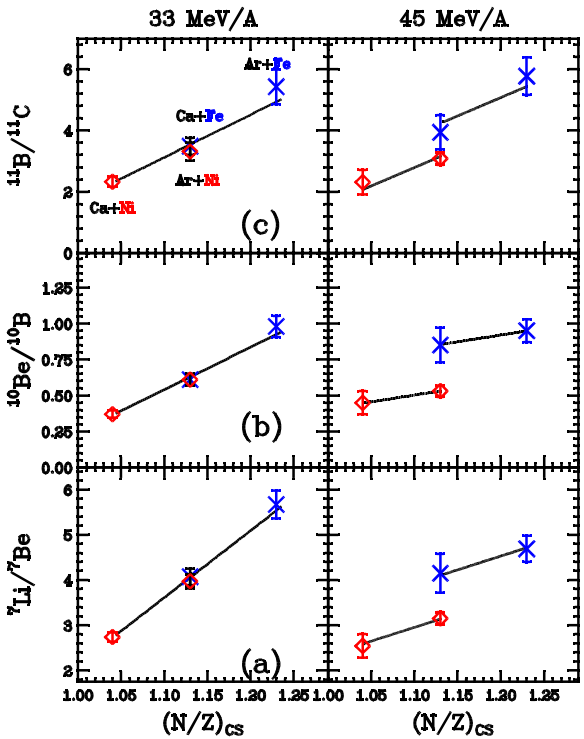
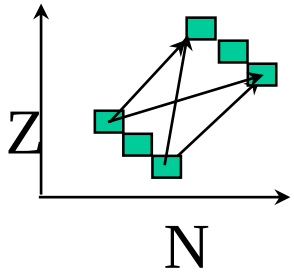
Fragment Isospin as a Probe of Heavy-Ion Collisions

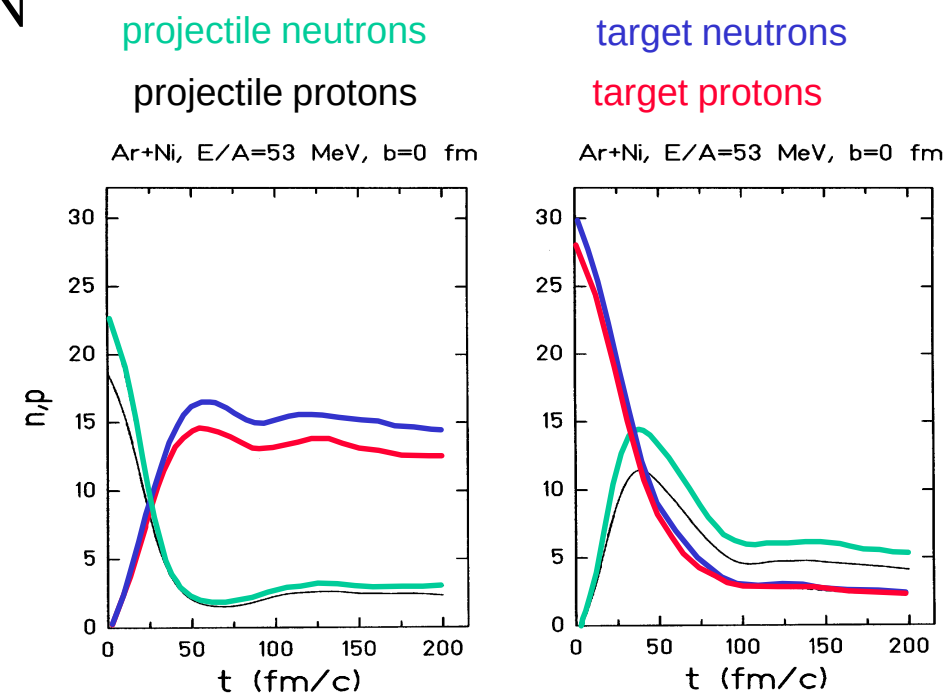
- Symmetry term of EOS
- Equilibration
- “Fractionation” – inhomogeneous distribution of isospin
- Source composition
- Energy spectra
- Dynamics : preequilibrium emission / PLF composition
- Statistical breakup: composition of fragments
- recent work at TAMU and IU
  - Peripheral / mid peripheral events: PLF and MR

Isospin Equilibration

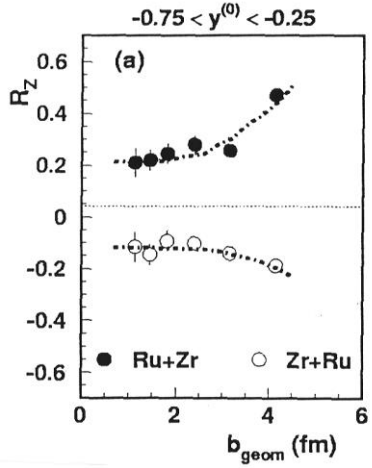


Johnston,1995





B.A. Li, 1996



$$R_z = \frac{2(Z_{\det}) - Z_{\det}^{Zr} - Z_{\det}^{Ru}}{Z_{\det}^{Zr} - Z_{\det}^{Ru}}$$

Rami, 2000

Martin poster

Isotopic composition of fragments as a signature of parent system

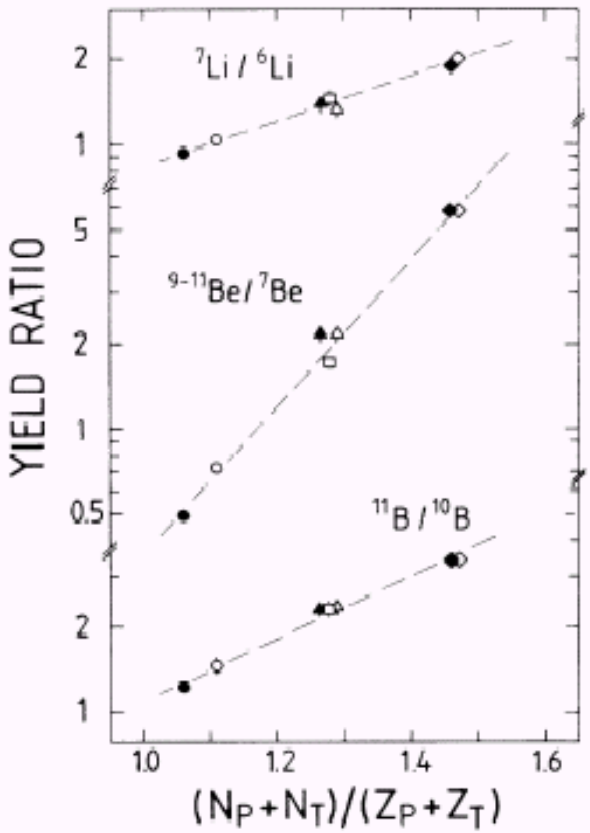


FIG. 1. Ratios of energy-integrated isotope yields, measured at $\theta_{lab}=40°$, as functions of the N/Z ratio of the combined system of projectile and target. Closed and open symbols denote ^{17}C and ^{18}O projectiles, respectively, circles, squares, triangles, and lozenges stand for ^{58}Ni, ^{64}Ni, ^{nat}Ag, and ^{197}Au targets, respectively. The dashed lines are meant to guide the eye.

