How much cooler would it be with some more neutrons?

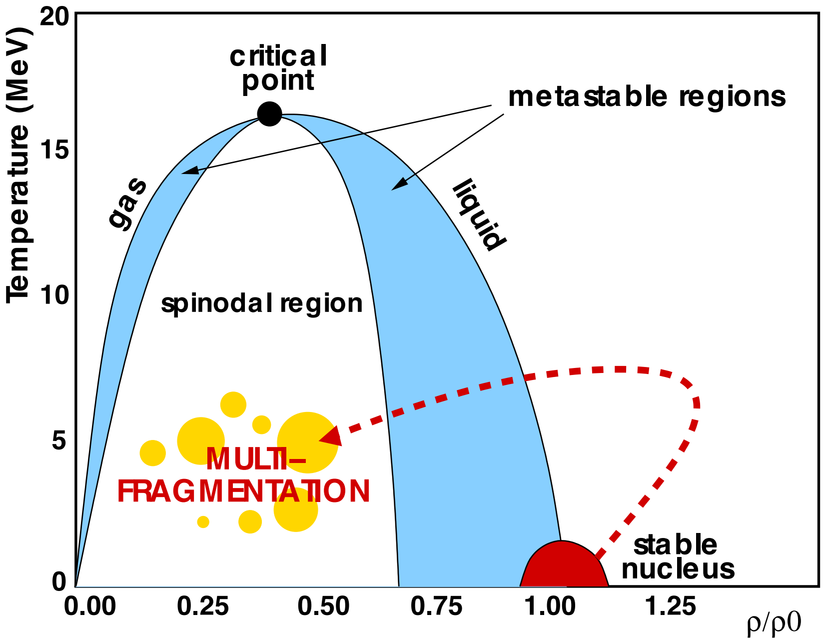
Asymmetry Dependence of the Nuclear Caloric Curve

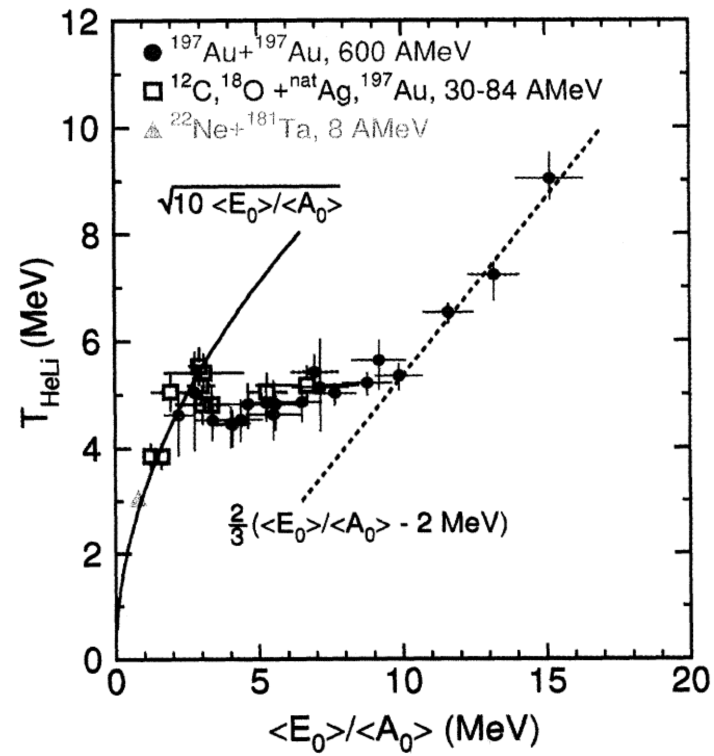
Alan McIntosh
Texas A&M University

- Nuclear Equation of State:
  Background and Motivation
- The Measurement:
  Reconstruction Excited Nuclei and Extracting Their Temperatures
- Results:
  Temperature Decreases Linearly with Neutron Content
- Plans:
  Independent Experiment to Measure the Effect is Set to Run

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

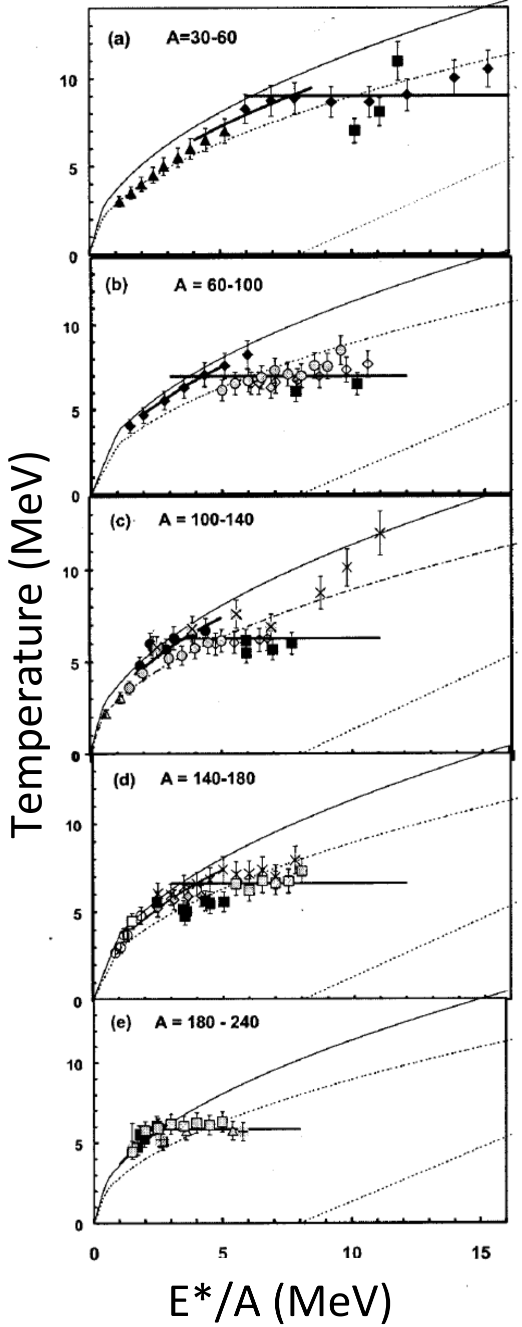
- ❖ Heavy Ion Collisions at All Energies
- ❖ Nuclear Structure (e.g. Resonances)
- ❖ Supernovae (nucleosynthesis
- ❖ Neutron Stars (Crust to Core)
- ➢ n-p Asymmetry Crucial





- 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. PRC, 034618 (2002)

MASS DEPENDENCE!

With increasing mass:

- Limiting Temperature decreases
- Onset of plateau at lower excitation

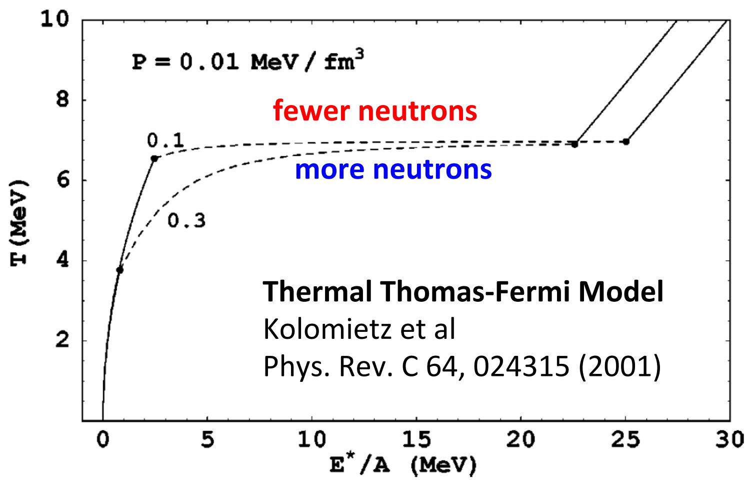
ASYMMETRY DEPENDENCE?

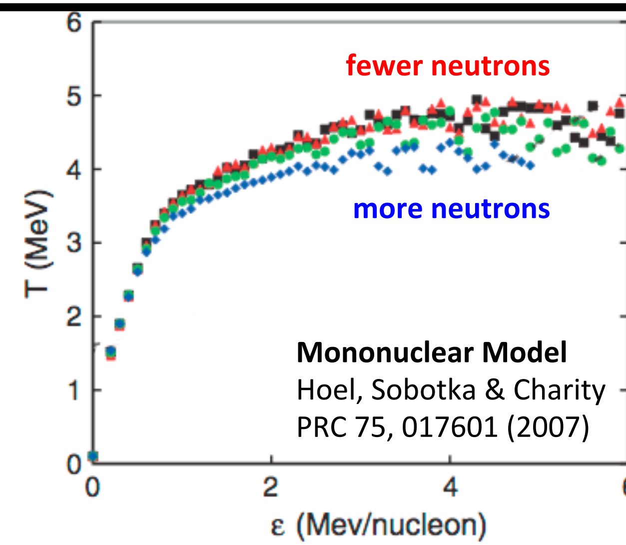
- Does an n-p Asymmetry Dependence Exist?
- Which way does it go?
- How strong is it?

Caloric Curve: Asymmetry Dependence?

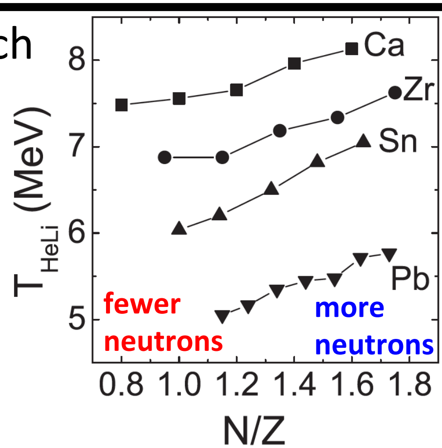
Theory Different models make very different predictions about how the caloric curve may depend on n-p asymmetry.

Neutron Rich
→ Lower T

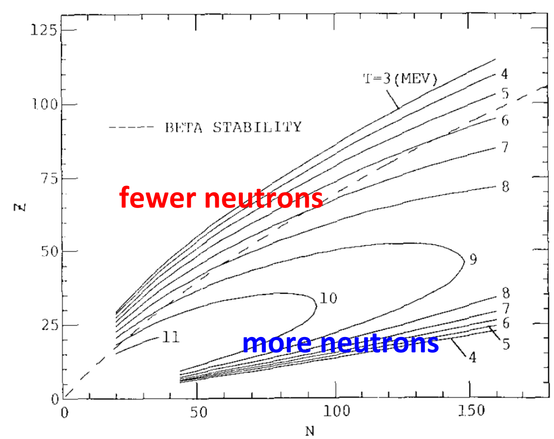




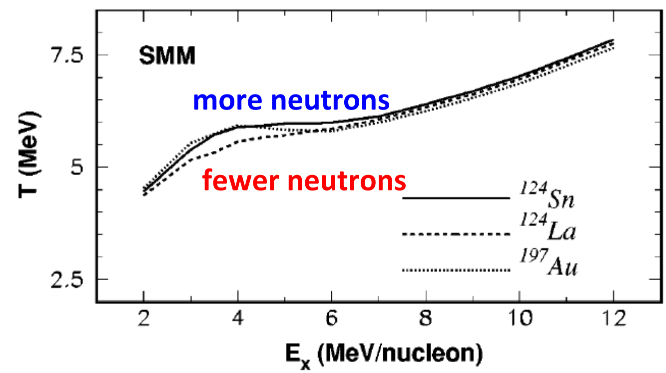
Neutron Rich
→ Higher T



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



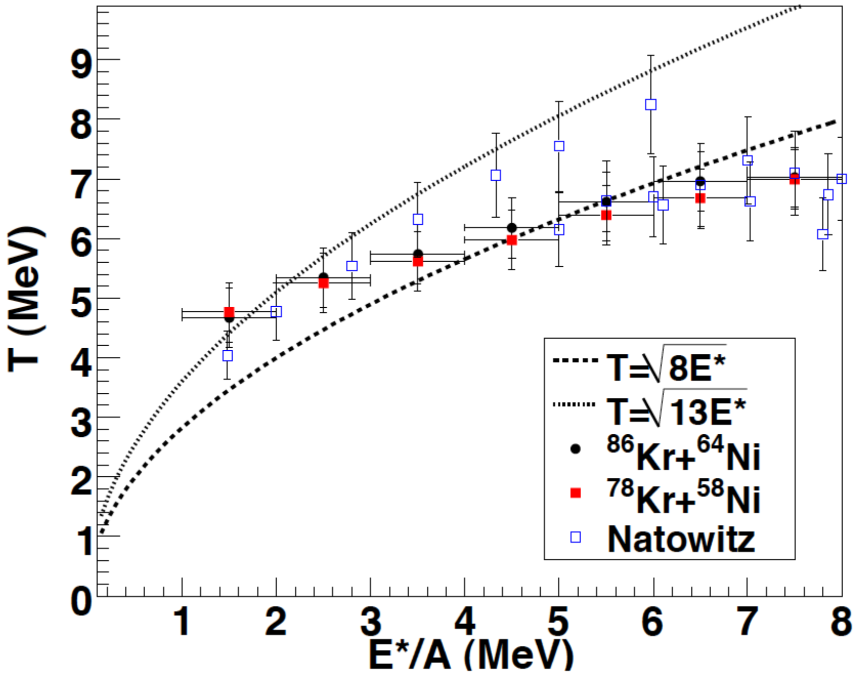
Hot Liquid Drop Model
Besprosvany & Levit
Phys. Lett B 217, 1 (1989)



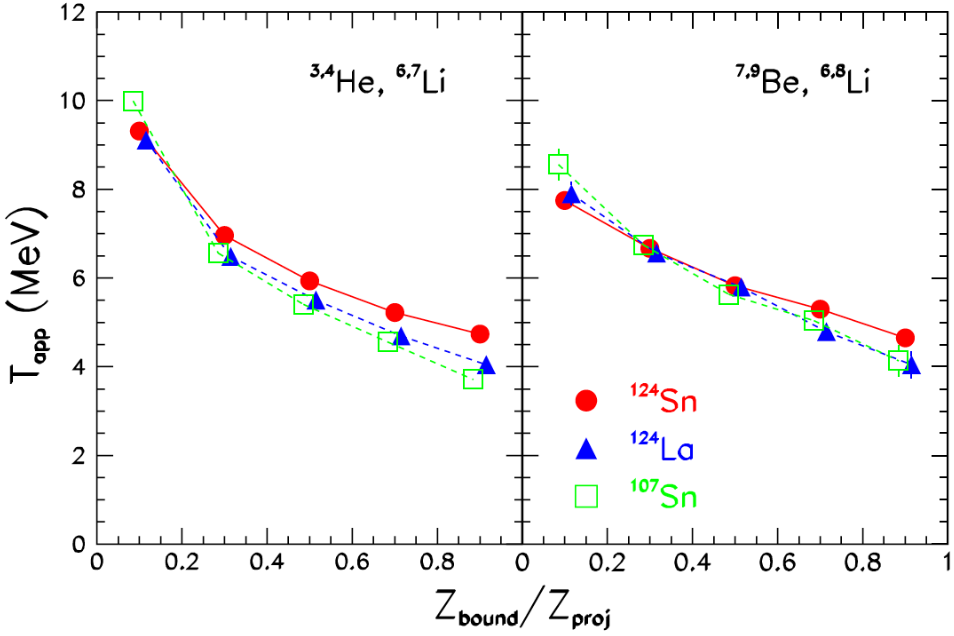
Statistical Multifragmentation Model
Ogul & Botvina
Phys. Rev. C 66, 051601 (2002)

Caloric Curve: Asymmetry Dependence?

