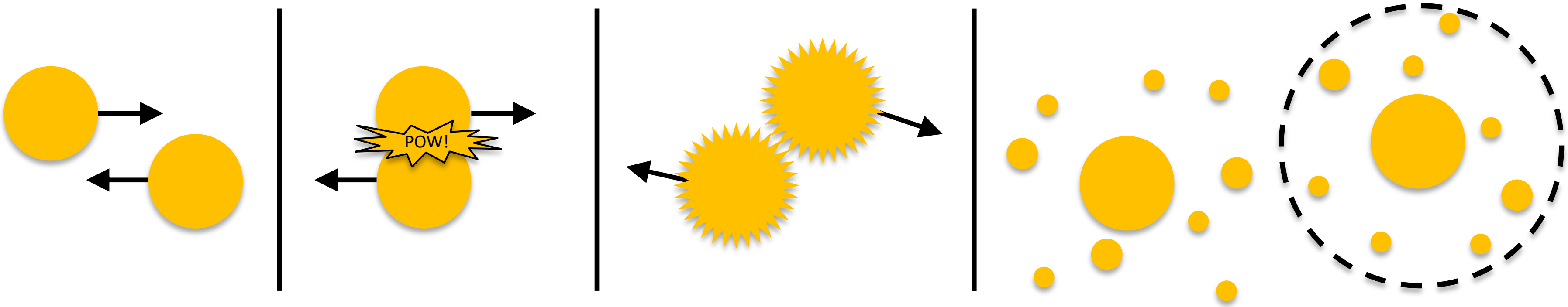


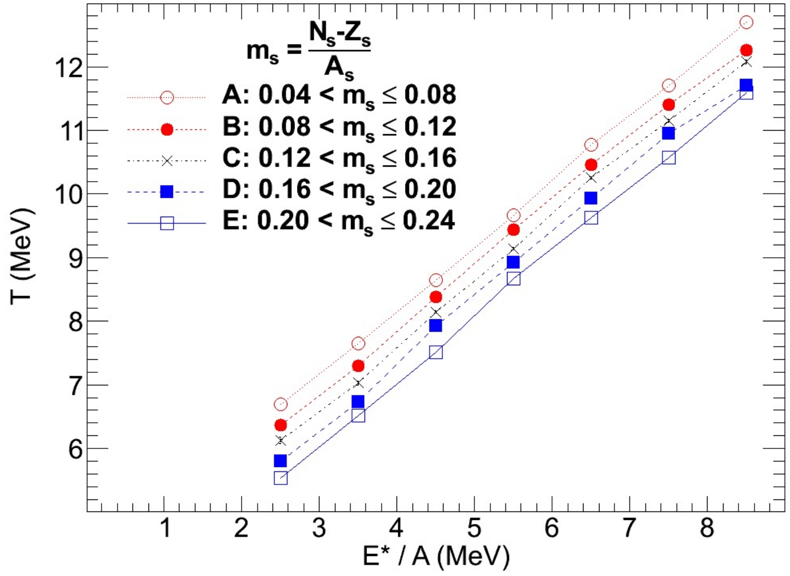
Temperature in Fusion-Evaporation Rxns

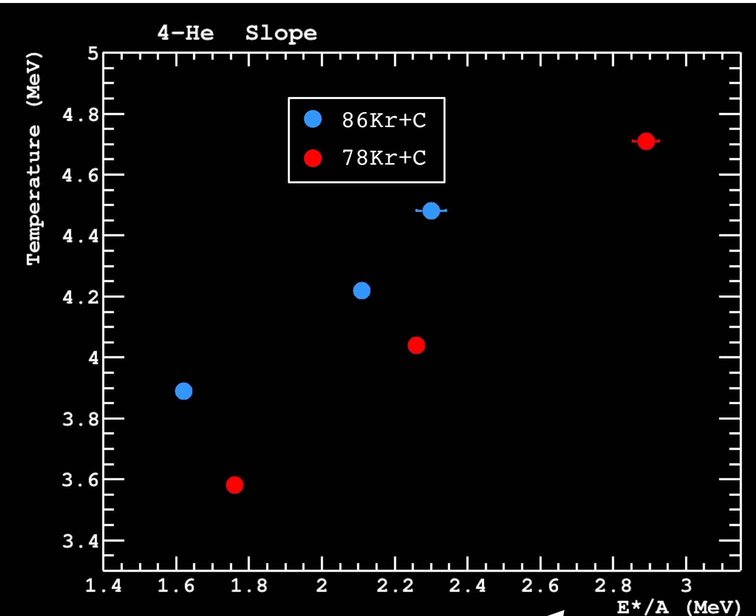


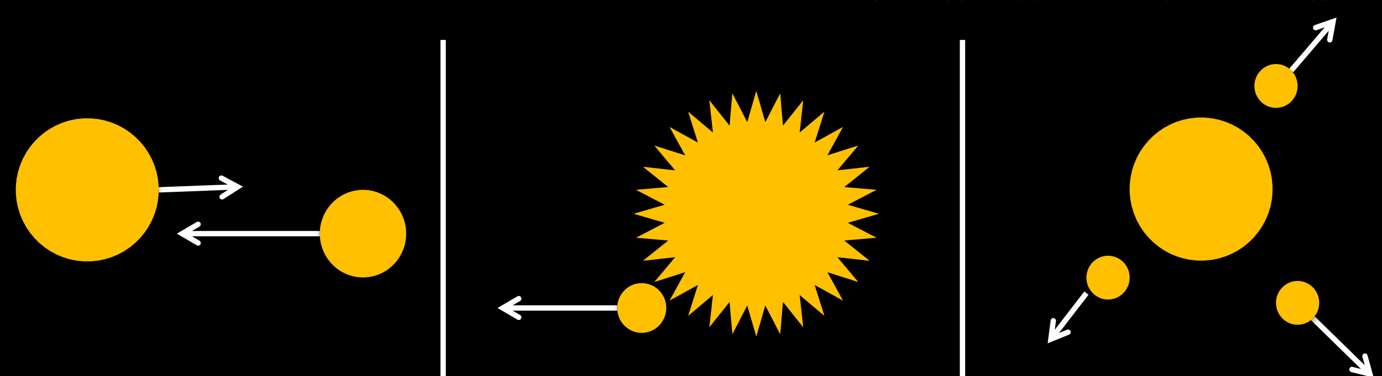
Temperature in Fusion-Evaporation Rxns




POW!


$m_s = \frac{N_s - Z_s}{A_s}$
A: $0.04 < m_s \leq 0.08$
B: $0.08 < m_s \leq 0.12$
C: $0.12 < m_s \leq 0.16$
D: $0.16 < m_s \leq 0.20$
E: $0.20 < m_s \leq 0.24$
T (MeV)
E* / A (MeV)


4-He Slope
86Kr+C
78Kr+C
Temperature (MeV)
E*/A (MeV)



Nuclear Equation of State
Nuclear Caloric Curve
Asymmetry Dependence

Theory:
some say cooler with more neutrons, some say hotter

Experiment without reconstruction:
Slight suggestion of higher T for neutron-rich

Reconstructed Quasi-Projectiles in HI Collisions
Lower T for neutron-rich

Fusion Reactions (78,86Kr+C @ 15,25,35 MeV/u)
Higher T for more neutron rich

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Yennello Research Group

A. Abbott, P. Cammarata, M. Chapman, J. Gauthier, K. Hagel, A. Hannaman, B. Harvey, A. Hood, M. Huang, A. Jedele, A. Keeler, L.A. McCann, A.B. McIntosh, L.A. McIntosh, Y.W. Lui, L.W. May, E. McCleskey, A. Paulson, A. Rodriguez Manso, S.J. Schultz, M. Sorensen, Z. Tobin, R. Wada, A. Wakhle, M.D. Youngs, A. Zarrella, K. Zegla, S.J. Yennello

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