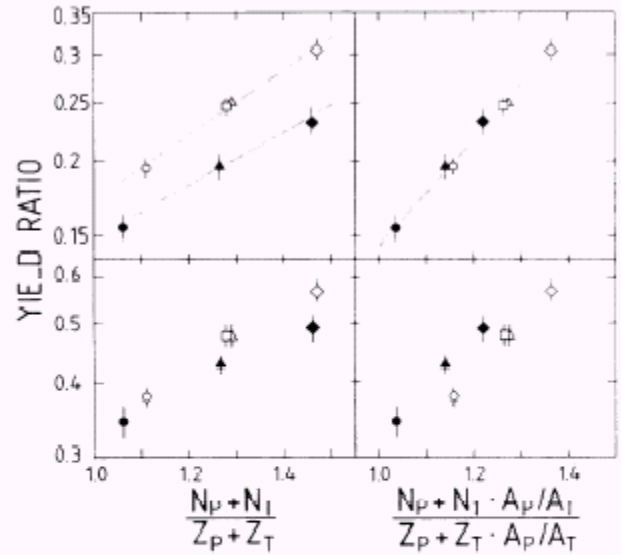
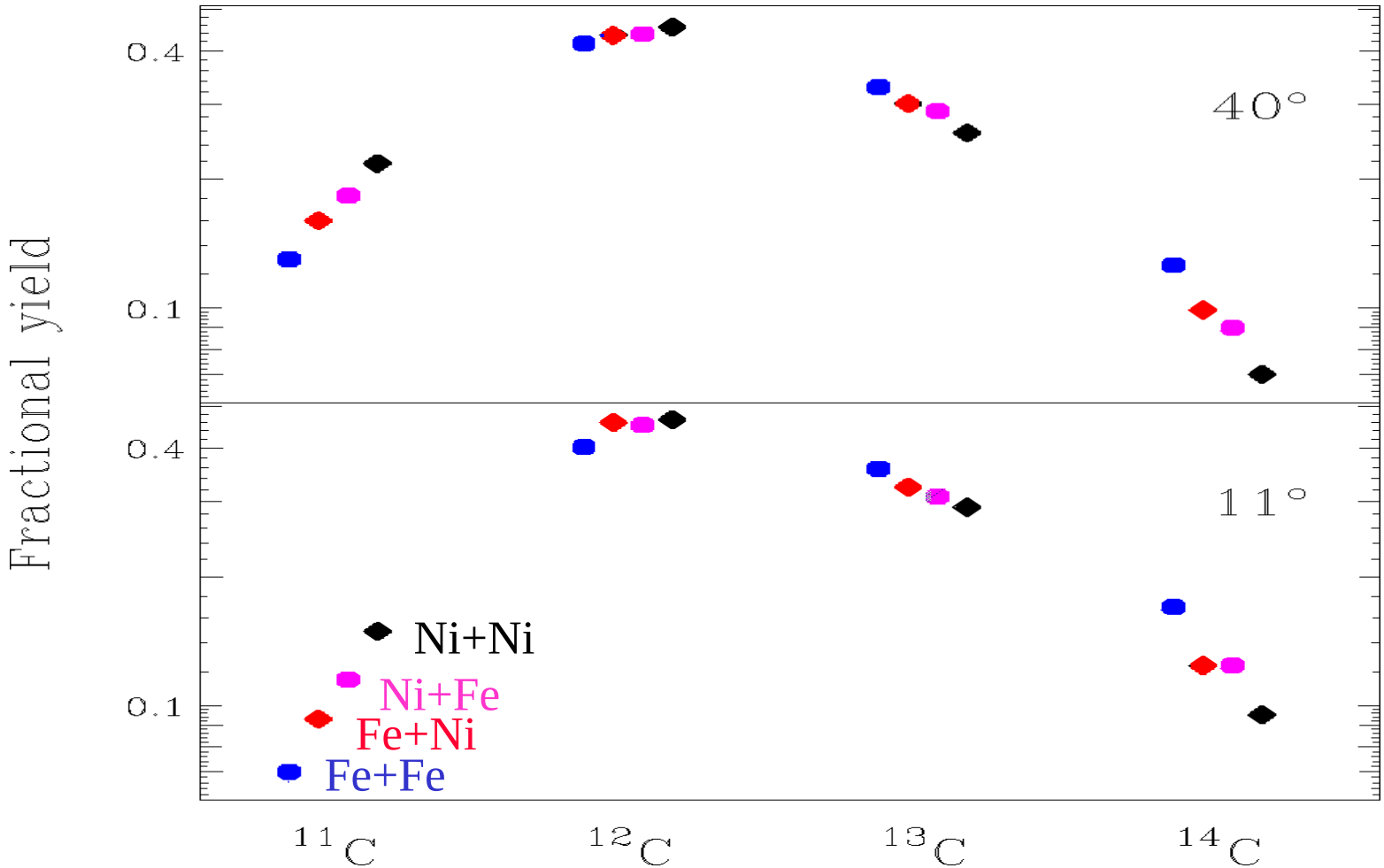


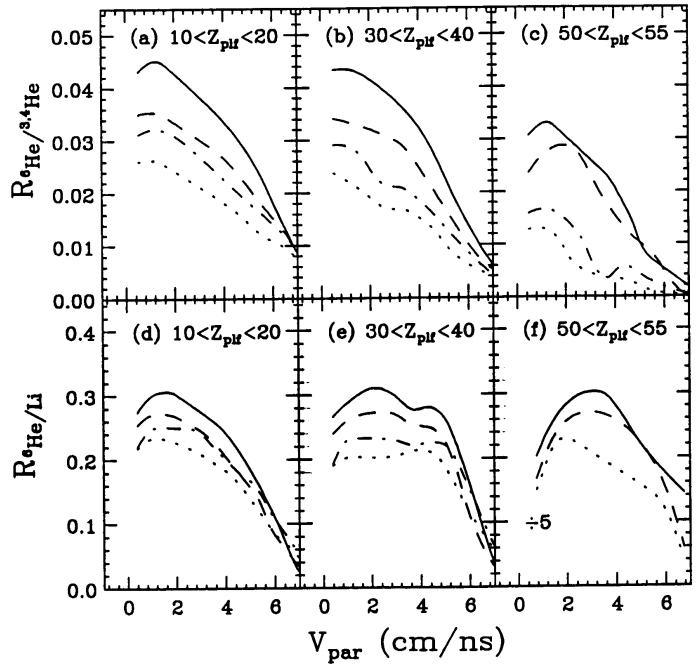
FIG. 2. Ratios of triton to proton yields (top) and triton to deuteron yields (bottom), measured at $\theta_{lab}=40°$, and plotted as functions of the N/Z ratios of the combined system (left-hand side) and of a source consisting of equal numbers of nucleons from the projectile and from the target (right-hand side). The symbols are chosen as in Fig. 1, the dashed lines are meant to guide the eye.

R. Wada, Phys. Rev. Lett. **58**, 1829-1832 (1987)

30MeV/nucleon ^{58}Fe,^{58}Ni + ^{58}Fe, ^{58}Ni
Carbon fragments



Ramakrishnan et al, PRC 57, 1803 (1998)