Experiment



S. Wuenschel, Ph.D. Thesis, 2009



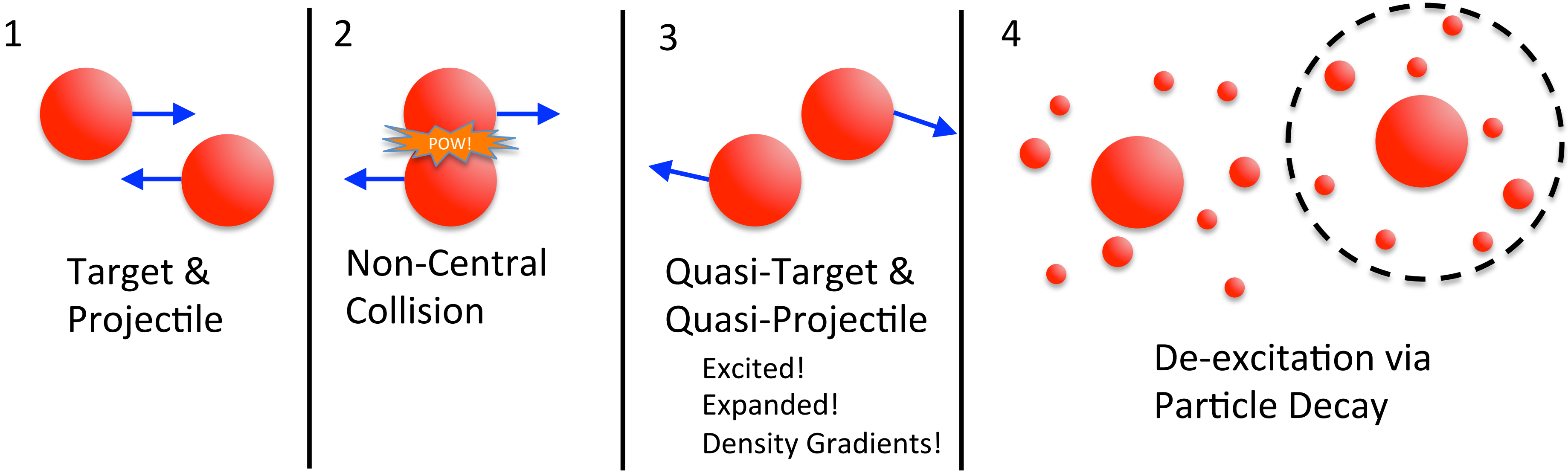
Sfienti et al., PRL 102, 152701 (2009)

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.
Should use **reconstructed-source composition**

Exciting Nuclear Matter!



The QP (quasi-projectile) is the primary excited fragment that exists momentarily after the nuclear collision

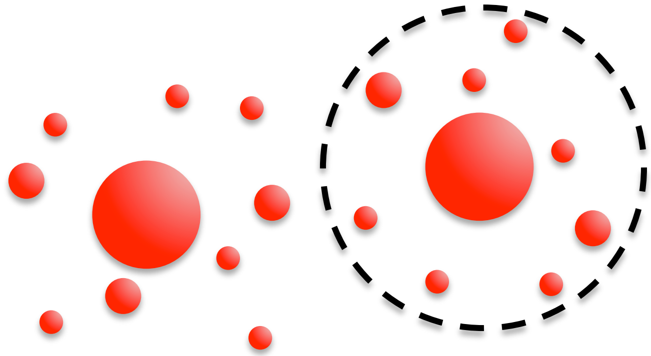
- We want to study the decay of the excited nuclear material (the QP)
- We use heavy ion collisions to create excited nuclear material
- From the reaction products, we reconstruct the QP

Experiment

- NIMROD-ISiS Array
  - Full Silicon Coverage (4π)
  - Isotopic Resolution to Z=17
  - Elemental Resolution to $Z_{projectile}$
  - Neutron Ball (4π)

70Zn + 70Zn
64Zn + 64Zn
64Ni + 64Ni
E = 35A MeV

QP Reconstruction



Goal: select events with an equilibrated source

1. **<u>Select particles</u>** that may comprise the QP
   - Charged particles & free neutrons
   - Phase space selection using velocity cut
   - Calculate Z, A, p, E*, and asymmetry = m_s = (N-Z)/A
2. **<u>Select mass</u>** (range) of the QP
3. **<u>Select on-average spherical QP</u>**

S. Wuenschel et al., Nucl. Inst. Meth. A 604 578 (2009)
Z. Kohley, Ph.D. Thesis, TAMU (2010)

Thermometer: MQF

Momentum Quadrupole Fluctuation Temperature

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, then

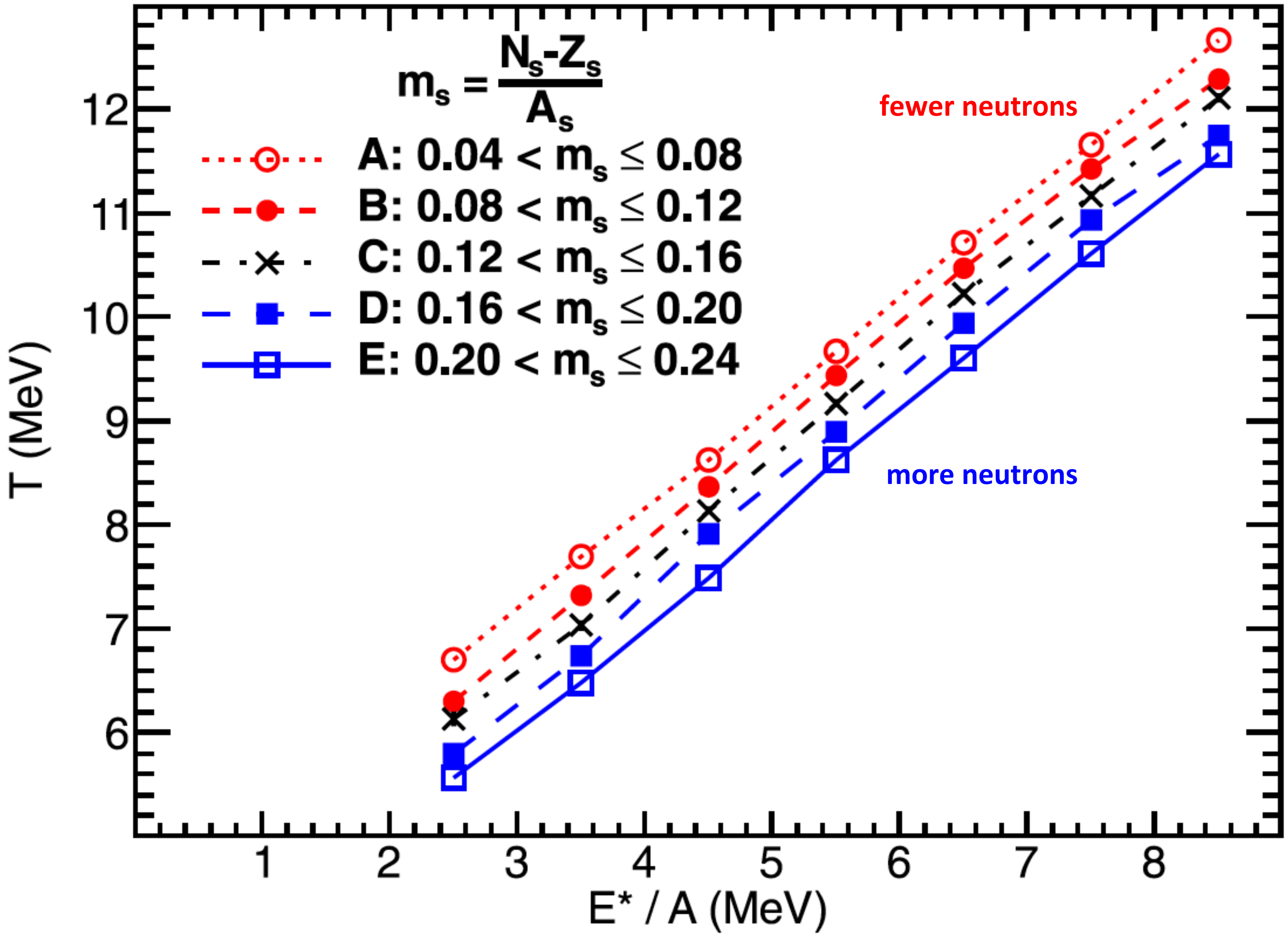
$$\sigma_{xy}^2 = 4m^2T^2$$

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

Asymmetry Dependent Temperature

MQF Thermometer, Protons as Probe

- $48 \leq A_{QP} \leq 52$
- 5 narrow asymmetry bins



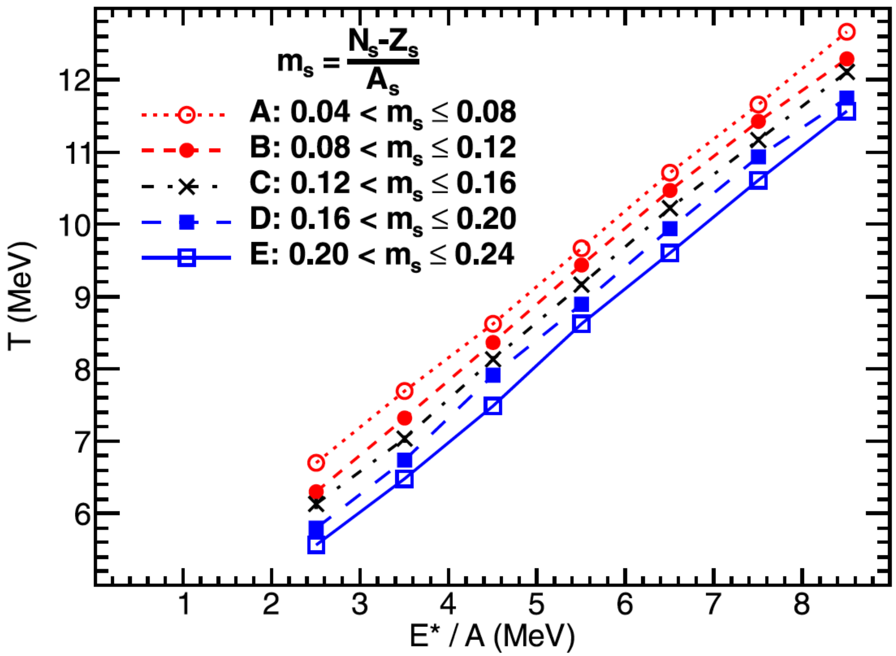
Larger Asymmetry
→ Lower Temperature

> 1 MeV shift!

Evenly Spaced

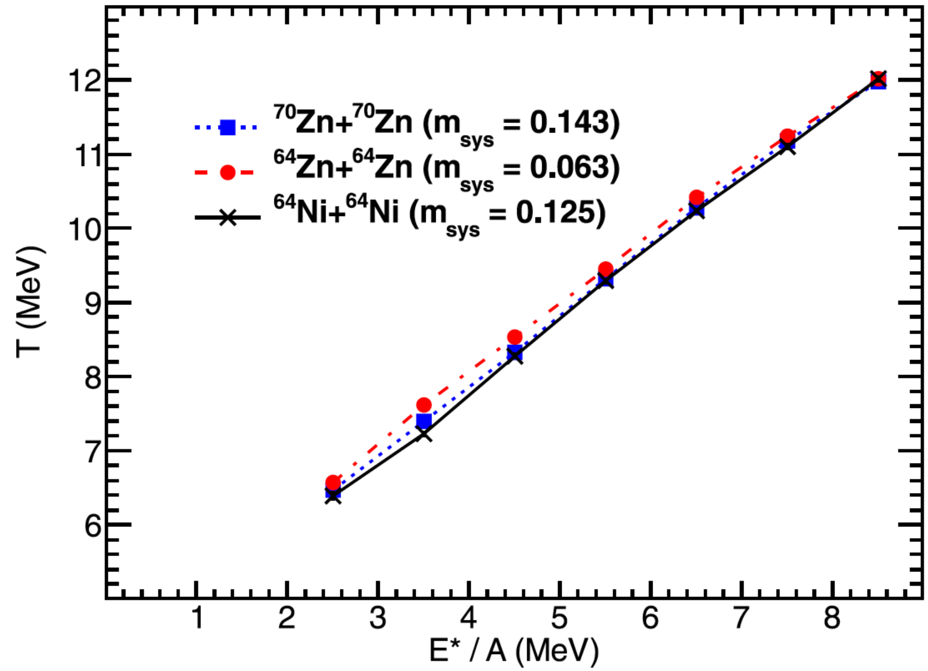
Importance of Reconstruction

Asymmetry of Isotopically Reconstructed Source



Asymmetry of Initial System

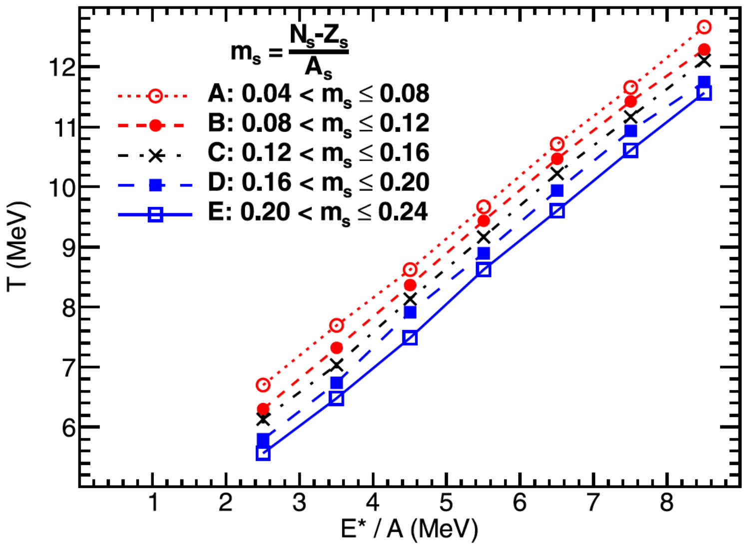
Each system may populate a broad range of QP asymmetry

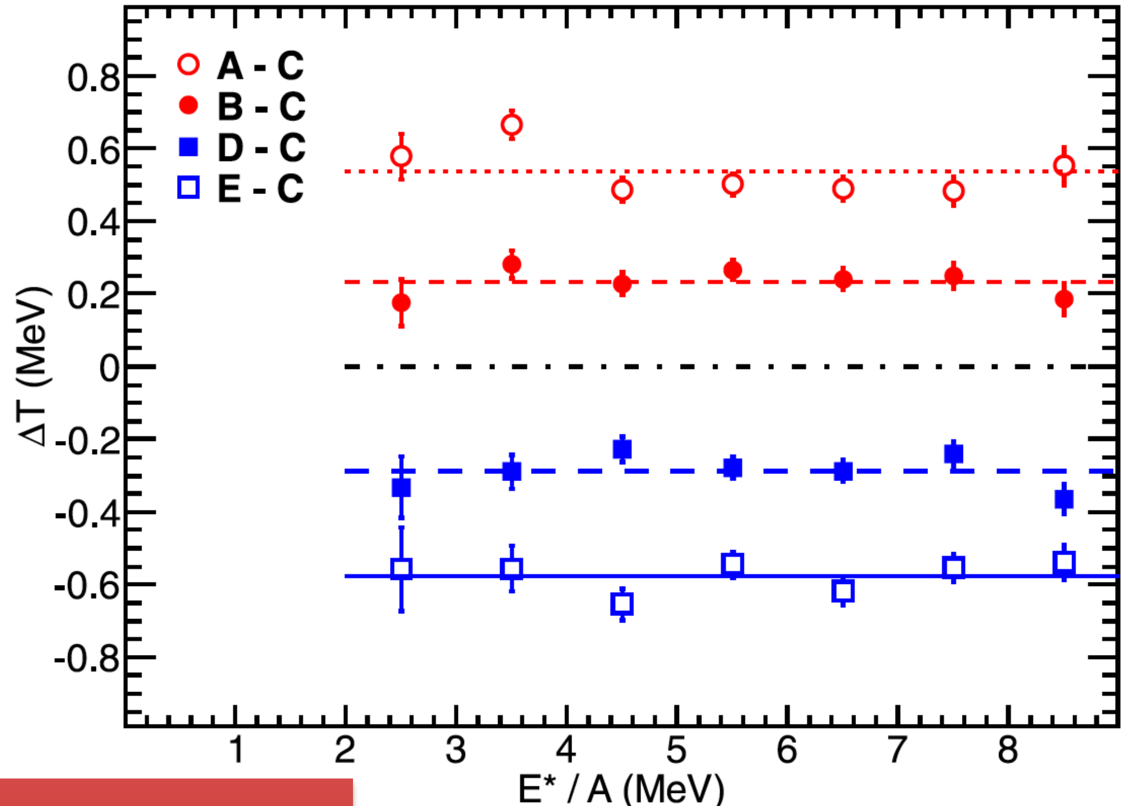


Larger Asymmetry
→ Lower Temperature
Observed either way, but...

Much more pronounced for selection on **source composition** rather than system composition

Excitation Independence



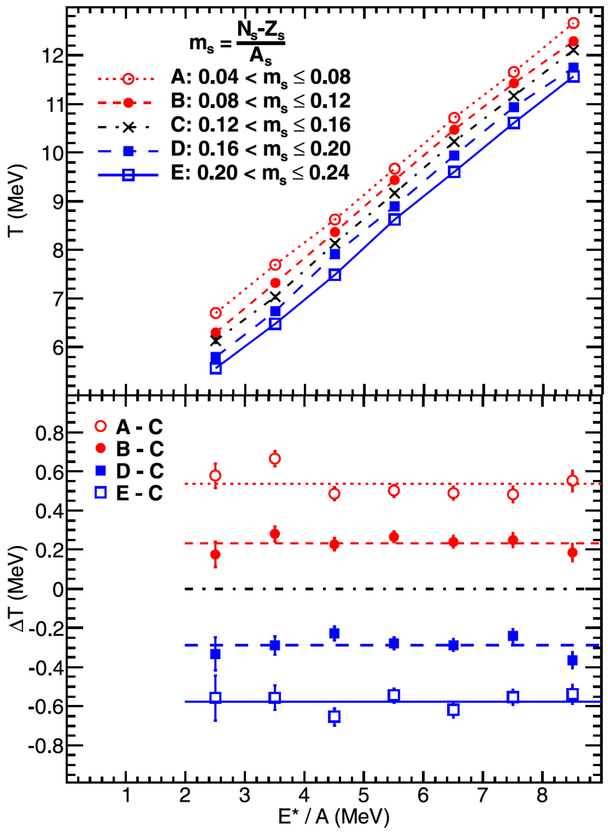


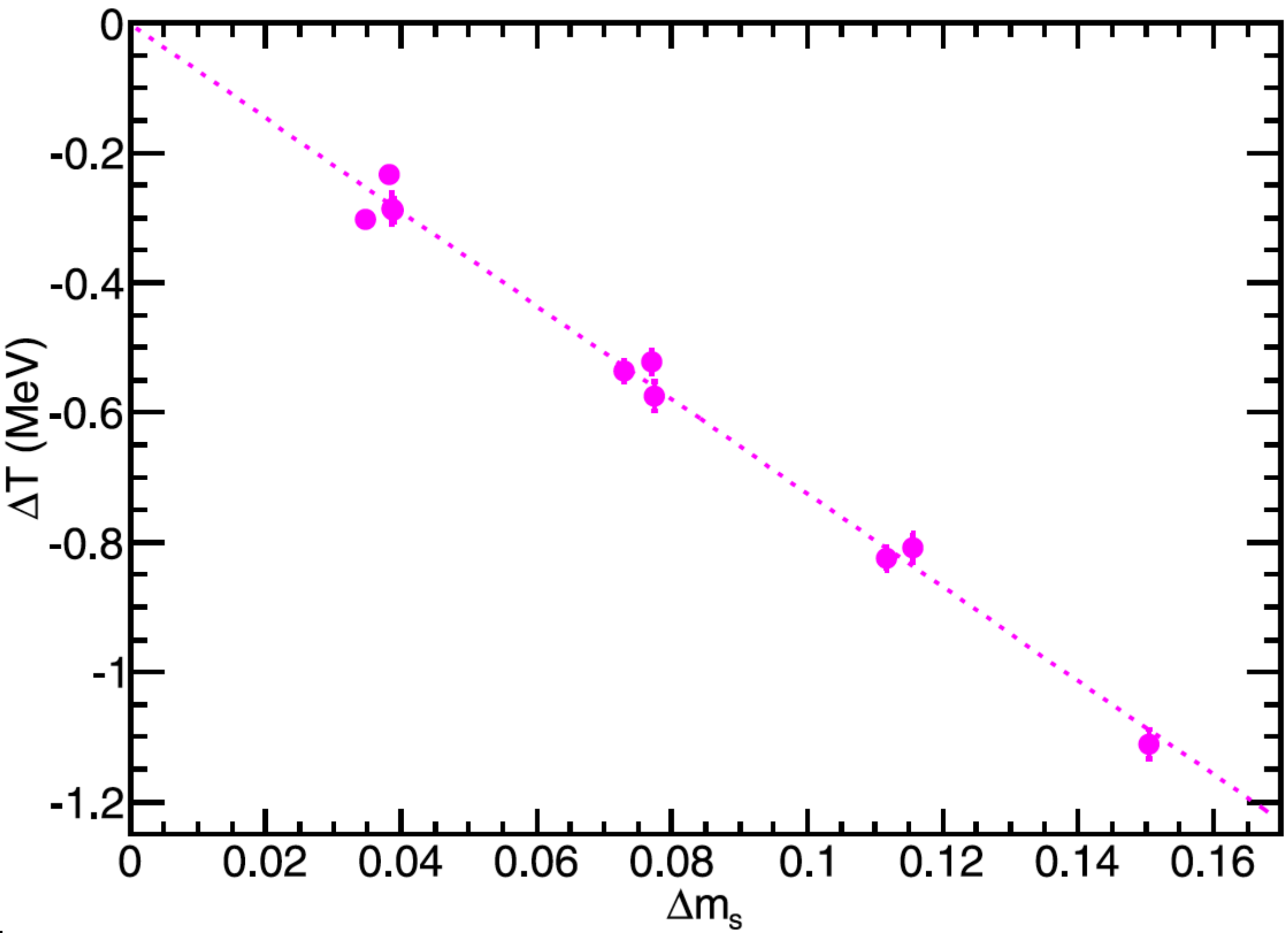
Larger Asymmetry
→ Lower Temperature

Temperature shift does not show a trend with excitation.

Four of ten pairwise differences shown.

Quantifying the Asymmetry Dependence





A change of 0.15 units of m_s = (N-Z)/A corresponds to a temperature decrease of 1.1 MeV

Linear relationship between change in asymmetry and change in temperature

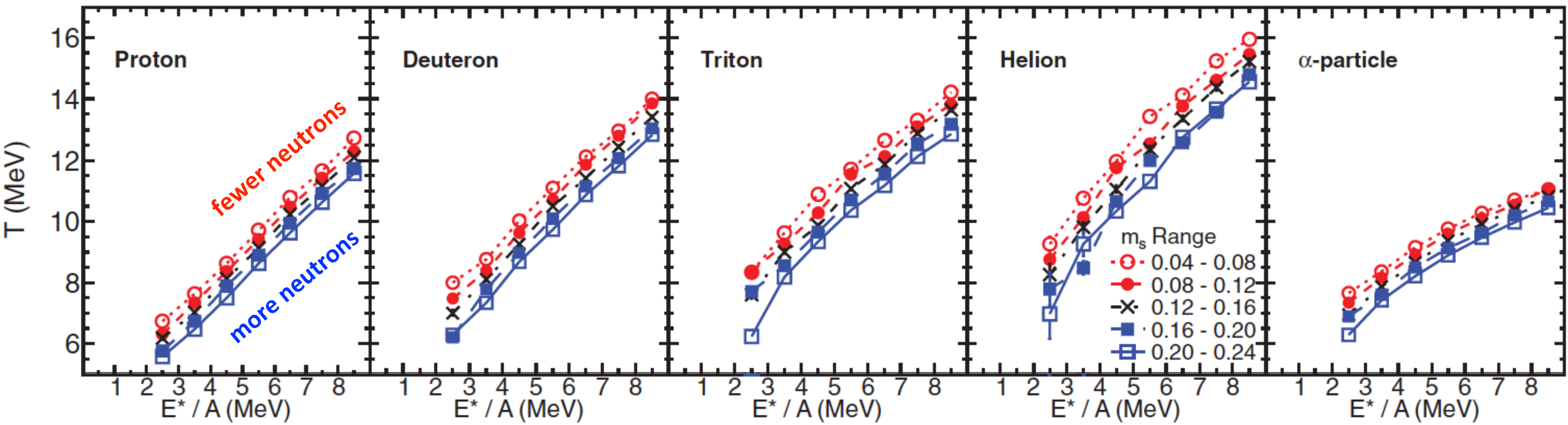
Asymmetry Dependence

✓ MQF Protons

Do other probes of the temperature exhibit an asymmetry dependence?

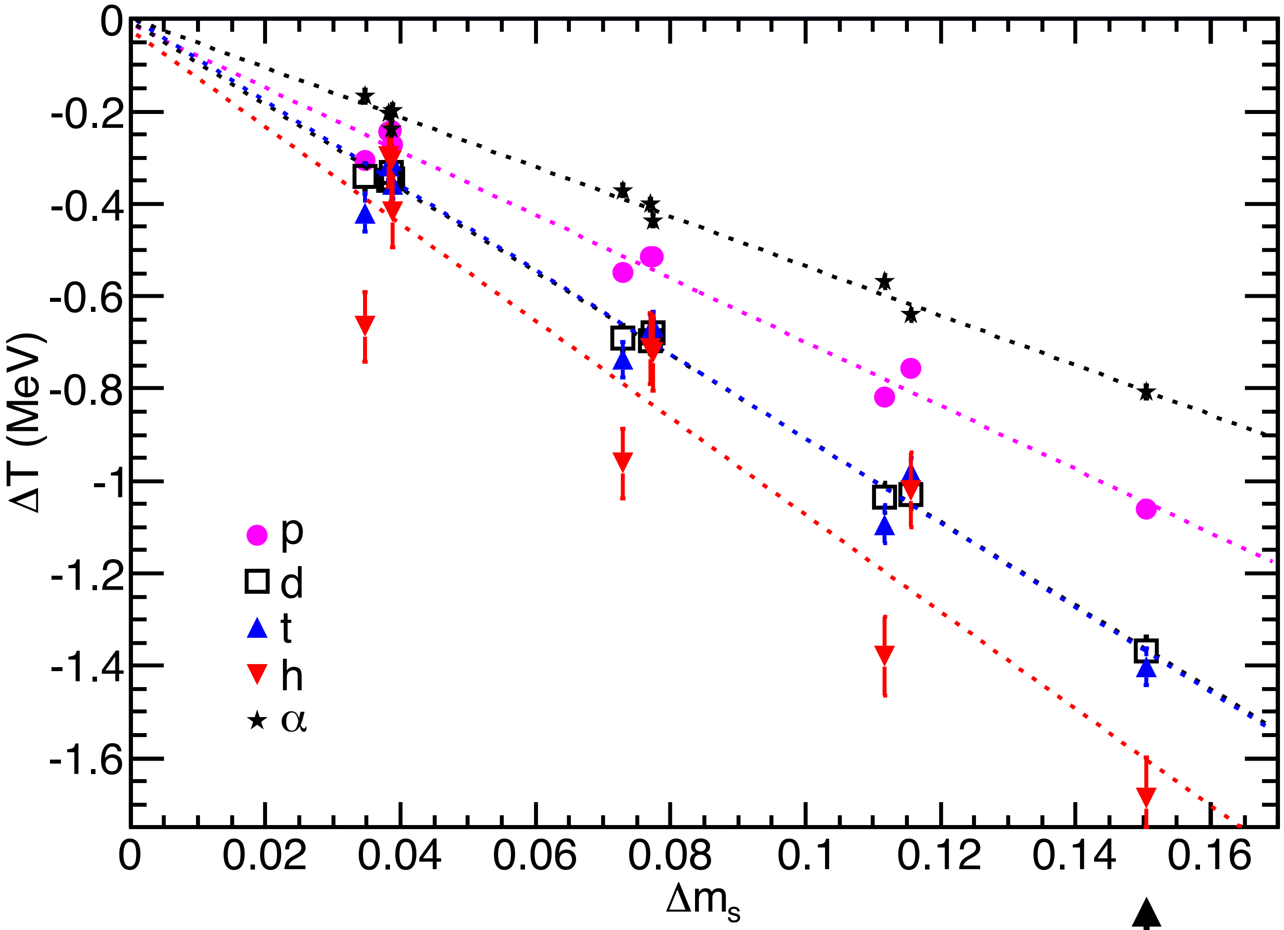
Caloric Curves for Light Charged Particles

Using the MQF Thermometer



For All LCPs:
Larger Asymmetry
→ Lower Temperature

Asymmetry Dependence of Temperature



Change of 4 protons to neutrons at A≈50

$\Delta T / \Delta m_s$

α: -5.5

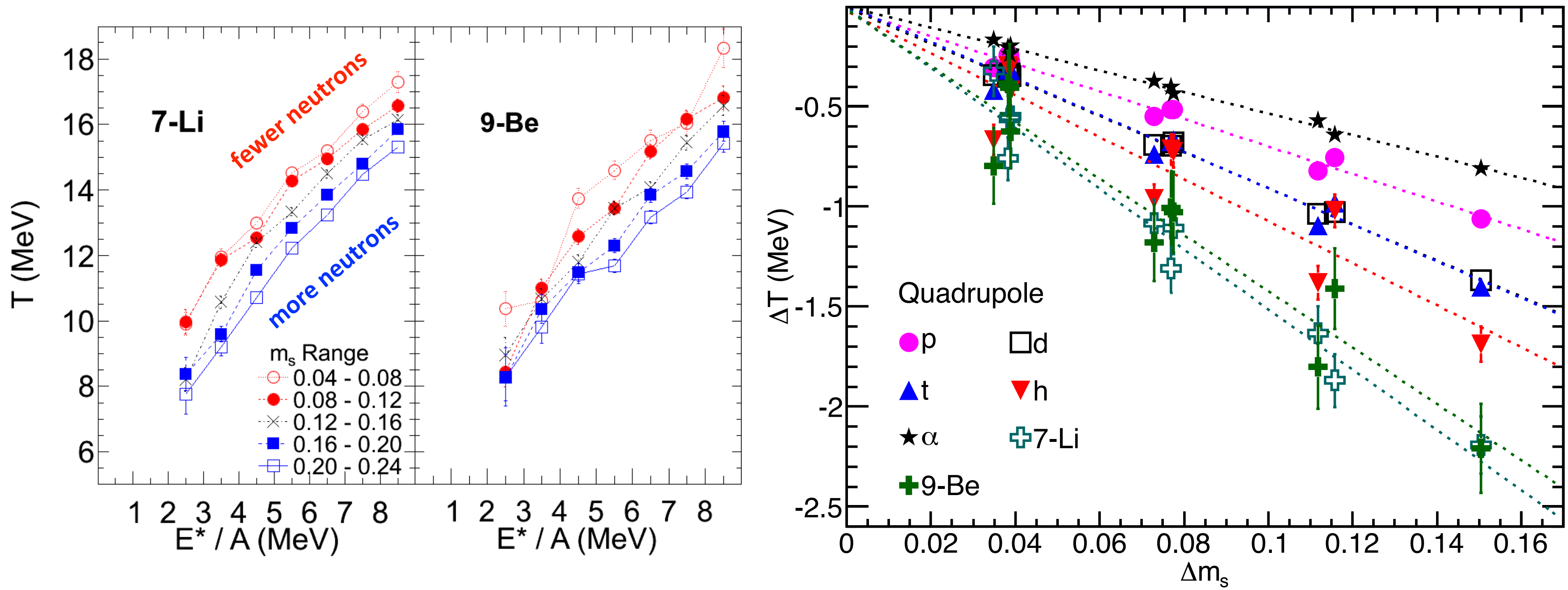
p: -7.3

d: -9.2

t: -9.3

h: -10/9

Temperatures Using Heavier Probes



Larger Asymmetry
→ Lower Temperature

Asymmetry Dependence

- ✓ MQF Protons
- ✓ MQF Deuterons
- ✓ MQF Tritons
- ✓ MQF Helions
- ✓ MQF Alphas
- ✓ MQF 7-Li
- ✓ MQF 9-Be