$^{124,136}Xe + {}^{112,124}Sn$

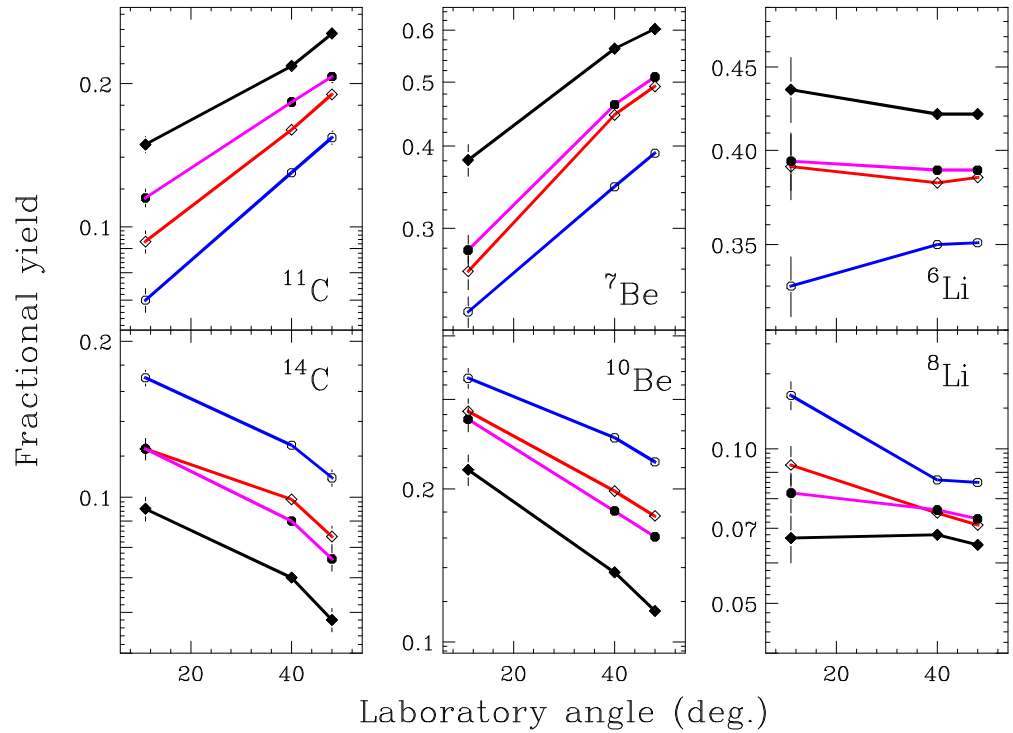
55MeV/nucleon

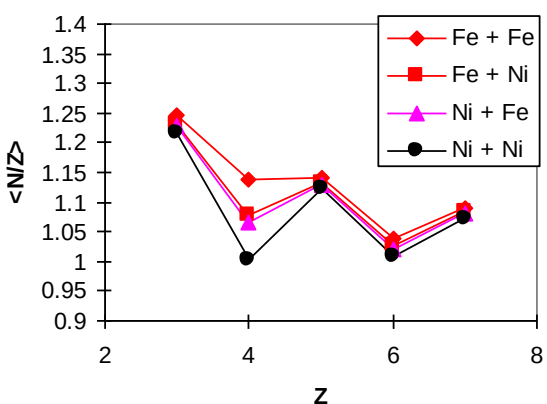
Dempsey et al, PRC 54, 1710(1996)

^{58}Fe, ^{58}Ni + ^{58}Fe, ^{58}Ni

30 MeV/nucleon

Ramakrishnan et al, PRC 57, 1803 (1998)





$$\left\langle \frac{N}{Z} \right\rangle = \frac{{}^{3}He + 2\left({}^{4}He\right) + 4\left({}^{6}He\right)}{2\left({}^{3}He + {}^{4}He + {}^{6}He\right)}.$$

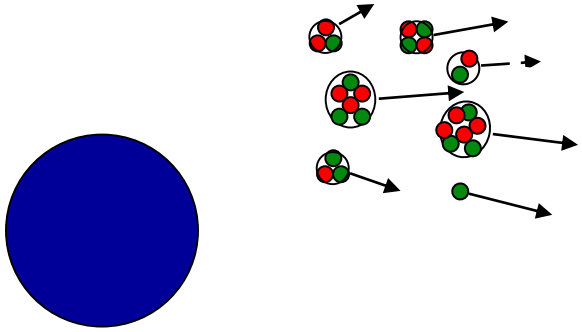
Martin, et al PRC (2000)

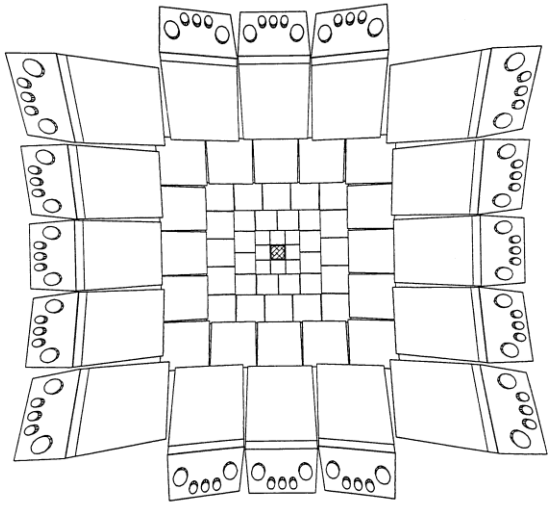
Projectile fragmentation
(with isotopically reconstructed QP)

- Isospin effects the dynamics
- QP with a diversity in isospin
- Possible route to neutron-rich RNB
  - > G.Souliotis clip

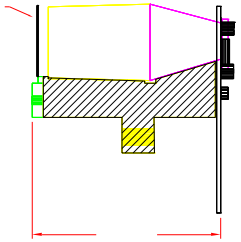
$^{28}Si + ^{112}Sn, ^{124}Sn$ @ 30,50MeV/nucleon

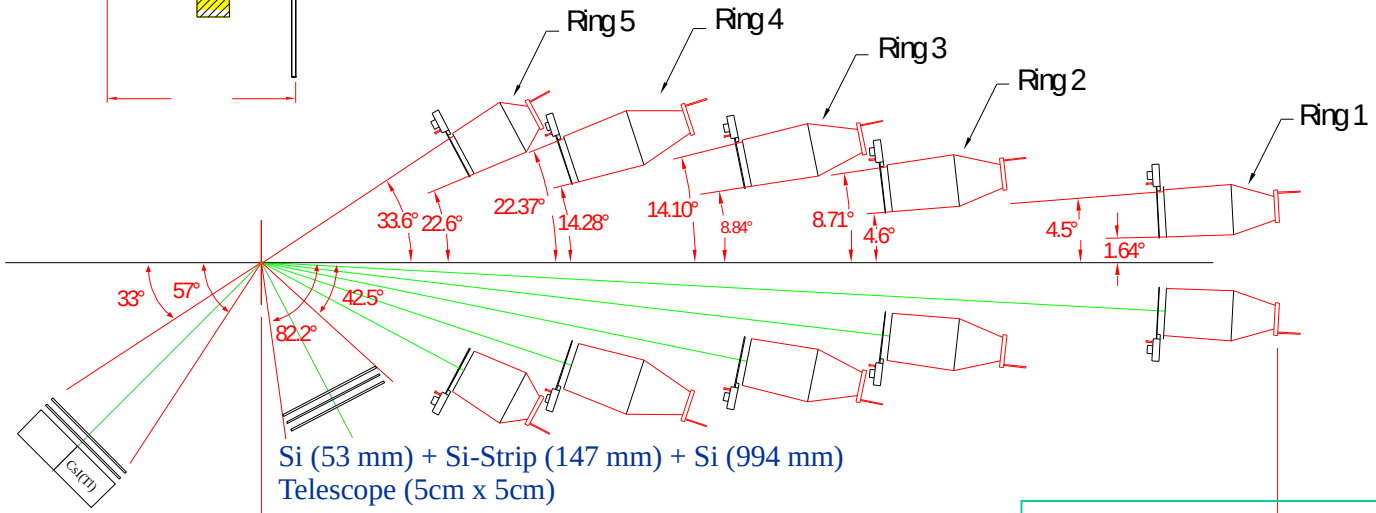
$^{20}F, ^{20}Ne, ^{20}Na + Au$ @ 32 MeV/nucleon





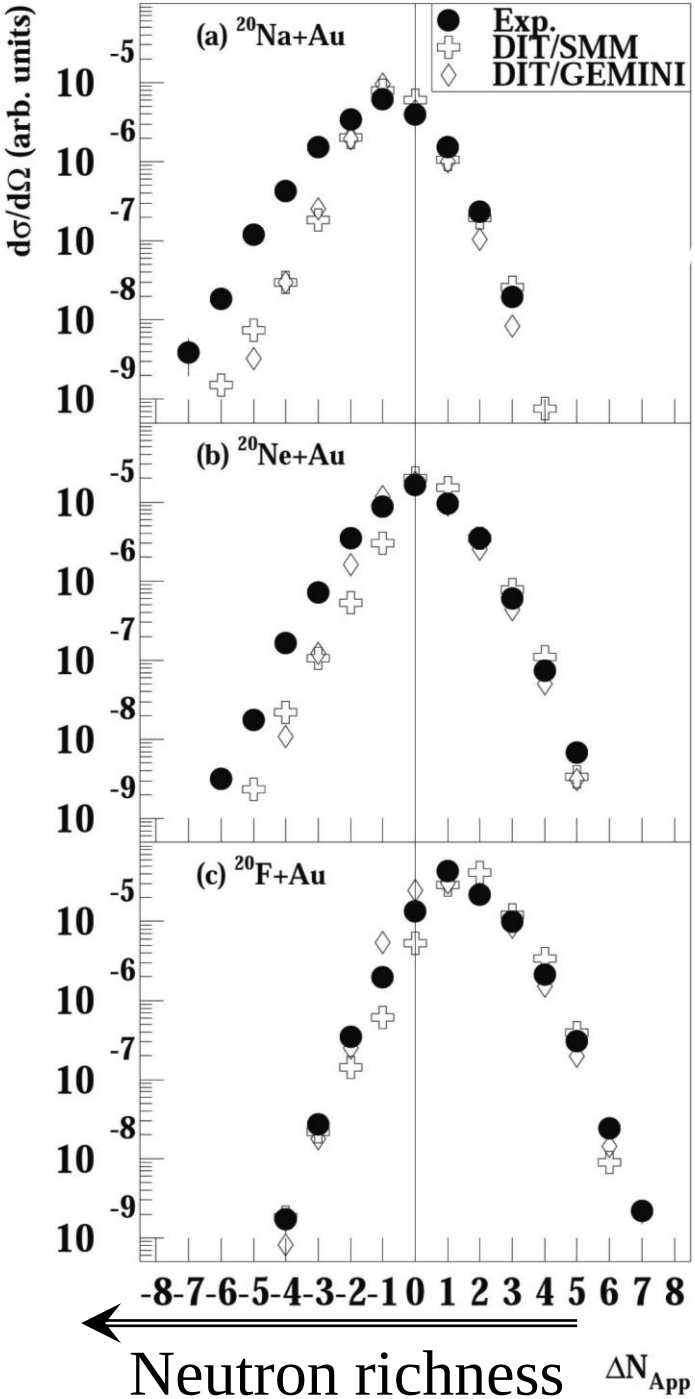
FAUST

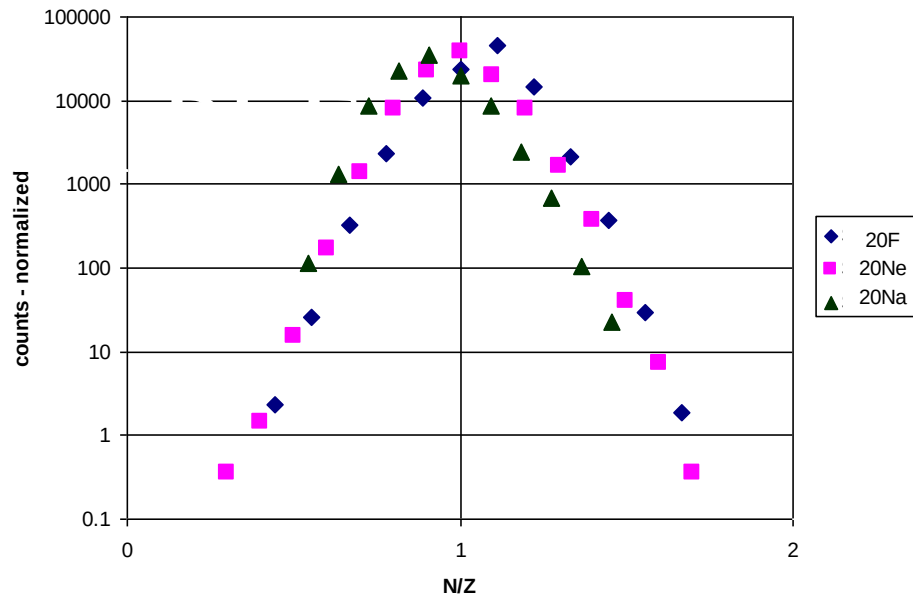




Keksis poster

^{20}F, ^{20}Ne, ^{20}Na + Au @ 32 MeV/nucleon

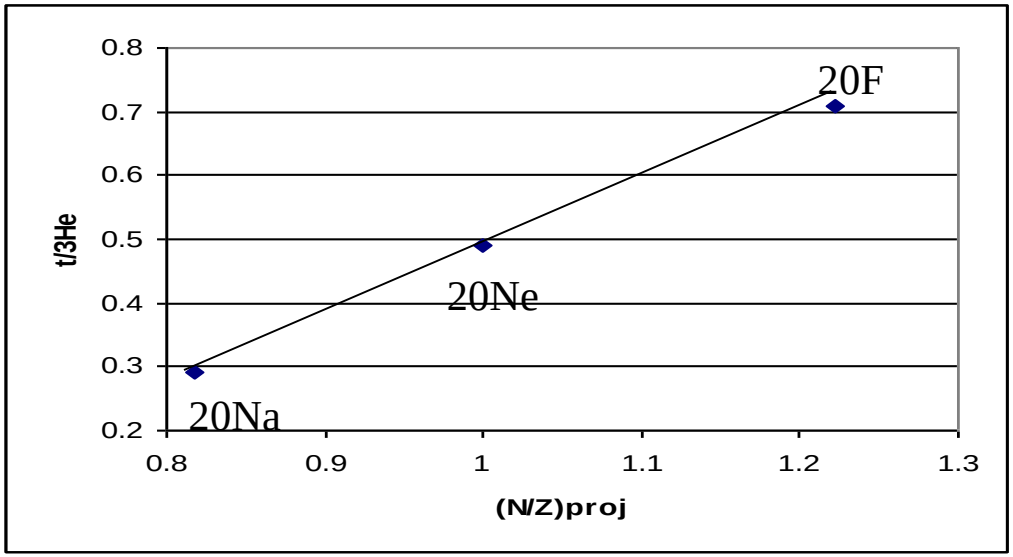




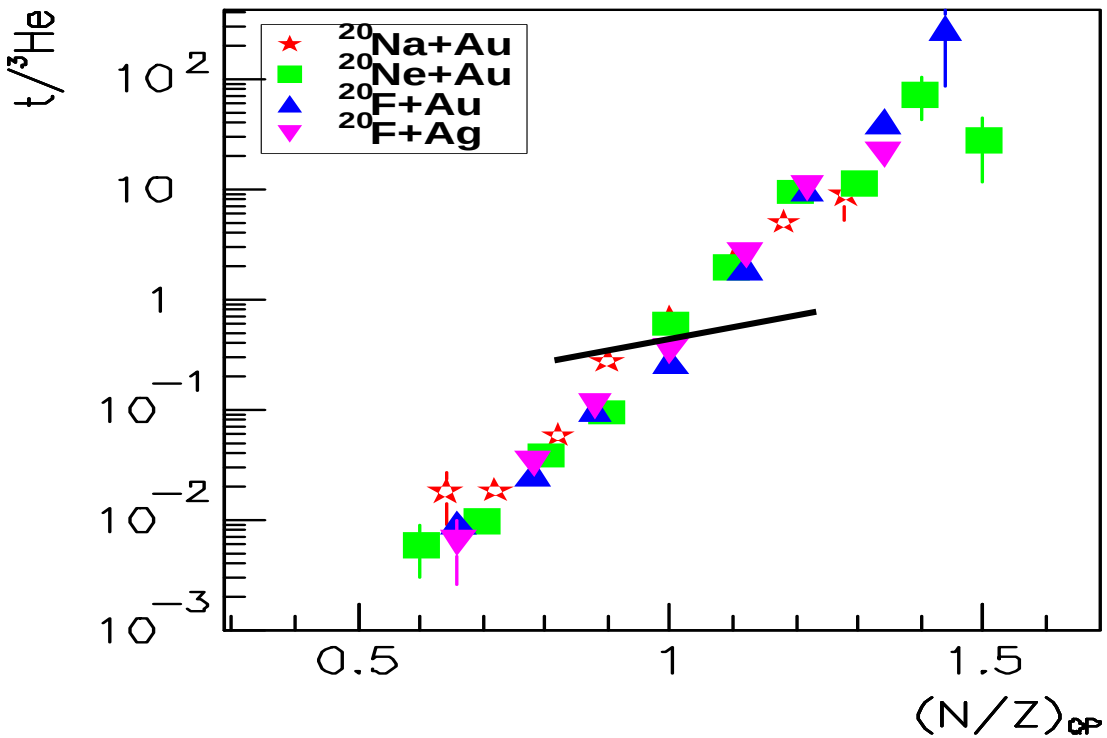
Beam	<N/Z> proj	<N/Z> DIT	<N/Z> DIT+evap	<N/Z> exp
20Na	.818	.926	.876	.912
20Ne	1	1.06	.953	1
20F	1.22	1.23	1.02	1.07