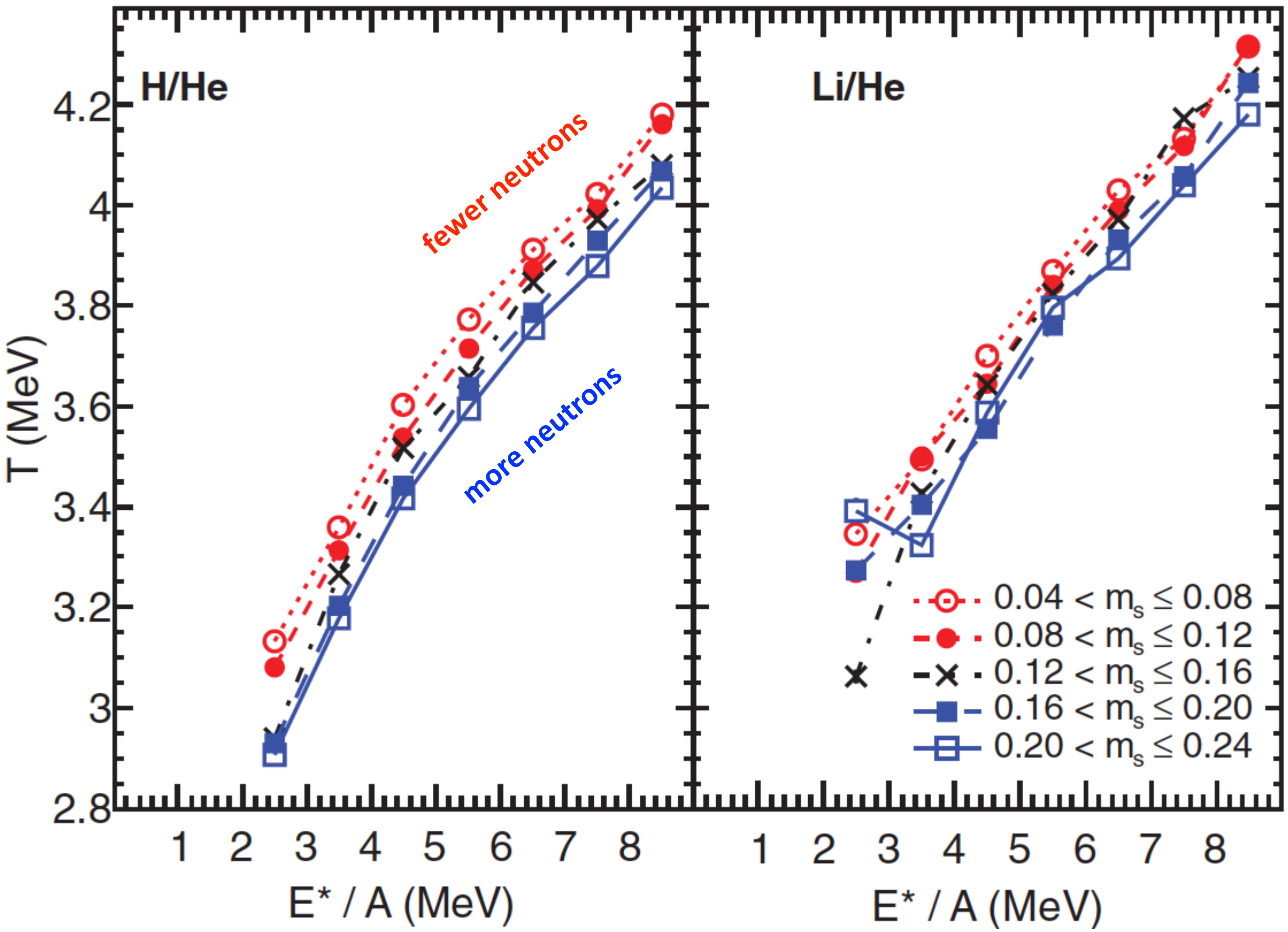
Do other probes of the temperature exhibit an asymmetry dependence?

Albergo 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	$T_{raw} = \frac{14.3MeV}{\ln(1.59R)}$	$T_{raw} = \frac{13.3MeV}{\ln(2.18R)}$
Correction for secondary decay (≈3%)	$\frac{1}{T} = \frac{1}{T_{raw}} - 0.0097$	$\frac{1}{T} = \frac{1}{T_{raw}} + 0.0051$

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

Albergo Temperature: Asymmetry Dependent

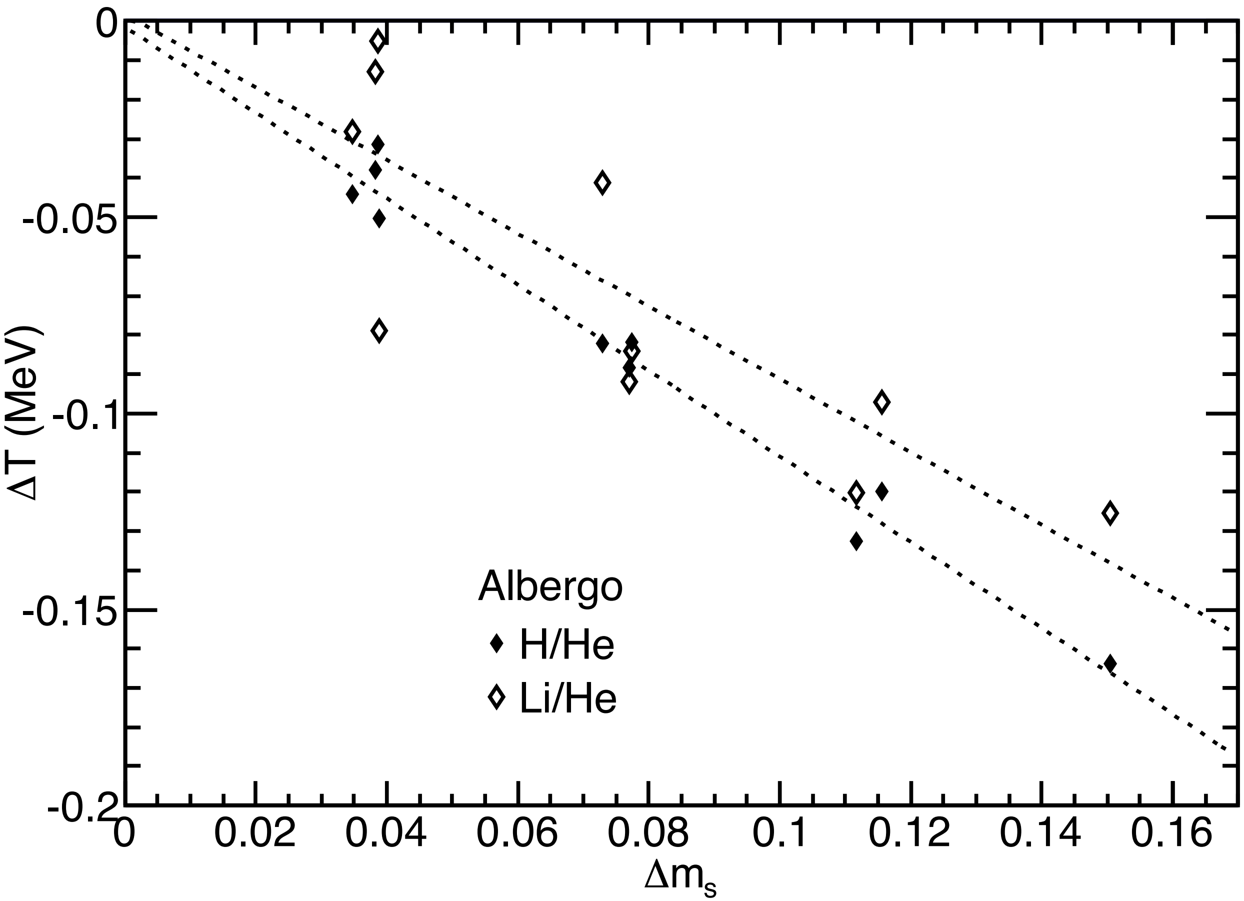


Temperature is smaller than for MQF (Chemical vs Kinetic)

Asymmetry dependence is smaller than MQF (Lower Temperature)

Larger Asymmetry
→ Lower Temperature

Albergo: Asymmetry Dependence of T



Larger Asymmetry
→ Lower Temperature

Linear Relationship

Stronger dependence for MQF than for Albergo

- Smaller value of temperature for Albergo then MQF
- Different methods (chemical vs kinetic)

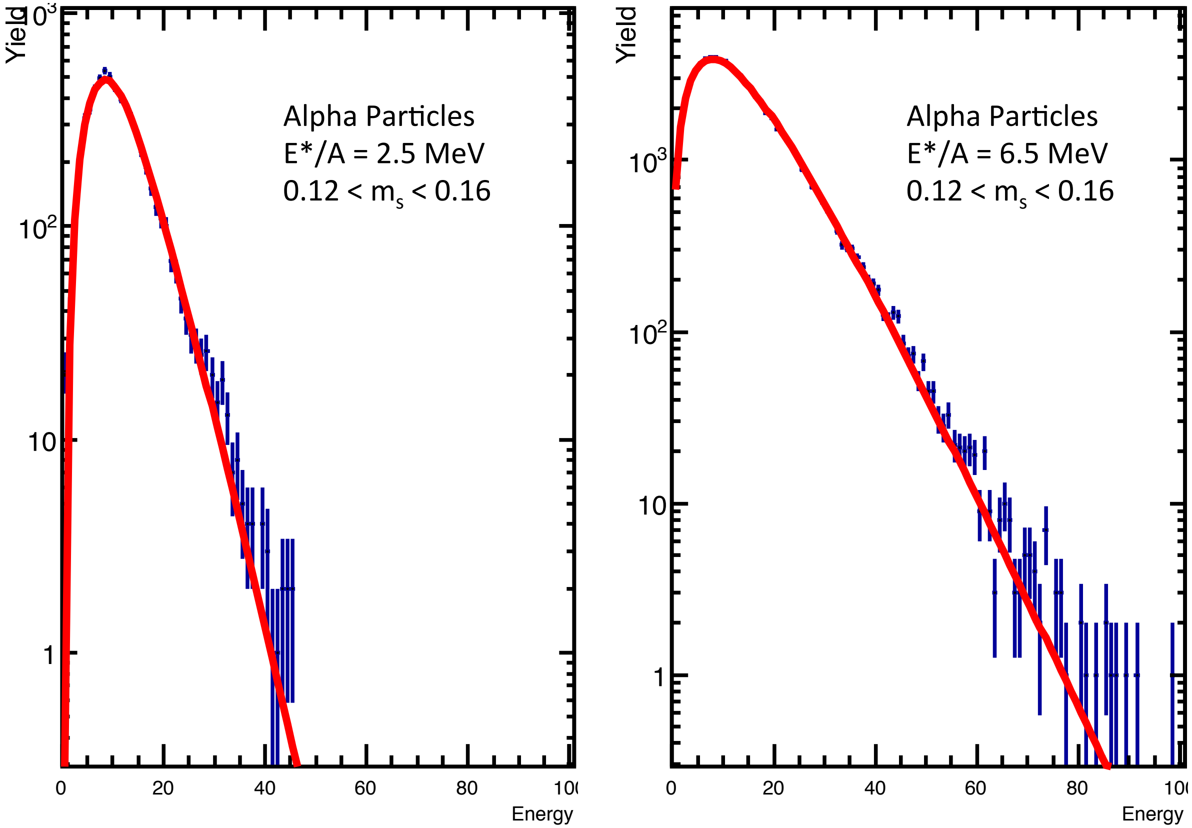
<u>Asymmetry Dependence</u>

- ✓ MQF Protons
- ✓ MQF Deuterons
- ✓ MQF Tritons
- ✓ MQF Helions
- ✓ MQF Alphas
- ✓ MQF 7-Li
- ✓ MQF 9-Be
- ✓ Albergo H / He
- ✓ Albergo Li / He

Do other probes of the temperature exhibit an asymmetry dependence?

Slope Temperatures

Kinetic Energies in the QP frame. θ < 90°



Maxwell-Boltzmann

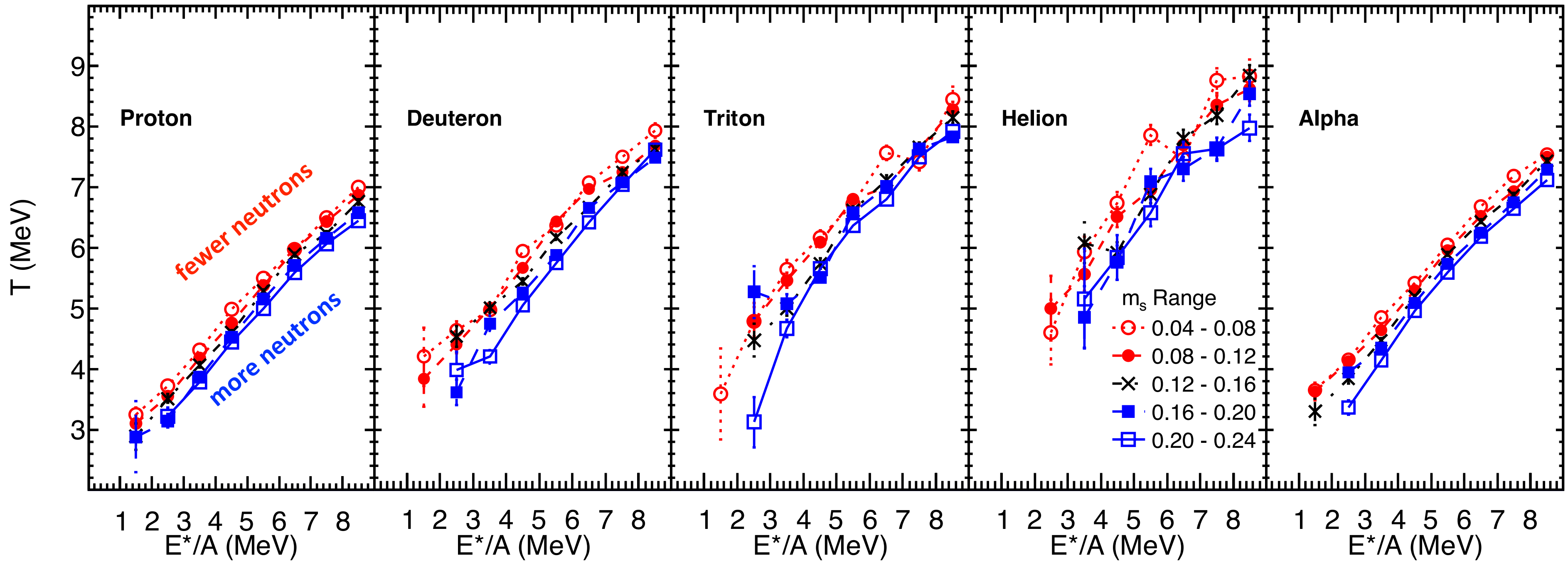
$$Y(E) \propto (E-B)\exp\left(-\frac{E}{T}\right)$$

$$for \quad E \geq B+T$$

With a modification for a diffuse barrier at lower energies.