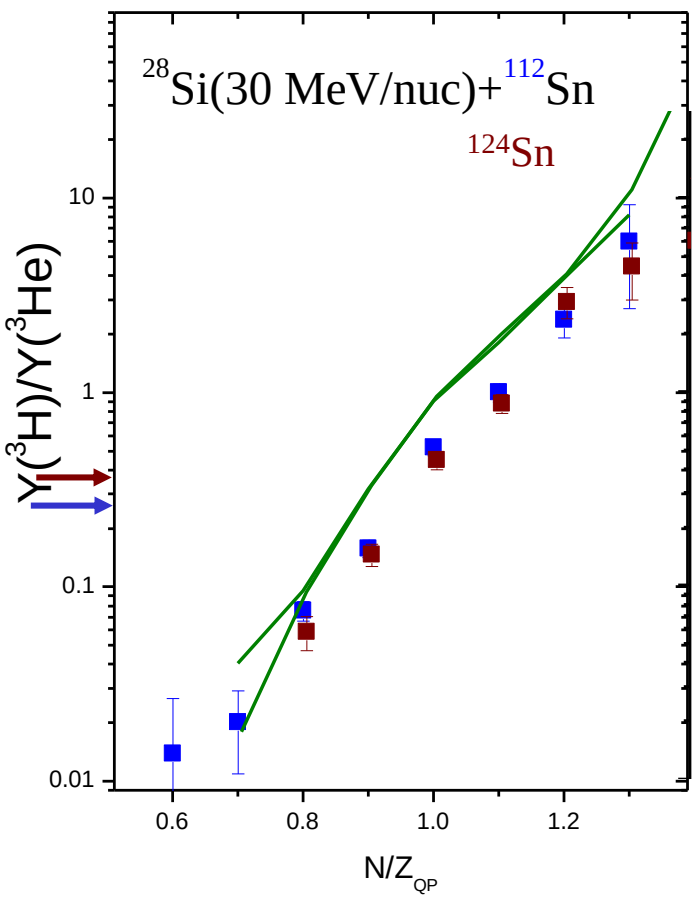
D. Rowland

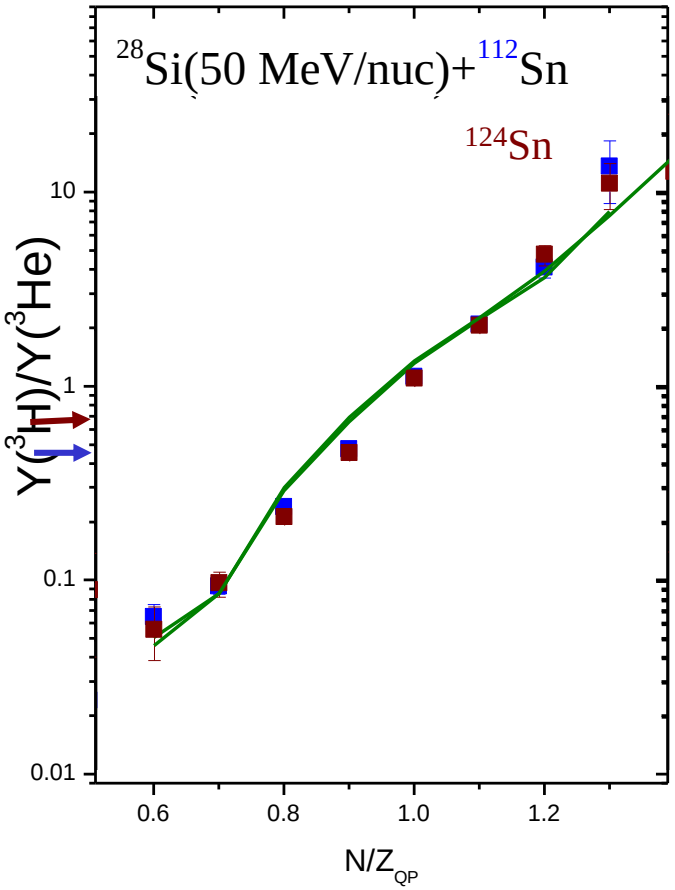
Distillation of a neutron-rich gas?



Projectile fragmentation of ^{20}Na,^{20}Ne,^{20}F at 35 Mev/nucleon



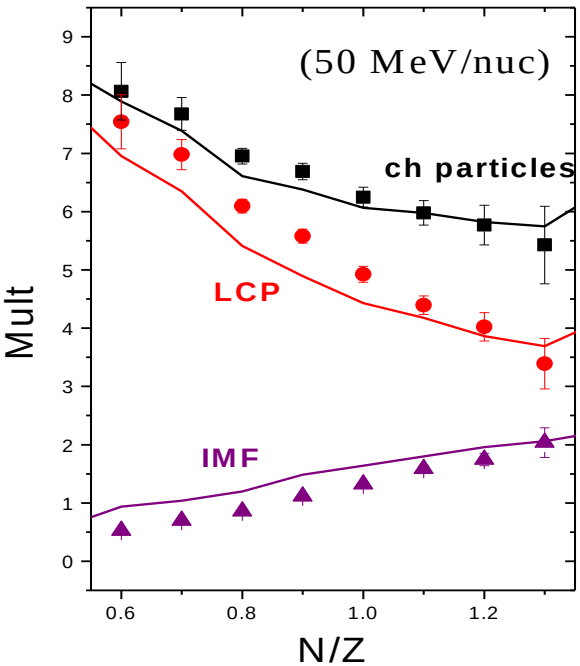


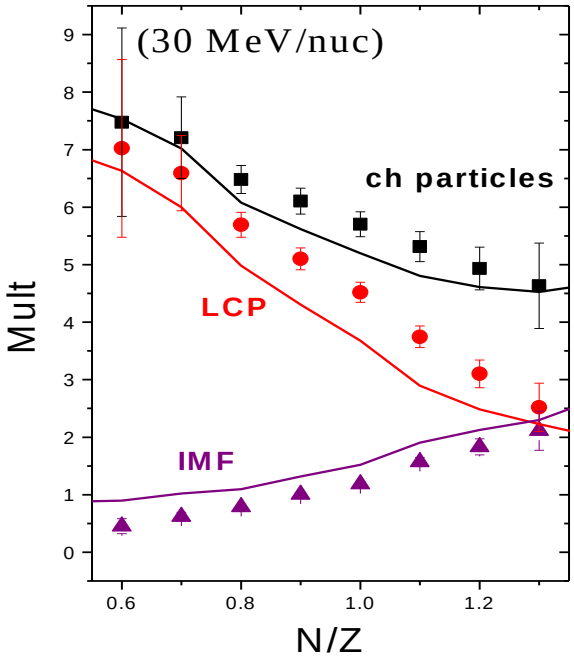


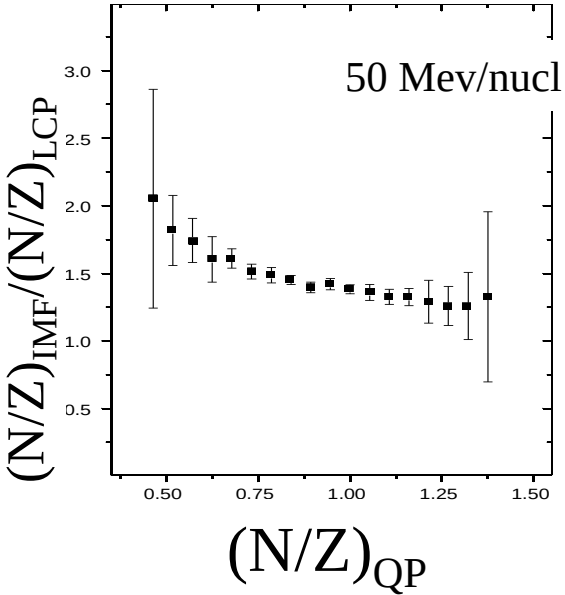
	30 MeV		50 MeV	
	^{28}Si + ^{112}Sn	^{28}Si + ^{124}Sn	^{28}Si + ^{112}Sn	^{28}Si + ^{124}Sn
exp	4.0 ± .4	4.1 ± .1	3.2 ± .2	2.8 ± .3
DIC+SMM	3.9 ± .2	4.6 ± .2	3.2 ± .2	3.1 ± .1

Veselsky, Phys. Rev. C **62**, 064613 (2000).