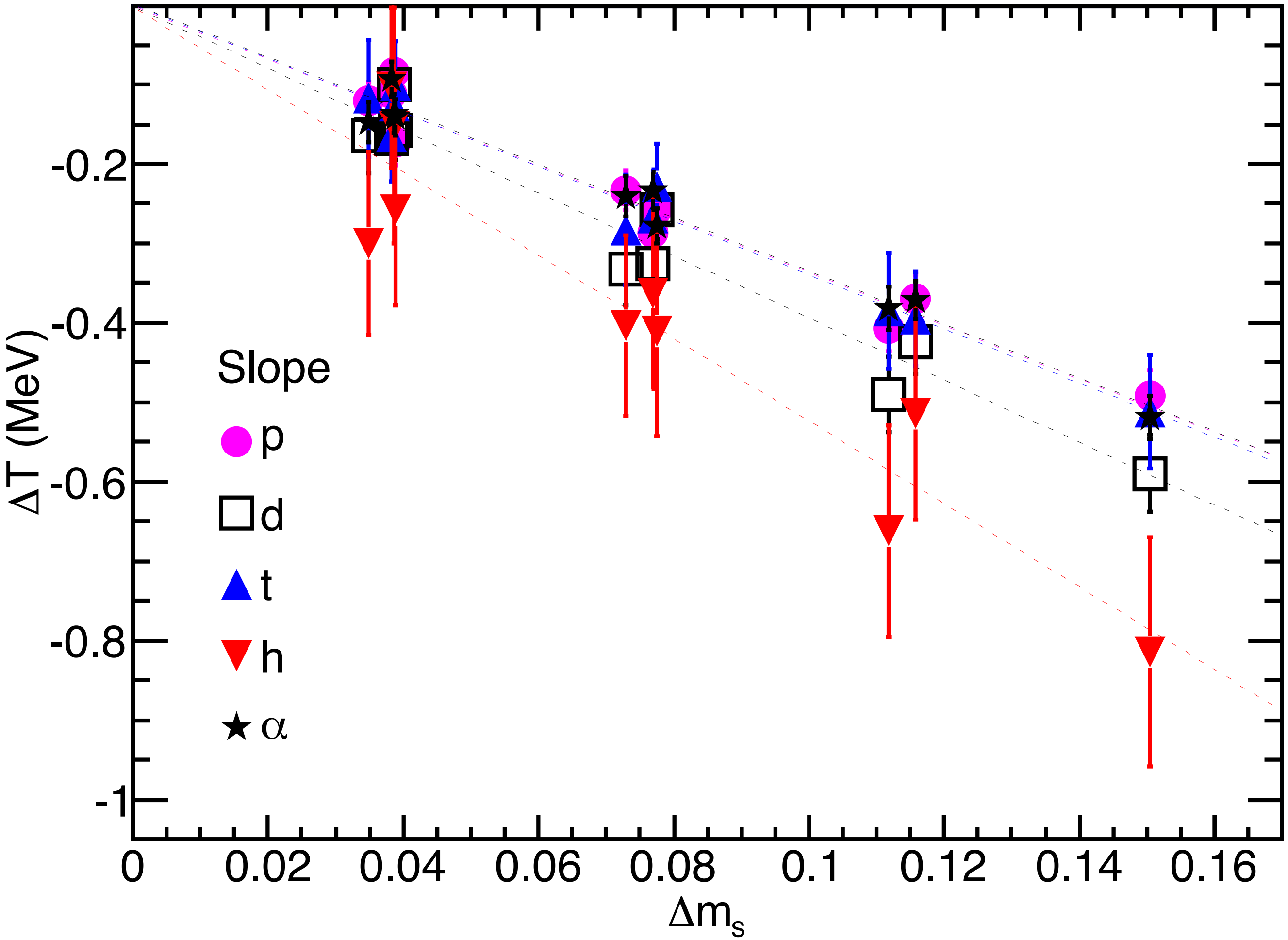
Yanez, Phys. Rev. C 68, 011602(R) (2003)

Slope Temperature: Asymmetry Dependent



Larger Asymmetry
→ Lower Temperature

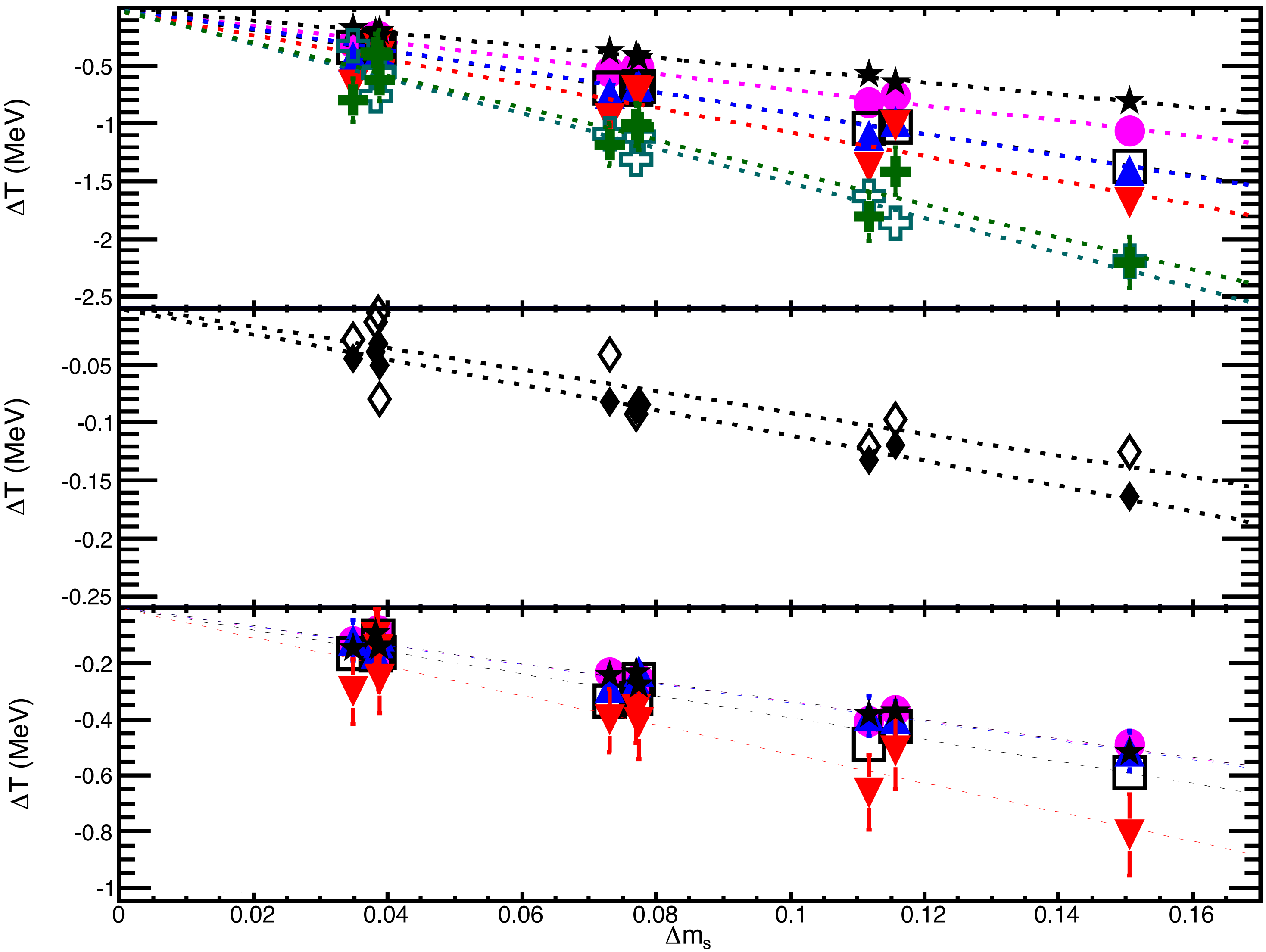
Asymmetry Dependence of Slope Temperature



Larger Asymmetry
→ Lower Temperature

Linear Relationship

Q: How much cooler would it be with some more neutrons?



- ✓ MQF Protons
- ✓ MQF Deuterons
- ✓ MQF Tritons
- ✓ MQF Helions
- ✓ MQF Alphas
- ✓ MQF 7-Li
- ✓ MQF 9-Be

- ✓ Albergo H / He
- ✓ Albergo Li / He

- ✓ Slope Protons
- ✓ Slope Deuterons
- ✓ Slope Tritons
- ✓ Slope Helions
- ✓ Slope Alphas

A: It depends on the thermometer, but it sure would be cooler.

Q: How much cooler would it be if we didn't need to measure neutrons?

Q: How much cooler would it be if we didn't need to measure neutrons?

To confirm our observation of an asymmetry dependence of the caloric curve, we will conduct a new experiment.

Fusion reactions produce excited nuclei with known n-p asymmetry and known excitation.

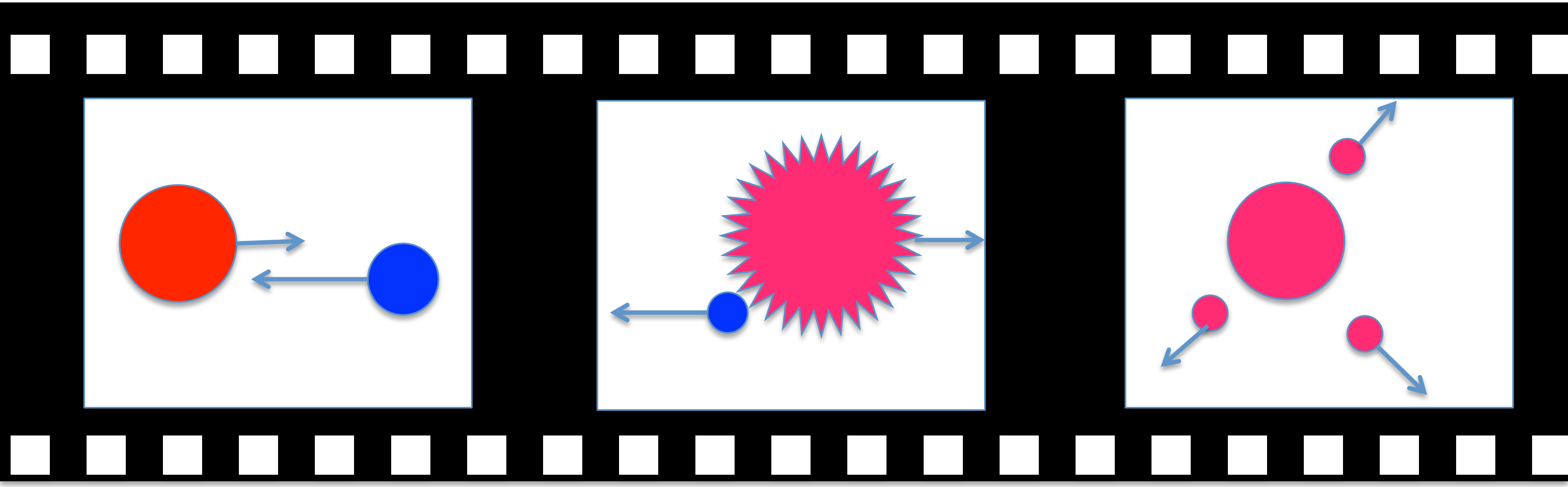
Free neutrons are not needed!

Fusion-evaporation residues will provide event characterization.

Light charged particles that are evaporated from the compound nucleus will provide the temperature in multiple ways.

The Fusion Reactions

^{78}Kr + ^{12}C
^{86}Kr + ^{12}C
E/A = 15, 25, 35 MeV



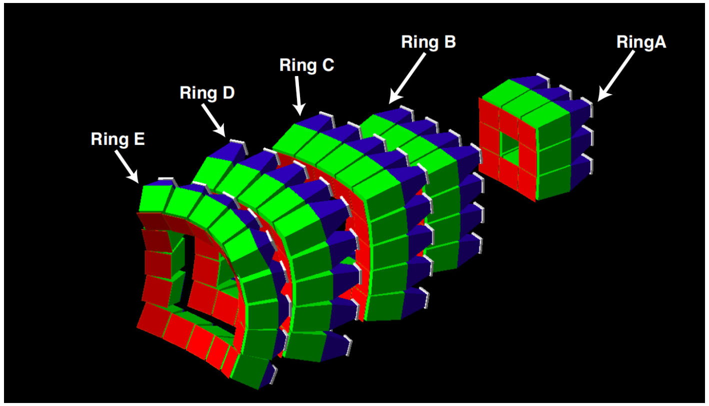
E*/A = 1.3 , 2.0 MeV, and 2.8 MeV for 86Kr.
For 78Kr, ~10% higher.

(N-Z)/A = 0.070 and 0.163

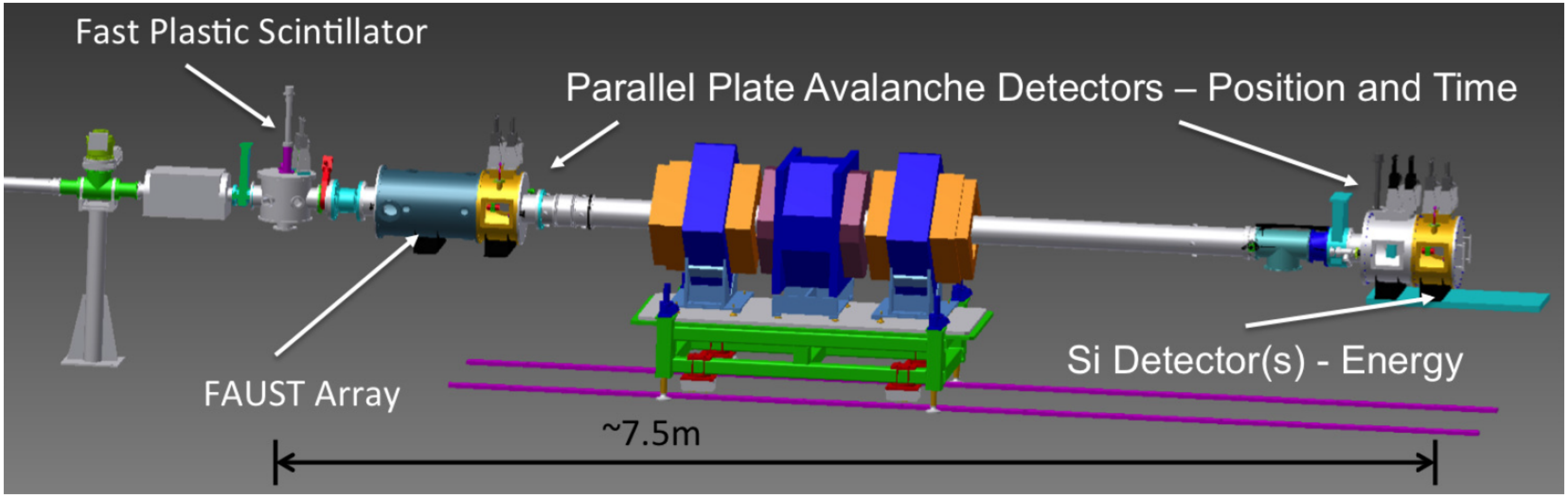
Experimental Configuration

Quadrupole Triplet Spectrometer
Measure Fusion-Evaporation Residues
Time-Of-Flight, ΔE, E → Velocity, Energy, Z, A
0.9° ≤ θ ≤ 2.3°

P. Cammarata et al., NIMA 792, 61 (2015)
L. Heilborn et al., article in preparation



FAUSTUPS
Measure Light Charged Particles
Position-Sensitive
ΔE, E → Z, A, Energy
1.6° ≤ θ ≤ 45°



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Cyclotron Institute
Texas A&M University

Department of Energy
DE-FG03-93ER40773

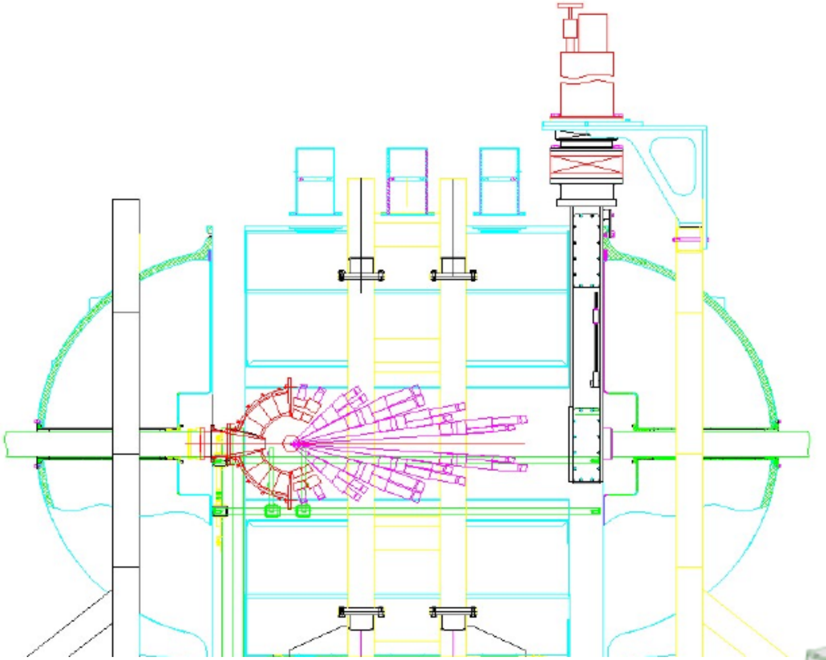
Welch Foundation
A-1266

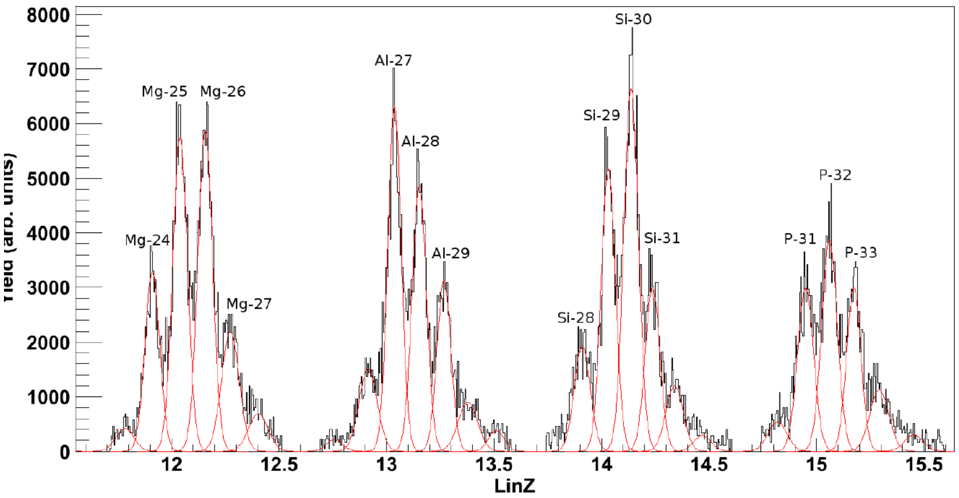
Supplementary Material

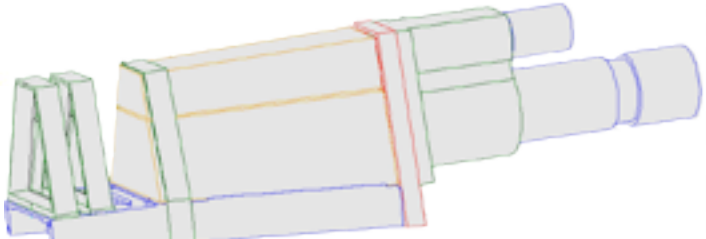
NIMROD-ISiS Array

- Full Silicon Coverage (4π)
- Isotopic Resolution to Z=17
- Elemental Resolution to $Z_{projectile}$
- Neutron Ball (4π)

70Zn + 70Zn
64Zn + 64Zn
64Ni + 64Ni
E = 35A MeV







S. Wuenschel et al., Nucl. Instrum. Methods. A604, 578–583 (2009)

Z. Kohley, Ph.D Thesis, TAMU (2010)

QP Reconstruction

Cut 1/3: Velocity

Remove particles that do not belong (on average) to a statistically emitting projectile-like source.

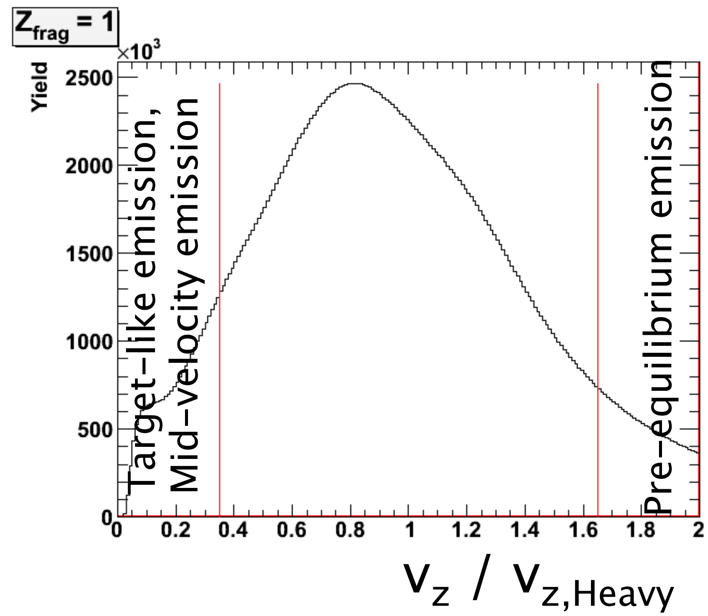
Compare laboratory parallel velocity of each particle to that of the heaviest charged particle measured in the event.

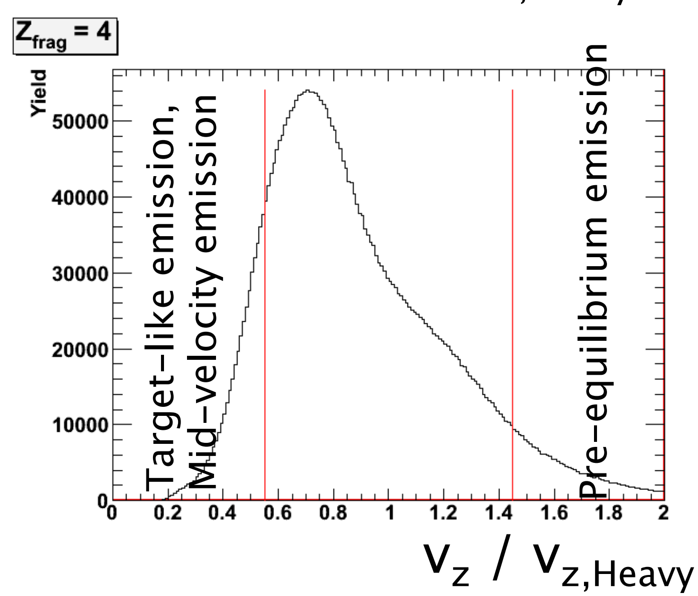
$$\mathbf{Z = 1:} \quad \mathbf{0.35 \leq \frac{v_z}{v_{z,PLF}} \leq 1.65}$$

$$\mathbf{Z = 2:} \quad \mathbf{0.40 \leq \frac{v_z}{v_{z,PLF}} \leq 1.60}$$

$$\mathbf{Z \geq 3:} \quad \mathbf{0.55 \leq \frac{v_z}{v_{z,PLF}} \leq 1.45}$$

Steckmeyer et al., NPA **686**, 537 (2001)





QP Reconstruction

- **Mass Selection Considerations**
- Mass close to beam - well defined system
- Not too close to beam: significant E*, overlap of target and projectile
- Sufficient statistics

$$48 \leq A_{QP} \leq 52$$

$$m_{source} = \frac{N_{QP} - Z_{QP}}{A_{QP}}$$

Largest uncertainty in A_{QP}: free neutron multiplicity

- Uncertainty in excitation
  - relatively small (compared to results)
- Uncertainty in asymmetry (N–Z)/A
  - relatively small (compared to results)

Marini et al., NIMA **707**, 80 (2013)

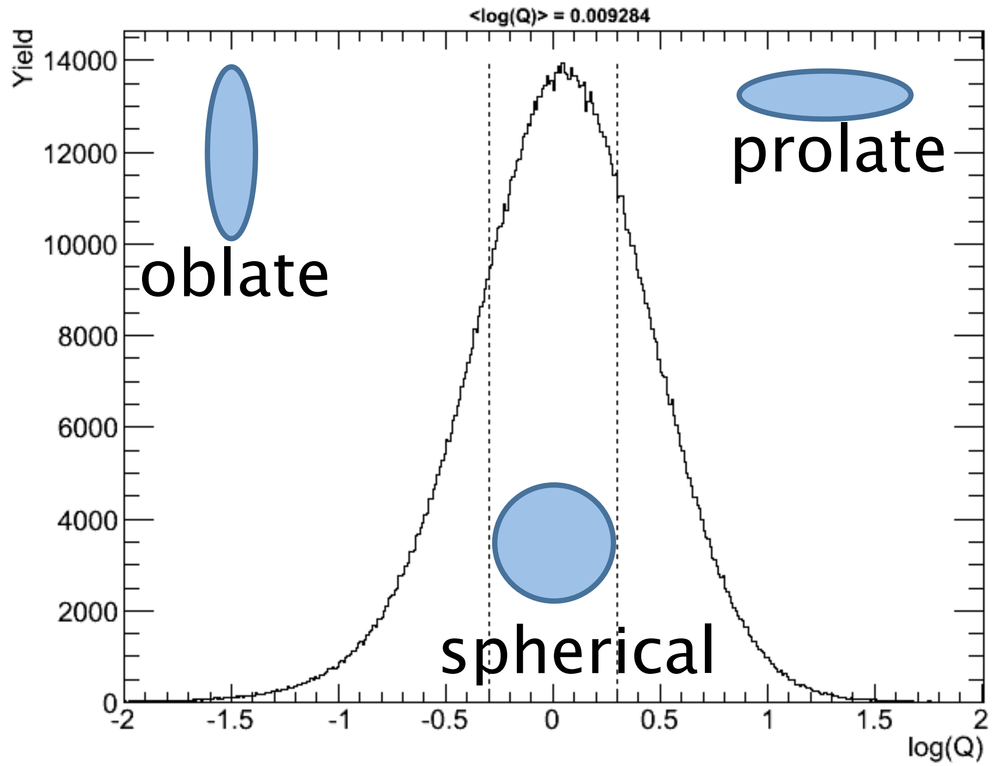
QP Reconstruction

Cut 3/3: Sphericity

$$Q = \frac{\sum p_{z,i}^2}{\frac{1}{2}\sum p_{T,i}^2}$$

$$-0.3 \leq \log Q \leq 0.3$$

Select events with near-zero average momentum quadrupole.



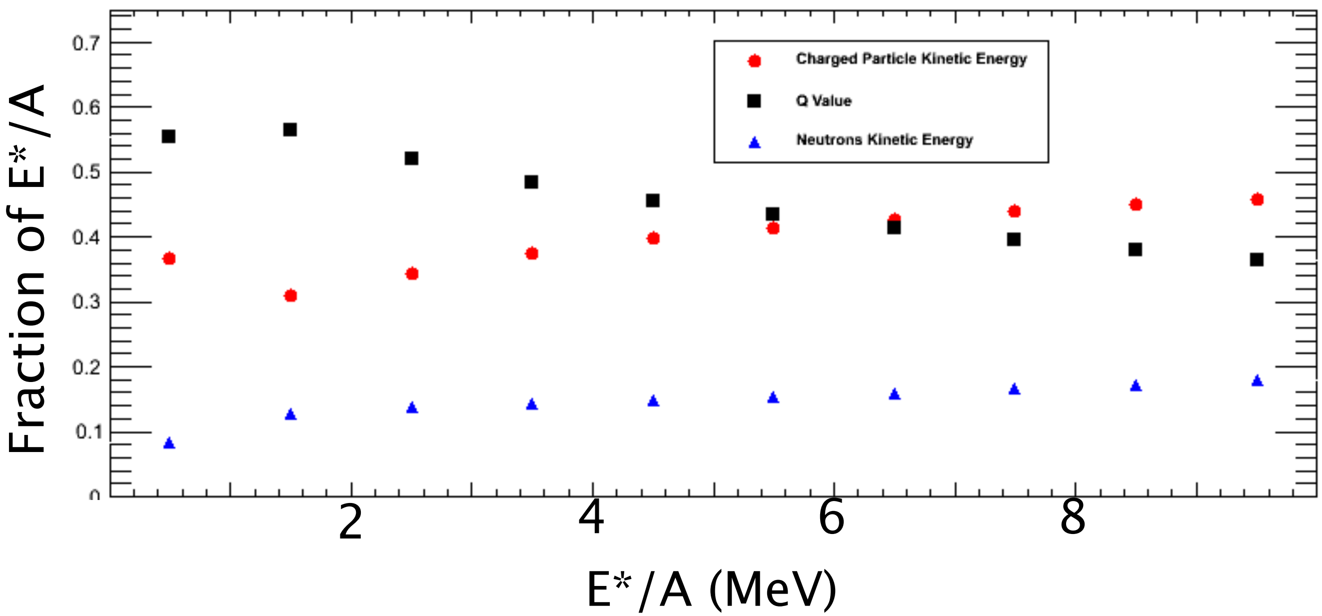
(Velocity cut and Mass cut imposed)

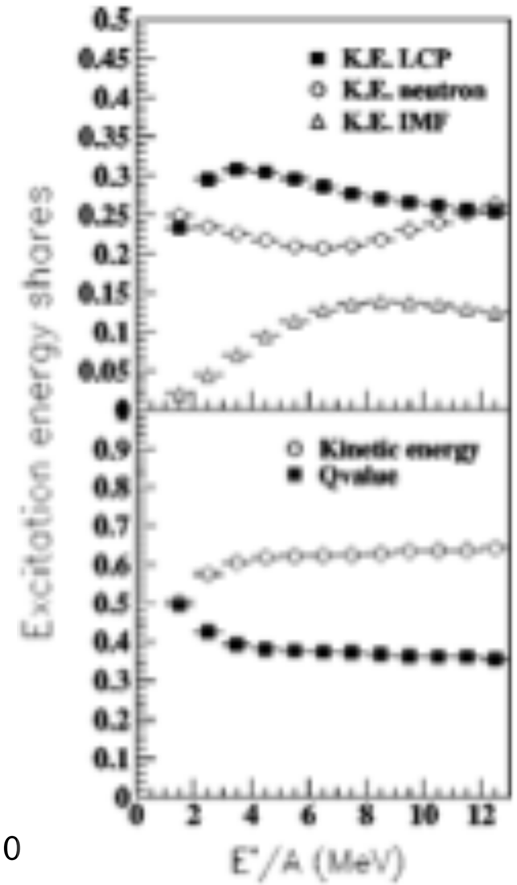
Concept to select thermally equilibrated events:
Shape equilibration is slow relative to thermal equilibration.

S. Wuenschel, NPA 843, 1 (2010)
S. Wuenschel, Ph.D. Thesis, Texas A&M University, (2009)

QP Identity

$$Z_{QP} = \sum_{i}^{CP} Z_i \qquad A_{QP} = \sum_{i}^{CP} A_i + M_n \qquad \vec{v}_{QP} m_{QP} = \sum_{i}^{CP} \vec{v}_i m_i \qquad E^*_{QP} = \sum_{i}^{CP} \tfrac{3}{2} K_{\perp,i} + M_n \langle K_n \rangle - Q$$





Excitation energy sharing is in reasonable agreement with previously published data:
~ 40% Charged particle KE
~ 40% Q value
~ 20% Neutrons

Lefort et al. PRC 64, 064603 (20
5-15 GeV/c Hadrons on Au

Neutron Measurement

$$\mathbf{M_{meas}} = (\epsilon_{\mathbf{QP}}\mathbf{M_{QP}} + \epsilon_{\mathbf{QT}}\mathbf{M_{QT}})\left(\frac{\epsilon_{\mathbf{lab}}}{\epsilon_{\mathbf{sim}}}\right) + \mathbf{M_{bkg}}$$

Efficiency ε_{lab} measured with a calibrated Cf source.

Simulations to determine efficiency ε_{QP}, ε_{QT}, ε_{sim}.

Efficiencies are model-independent (CoMD, HIPSE-SIMON).

Efficiencies are system-independent.

$$\mathbf{M_n} = \frac{\mathbf{M_{meas}} - \mathbf{M_{bkg}}}{\left(\epsilon_{\mathbf{QP}} + \frac{\mathbf{N_T}}{\mathbf{N_P}}\epsilon_{\mathbf{QT}}\right)\left(\frac{\epsilon_{\mathbf{lab}}}{\epsilon_{\mathbf{sim}}}\right)}$$

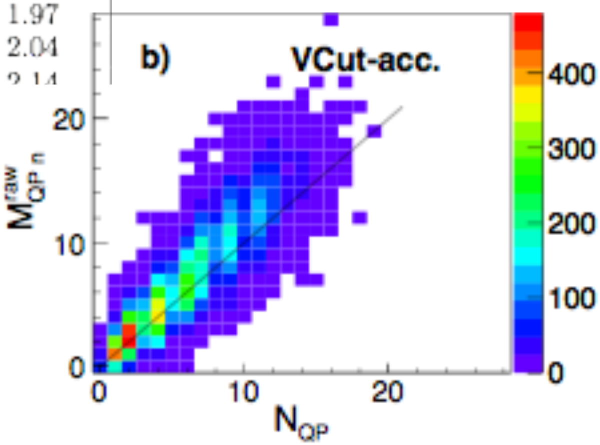
Marini et al., NIMA **707**, 80 (2013)
Wada et al., PRC 69, 044610 (2004)

Neutron Uncertainty

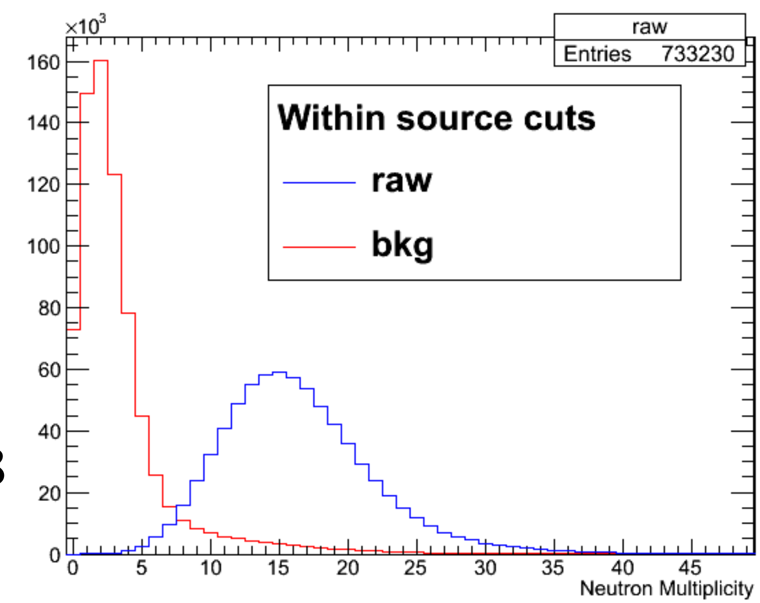
$$\sigma^2_{\mathbf{raw}} = \sigma^2_{\mathbf{true}} + \sigma^2_{\mathbf{eff}} + \sigma^2_{\mathbf{bkg}}$$

N_{QP}	$\langle M^{raw}_{QP_n} \rangle$	$\sigma(M^{raw}_{QP_n})$
	HIPSE	
0	1.46	1.10
1	2.13	1.21
2	3.02	1.64
3	3.67	1.68
4	4.06	1.75
5	4.72	1.88
6	5.28	1.97
7	5.94	2.04
8	[illegible]	2.14

raw width: 5.36
width due to efficiency: < 2.1 (worst case)
efficiency: 9% effect



raw width: 5.36
width due to background: 1.8
efficiency: 6% effect



Marini et al., NIMA **707**, 80 (2013)

Net effect: we know the QP neutron multiplicity to within 11% (1σ).