$^{28}Si + ^{112}Sn$; 30 & 50 Mev/nuc projectile fragmentation reactions



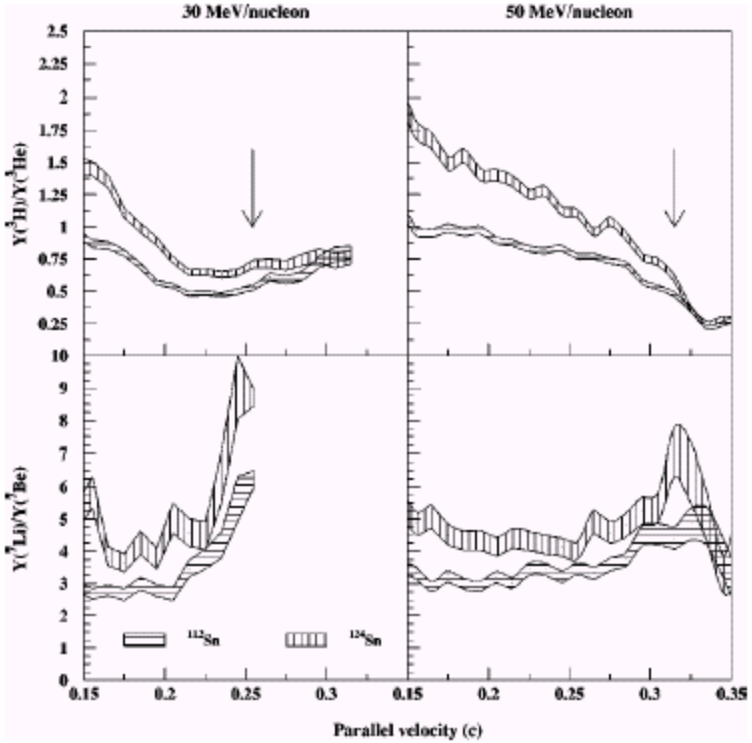




Both the multiplicity and neutron content of the fragmentation products are dependent on the N/Z of the fragmenting system

Veselsky, *Phys. Rev. C* **62**, 041605 (2000)

PLF : Z=12-15 => second source



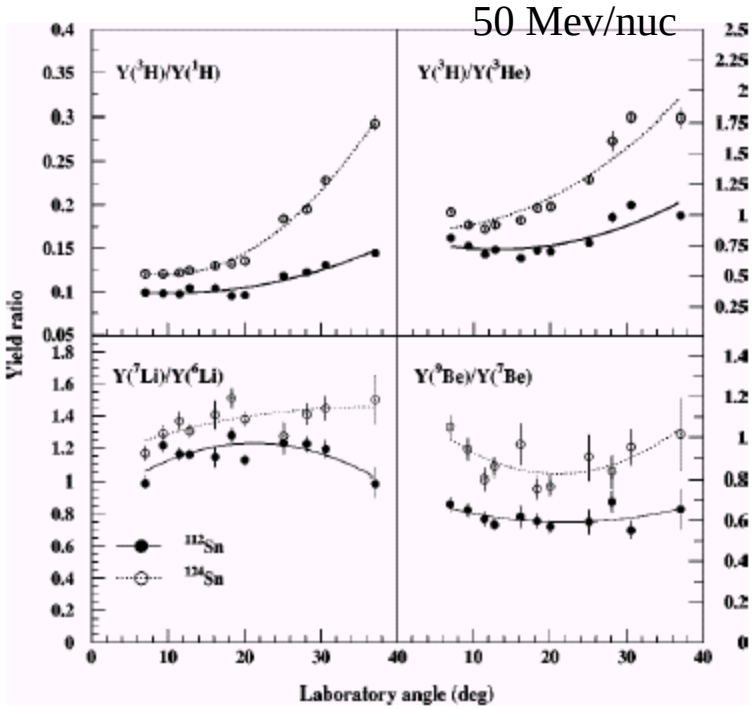
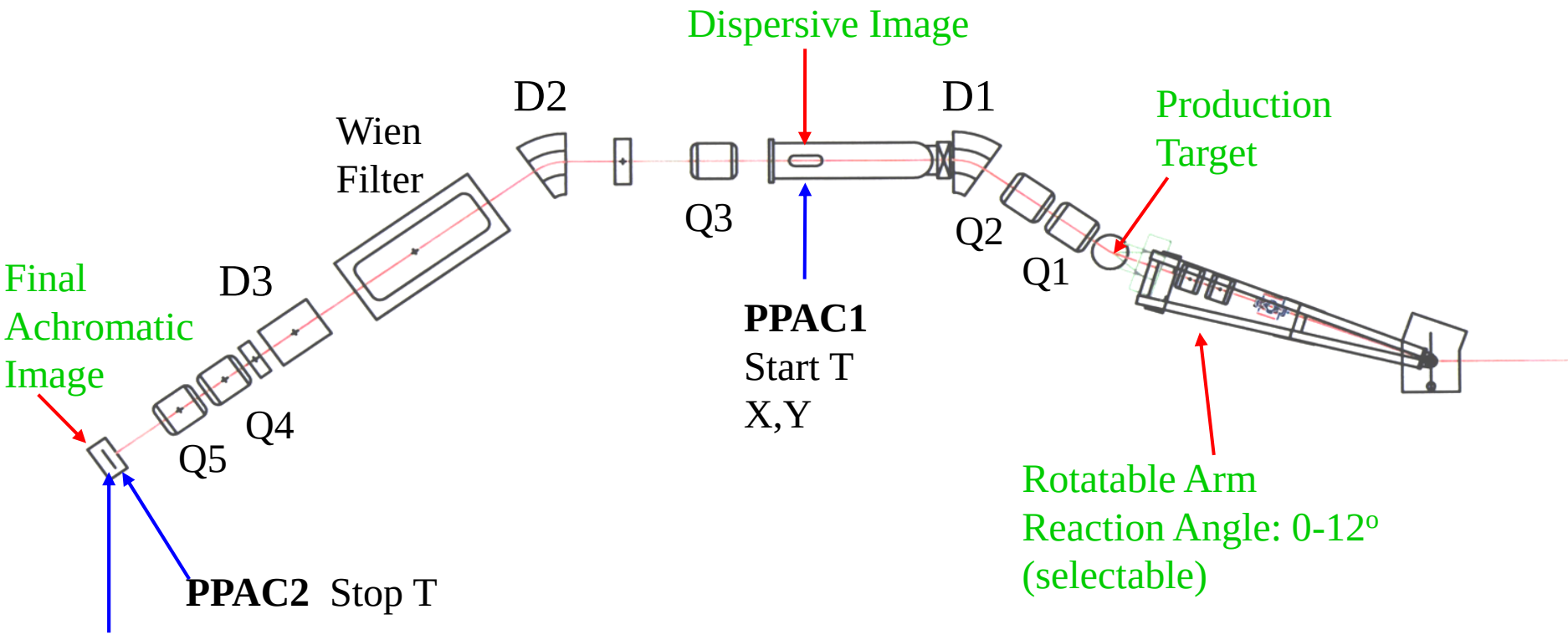


TABLE II. Yields of light charged particles from reconstructed events of $^{28}Si+^{112}Sn$ at 50 MeV/nucleon divided by the yields from $^{28}Si+^{124}Sn$. The ratios were normalized for the same number of events for both targets. All LCPs were measured in the range of 1.64°–33.6° in the laboratory.