Calculation of Neutron Uncertainty

We know the QP neutron multiplicity to within 11% (1σ).
How big is this?

excitation

For a source of 50 nucleons where 5 become free neutrons, the free neutrons contribute 0.97 MeV/nucleon to the excitation energy.

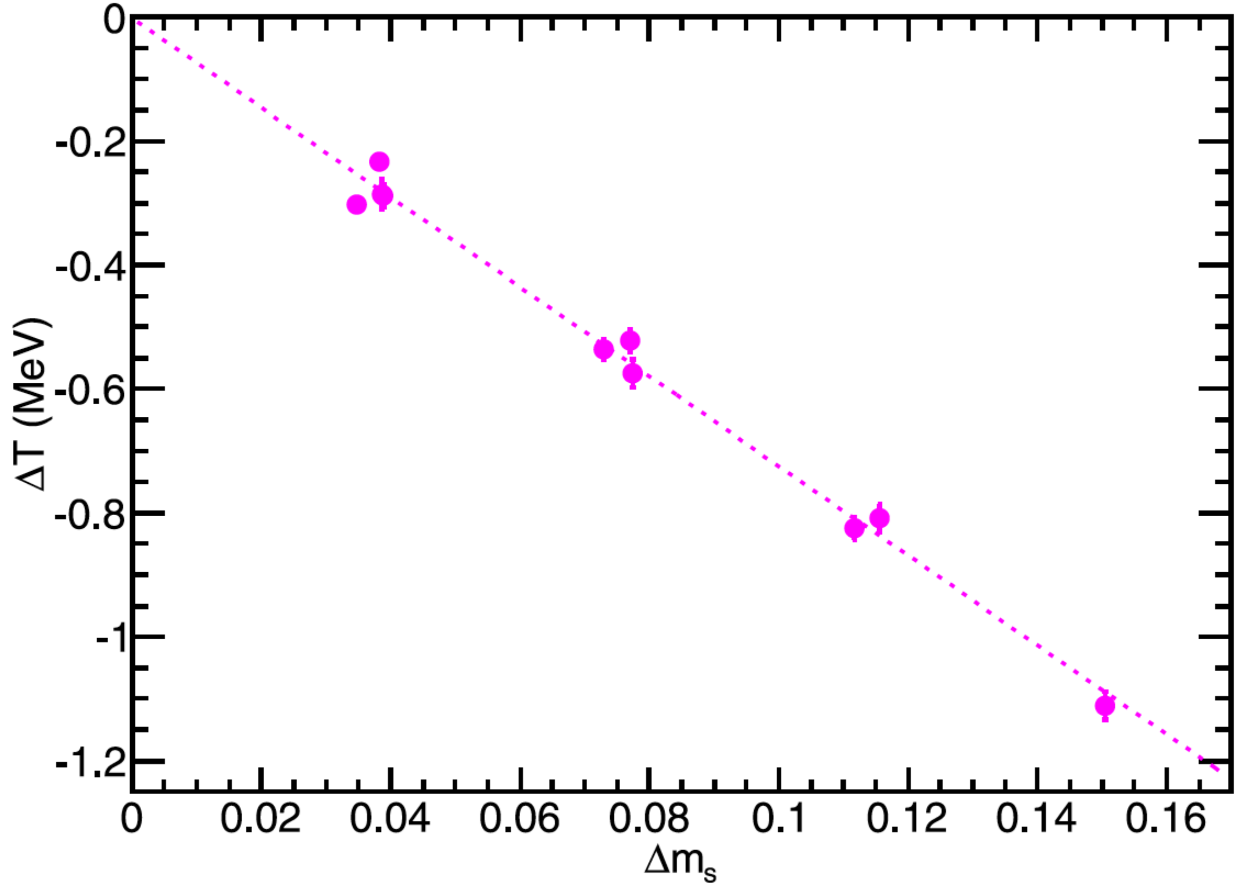
An uncertainty of 11% on the free neutron multiplicity corresponds to an uncertainty of 0.11 MeV/nucleon.

This uncertainty of 0.11 MeV/nucleon is significantly smaller than the spacing between even the closest caloric curves.

asymmetry

For a source of 50 nucleons where 5 become free neutrons, an error of 1 neutron corresponds to a 2σ variation. It would require an error of 4σ to shift from one asymmetry bin to another.

Robust Asymmetry Dependence



We vary the neutron kinetic energy to physically unrealistic extremes:

- Neutron KE to 50%: slope ΔT/Δms decreases only to 75%
- Neutron KE to 150%: slope ΔT/Δms increases only to 125%

➡ Some uncertainty in magnitude of the correlation, but not in its existence

TARGET:

If target is too small, excitation energy is very low

e.g. Kr+p gives E*/A below 1MeV, even at E_{beam}=35A MeV

If target is too large, incomplete fusion is very incomplete

e.g. in Kr+Al, the zinc fuses with less of the aluminum target than Kr+C

Target of 12C is good compromise

Kr+C at 15,25,35A MeV fuses with more than half of the target

Reaches nearly E*/A = 3MeV

PROJECTILE:

If projectile is too heavy, E*/A will be low, cyclotron limitation

e.g. Sn+C: Sn max energy around 15A MeV → E*/A = 1.2MeV

If projectile is too light, compound nucleus lighter than I'd like

e.g. Ar+C→Cr (A=48) is not terrible, but larger A is better to study caloric curve

ASYMMETRY:

Choose combination with large range in (N-Z)/A

78Kr + 8Be → 86Zr (8Be is 2/3 of 12C target)

86Kr + 8Be → 94Zr

→ (N-Z)/A = 0.070 and 0.163

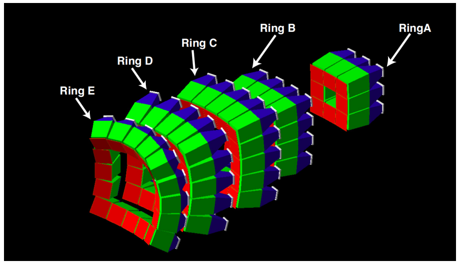
BEAM ENERGY:

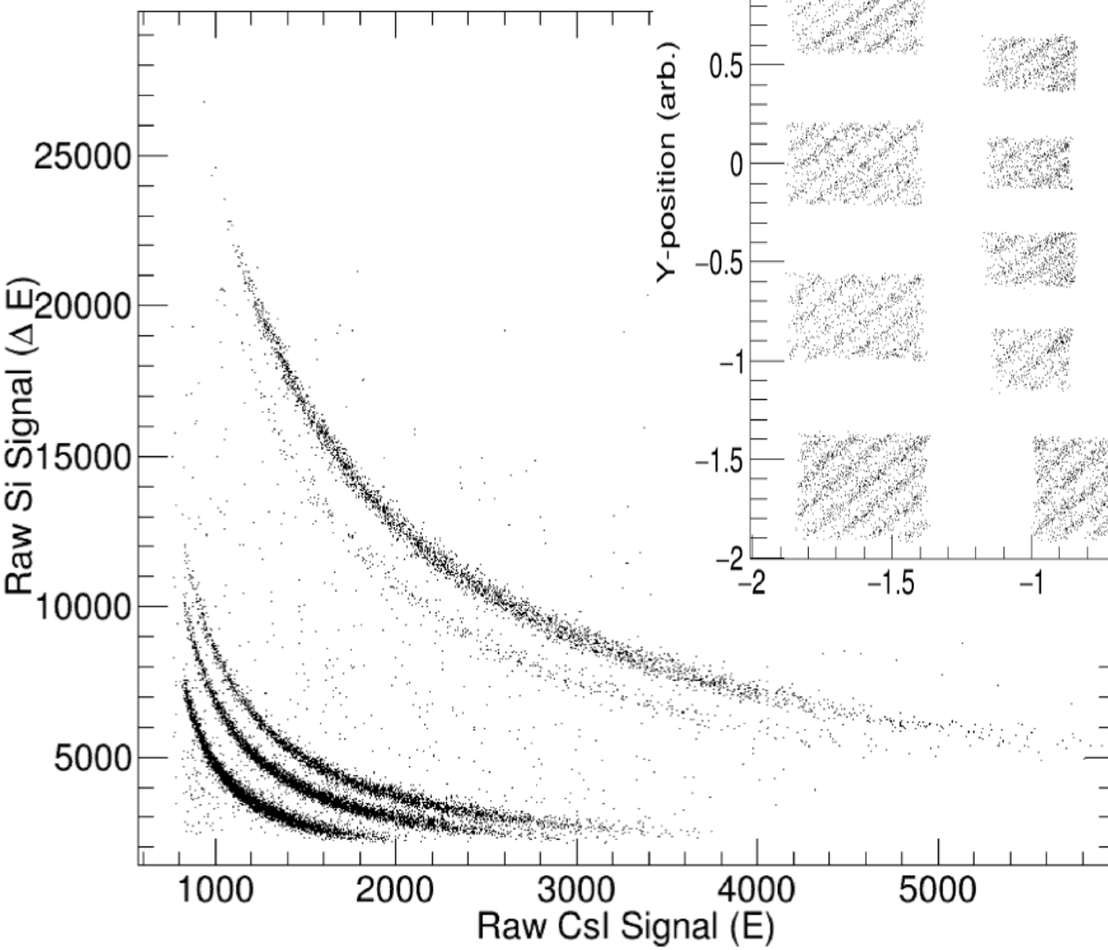
@ 15, 25, 35 A MeV

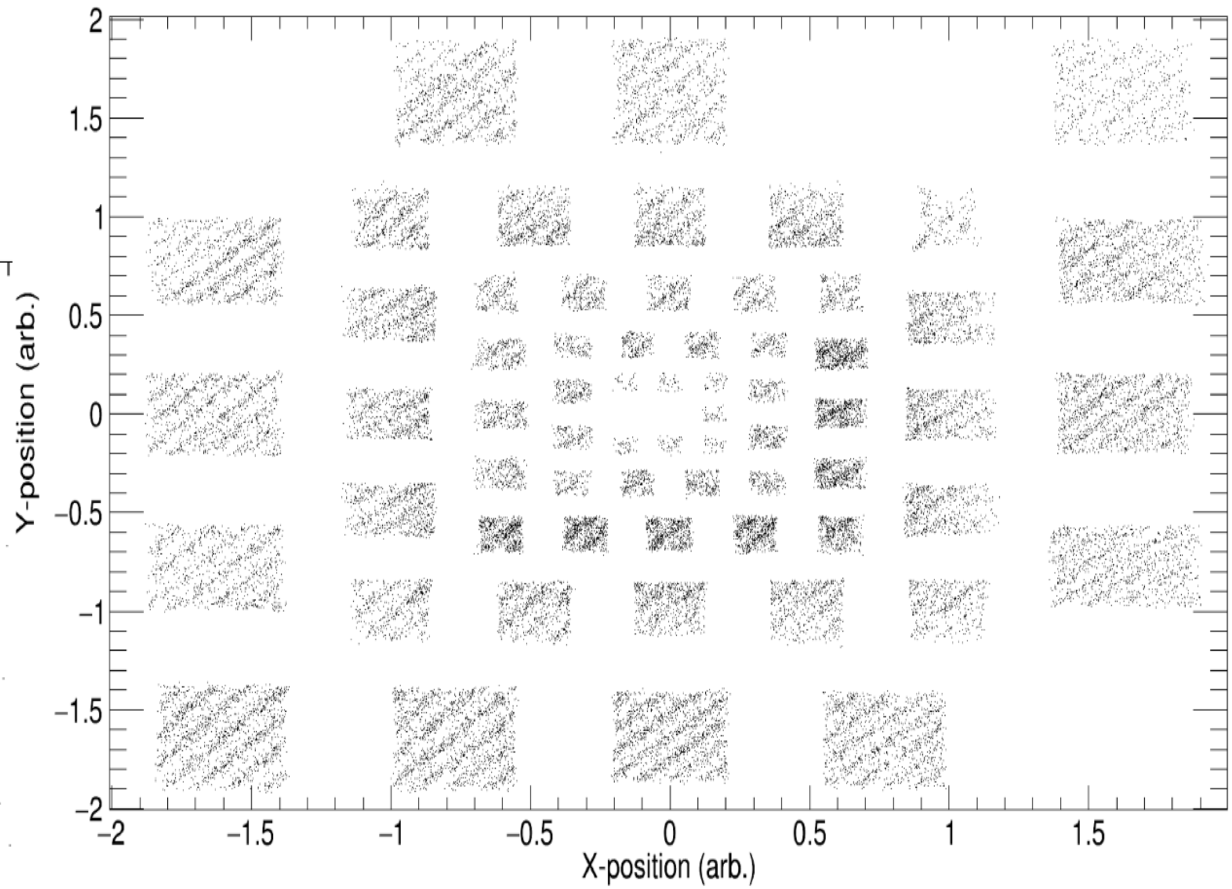
→ E*/A = 1.3 MeV, 2.0 MeV, and 2.8 MeV for 86Kr beam. For 78Kr, ~10% higher.