Particle	Overall	QP decay	Direct emission
^{1}H	1.36	1.24	2.58
^{2}H	1.15	1.11	1.40
^{3}H	0.96	1.01	0.53
^{3}He	1.32	1.23	1.74
^{4}He	1.12	1.10	1.18

Laforest, PRC 59, 2567 (1999)

Rare Isotope Production with MARS



Silicon Telescope:
ΔE_1, X,Y (Strips)
ΔE_2, Er

MARS Acceptances:
Anglular: 9 msr
Momentum: 4 %

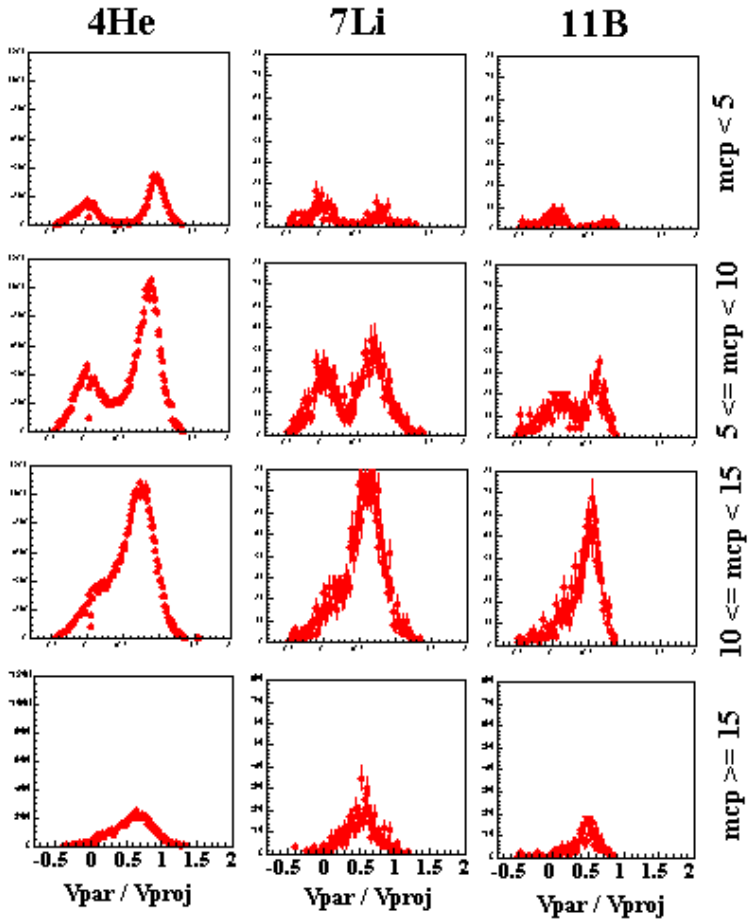
Souliotis Clip

Fragments at mid rapidity

larger fragments from midrapidity

(Rapidity Dist. for Z = 2, 3, 4 for different Multiplicity Bins)

^{124}Xe, ^{124}Sn + ^{112,124}Sn



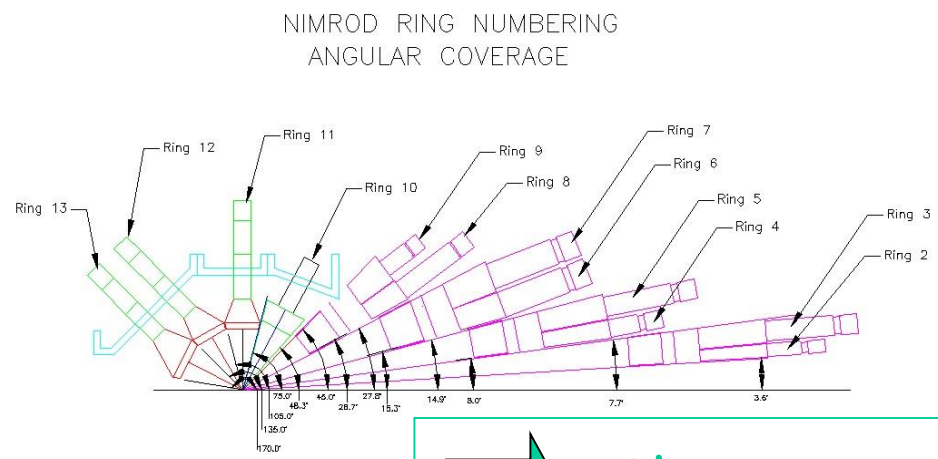
28MeV/A ^{209}Bi + ^{136}Xe

<b> = 12.4 fm

TABLE I. Characterization of LCP and IMF yields from the peripheral ($\langle E_{loss} \rangle \simeq 0.3$ GeV) ^{209}Bi + ^{136}Xe reactions at $E_{lab}/A = 28$ MeV in terms of partial multiplicities associated with TLF, PLF, and NZ sources, and in terms of in-plane versus out-of-plane anisotropy of intermediate-velocity fragment yield ($0°/90°_{NZ}$).

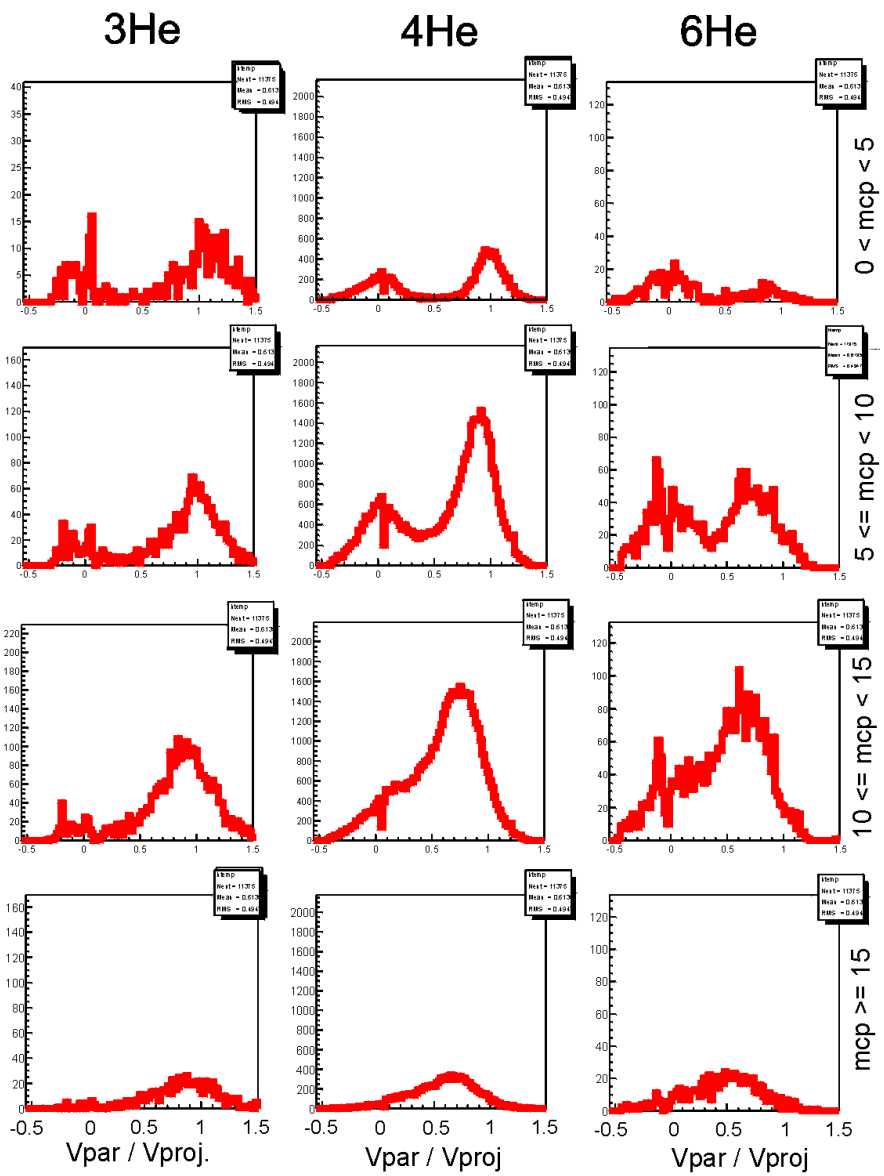
	p	d	t	α	Li	Be	B	C	$6 \le Z \le 8$
$\langle m_{TLF} \rangle$	0.35	0.16	0.15	0.48	0.02	0.01	0.01	0.01	0.02
$\langle m_{PLF} \rangle$	0.28	0.08	0.07	0.28	0.01	0.01	0.00	0.00	0.01
$\langle m_{NZ} \rangle$	0.02	0.02	0.08	0.33	0.06	0.04	0.04	0.03	0.10
% in NZ	4	9	26	30	68	82	83	81	82
$0°/90°_{NZ}$	1.1	1.6	1.6	1.8	2.1	2.5	2.4	2.3	2.4