FAUSTUPS

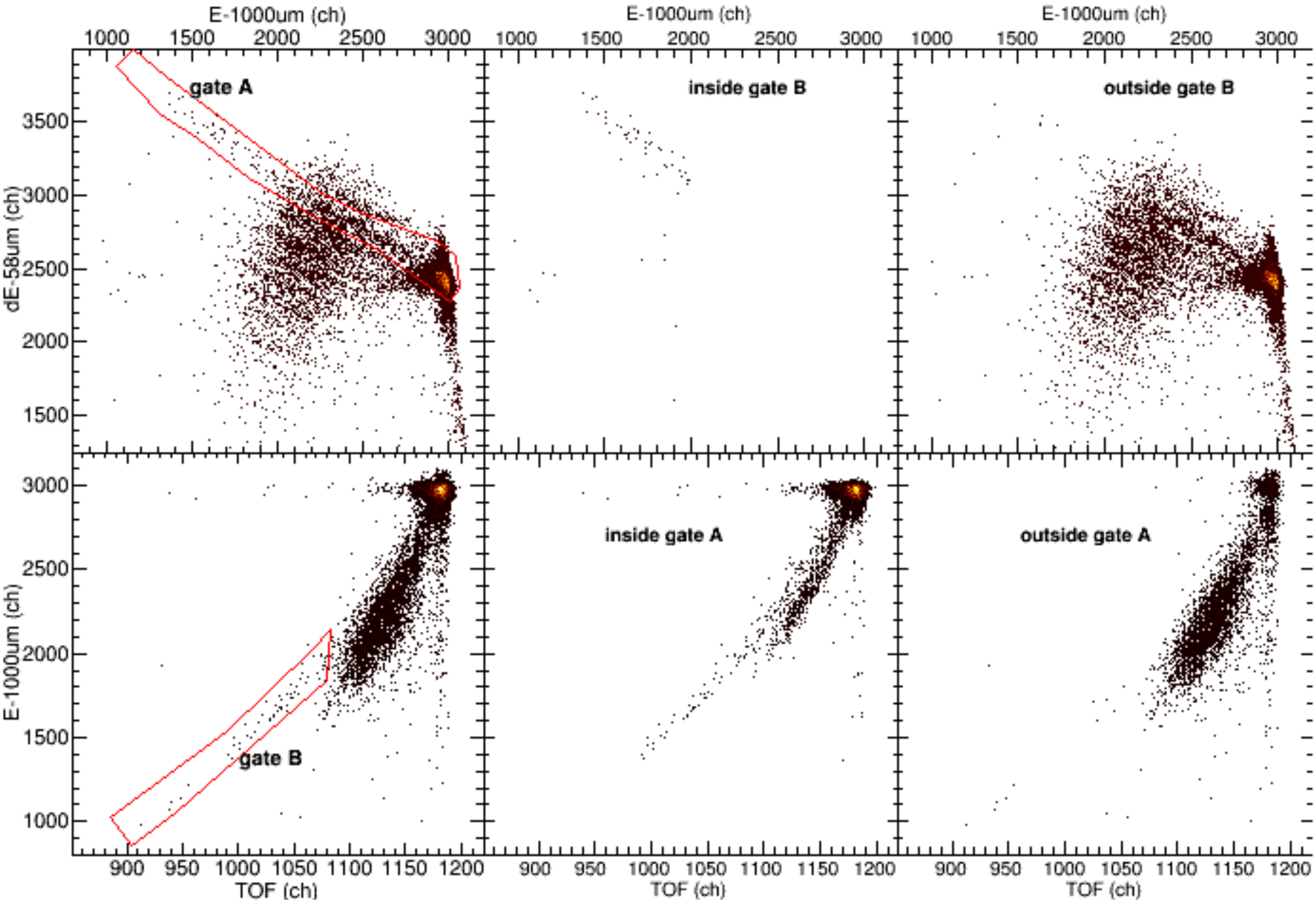
Upgrade to excellent position resolution.
Retain excellent energy and isotopic resolution



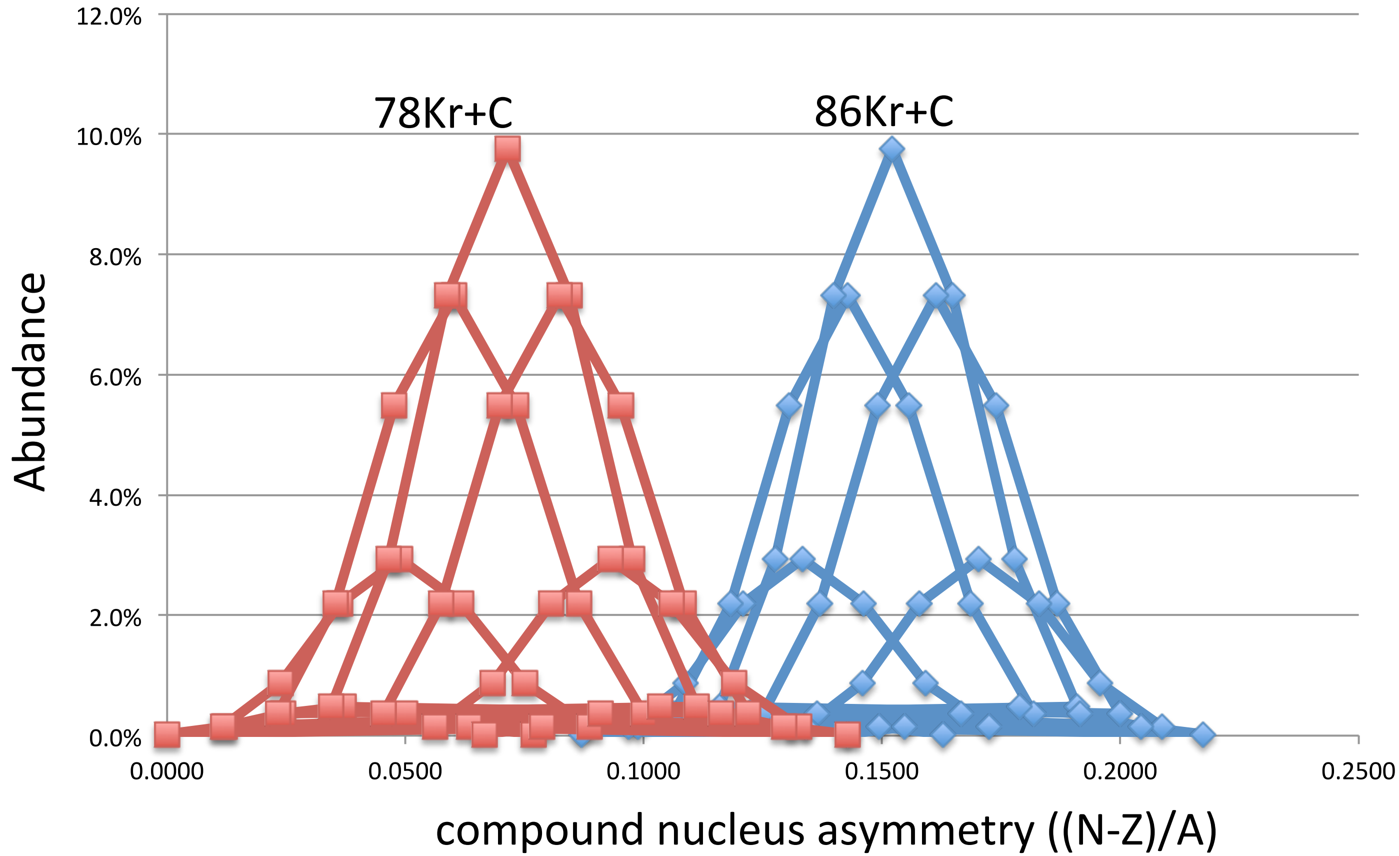




Quadrupole Triplet Spectrometer Provides {Z, A, E, V} using, {TOF, ΔE, E}



Even if you pick up every possible number of neutrons and protons with equal probability, the asymmetries of the compound nuclei for the 86Kr and 78Kr systems are still well separated.



This is combinatorics only. Physics may narrow the distributions since many of these cases don't occur and some others will be filtered out by the triplet. The distributions may shift toward each other if the 78Kr prefers to pick up neutrons and the 86Kr prefers to pick up protons.

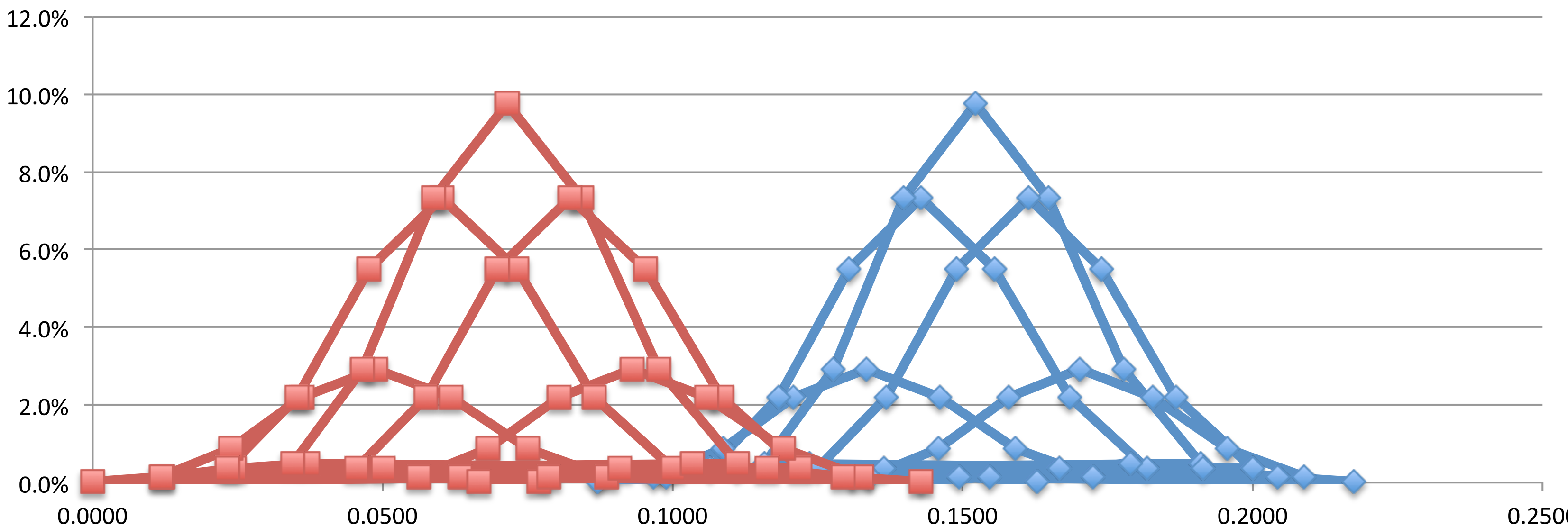
Preferential nucleon pickup

	beam			pickup		compound nucleus			
	Z	A	N	ΔZ	ΔN	Z	N	A	**delta**
78Kr	36	78	42	2	6	38	48	86	**0.116**
78Kr	36	78	42	3	5	39	47	86	**0.093**
78Kr	36	78	42	4	4	40	46	86	**0.070**
78Kr	36	78	42	5	3	41	45	86	**0.047**
78Kr	36	78	42	6	2	42	44	86	**0.023**
86Kr	36	86	50	2	6	38	56	94	**0.191**
86Kr	36	86	50	3	5	39	55	94	**0.170**
86Kr	36	86	50	4	4	40	54	94	**0.149**
86Kr	36	86	50	5	3	41	53	94	**0.128**
86Kr	36	86	50	6	2	42	52	94	**0.106**

If the 78Kr prefers 5 neutron + 3 proton pickup and the 86Kr prefers 3 neutron + 5 proton pickup, then the central asymmetry of the two systems will still be separated in asymmetry.

A difference of 6/2 vs 2/6 will actually switch the asymmetries of the systems.

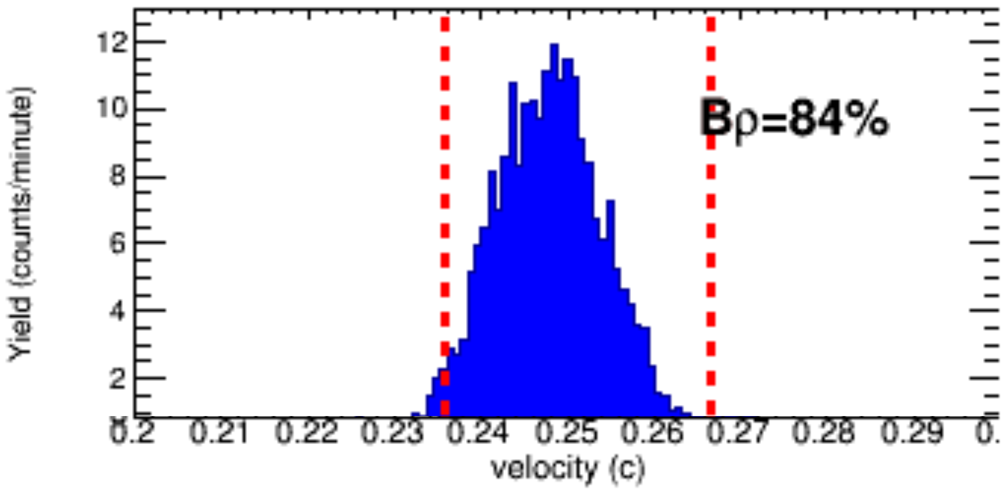
Is it true that $(\Delta Z-\Delta N)_{86} > -2$?
Is is also true that $(\Delta Z-\Delta N)8_8 < 2$?
Cluster structure of 12C to the rescue!... →

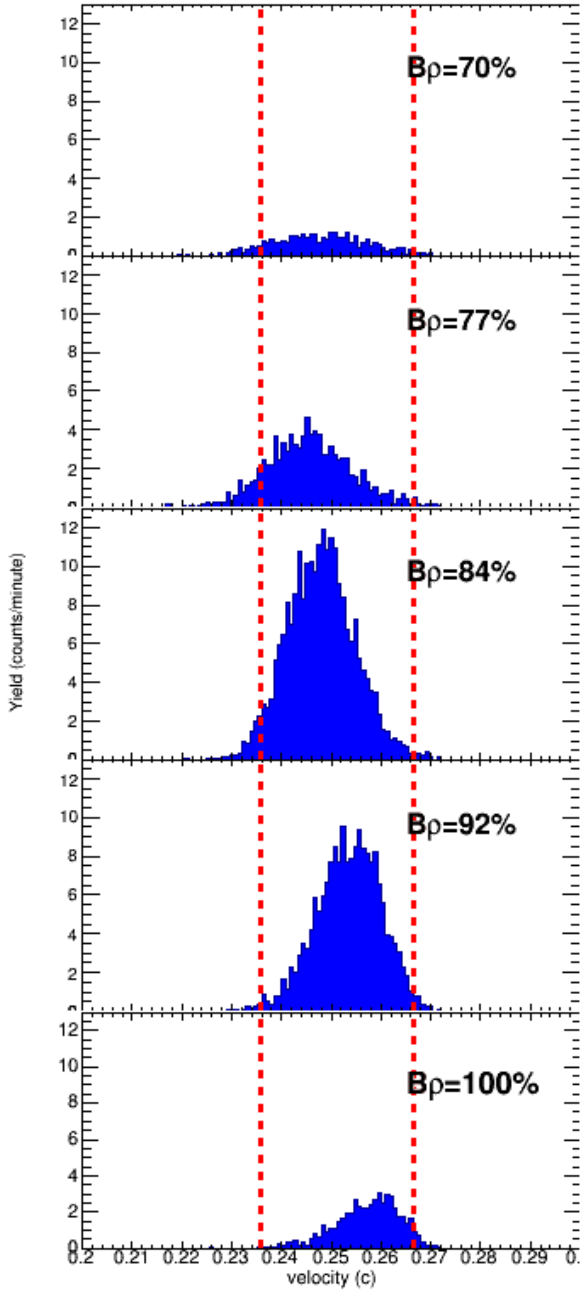


86Kr + C @ 35A MeV

Velocity distribution of fusion-evaporation residues measured.

The velocity distributions indicate that on average about 8 of the 12 nucleons of the target fuse with the heavy projectile.





86Kr + C @ 35A MeV

Velocity distribution of fusion-evaporation residues measured.

The velocity distributions indicate that on average about 8 of the 12 nucleons of the target fuse with the heavy projectile.

What if the un-fused part of the target gets dragged along some?

Bohne et al PRC 41 R5 (1990)

$$\epsilon^* = \tfrac{1}{2}(\cos\theta_R v_P - v_R)v_R + Q_{gg}/m_R$$
$$+ \tfrac{1}{2}\Delta m_P/m_R(\cos\theta_P v_P - v_{P'})v_{P'}$$
$$+ \tfrac{1}{2}\Delta m_T/m_R(\cos\theta_T v_P - v_{T'})v_{T'},$$

using cos = 1, and having 8 nucleon pickup from the carbon, and neglecting Q:
e* = (1/2)(vp-vr)vr + (1/2)(4/94)(vp-vt')vt'

if vt' = 0:
e* = (1/2)(vp-vr)vr =0.5*(0.2666-0.2453)(0.2453) = 0.00401 c^2

if vt' = vr:
e* = (1/2)(vp-vr)vr * (1+ (4/94)) = 0.00418 c^2
That's (obviously) a relative difference of 4/94 = 4.3% in the excitation energy
for the two extreme cases of pre-equilibrium at rest and pre-equilibrium at residue velocity.

BUT cos=1 is not good. cosθt can be much smaller than 1. Extreme is if vp.cosθt = vr.
This also makes the term zero. There will be a maximum around vt' = 0.5 cosθt vp.
then if vt'=0:
e* = (1/2)(vp-vr)vr + (1/2)(4/94)(cosθt vp – vt')vt' = 0.5*(0.2666-0.2453)(0.2453) = 0.00401 c^2
or if vt' = 0.5 cosθt vp:
e* = (1/2)(vp-vr)vr + (1/2)(4/94)(cosθt vp – vt')vt' = 0.00401 + (1/2)*(4/94) vt'^2
e* = 0.00401 + 0.000378 = 0.00439. **This is a 9% effect.**