Toke, PRL 75, 2920 (1995)



Shetty poster

Rapidity Dist. for ^{3}He, ^{4}He, ^{6}He for different Multiplicity Bins

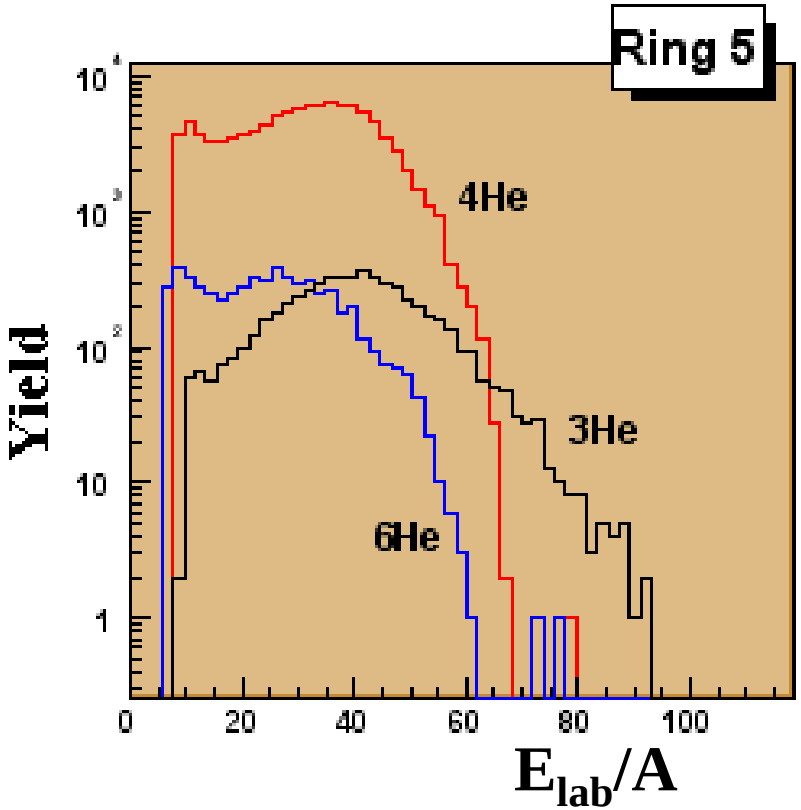


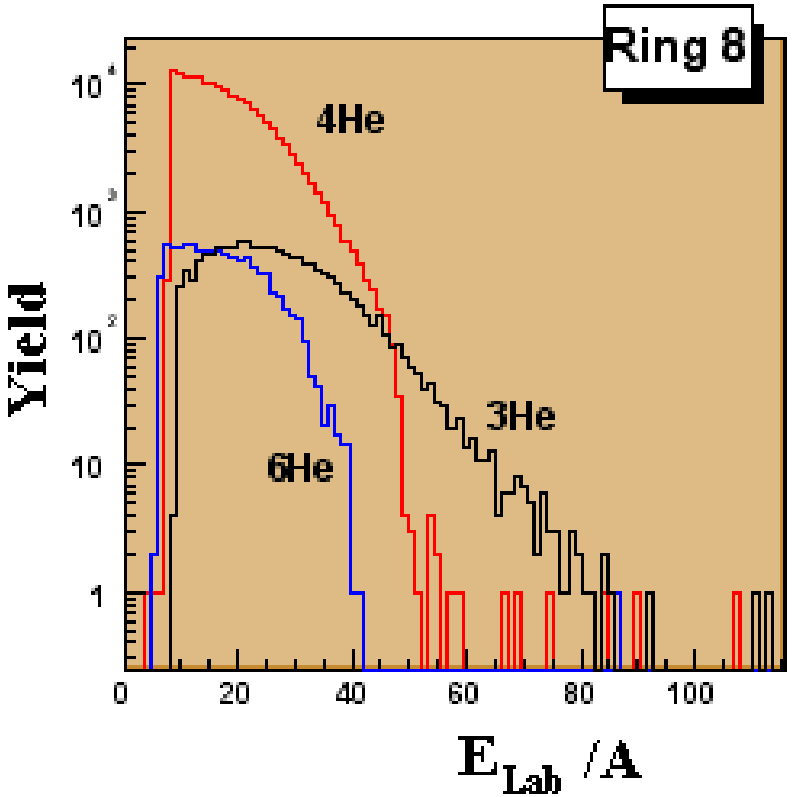
^{124}Xe, ^{124}Sn + $^{112,124}Sn$

Shetty poster

3He, 4He, 6He Spectra Comparison

^{124}Xe, ^{124}Sn + $^{112,124}Sn$



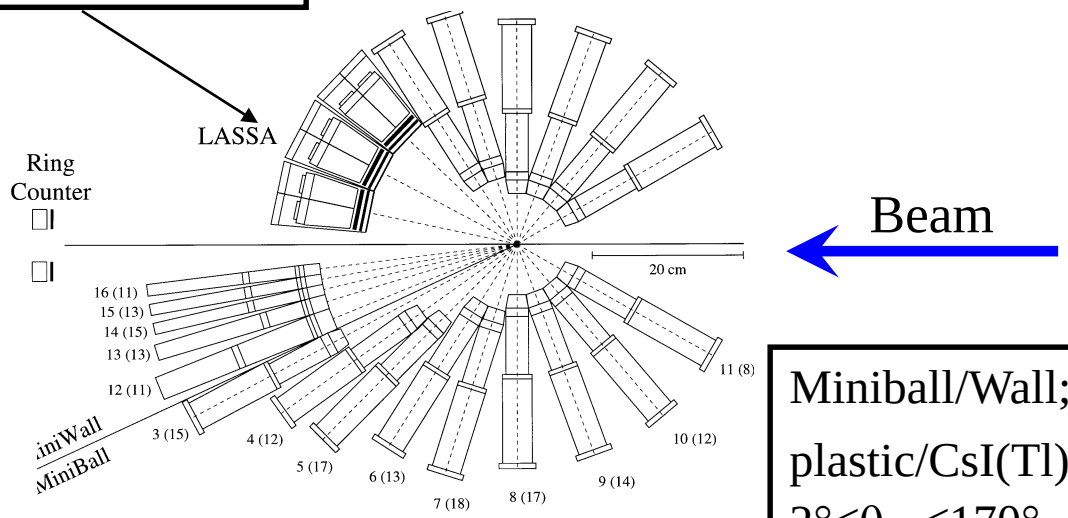


^{114,106}Cd + ^{92,98}Mo at E/A = 50 MeV

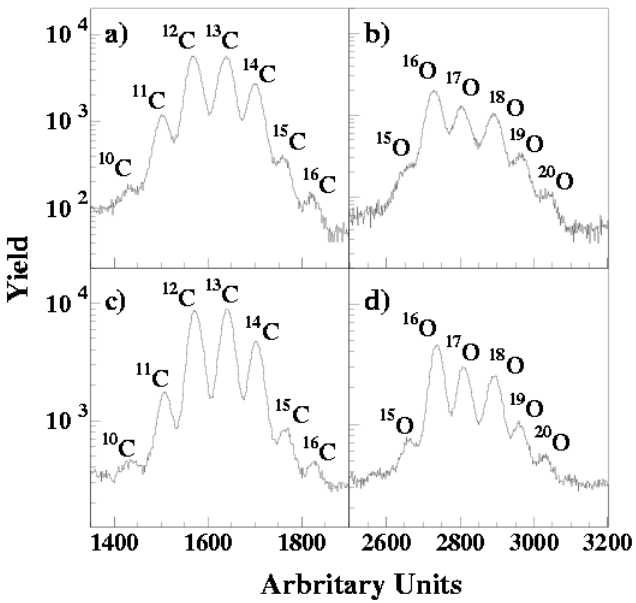
LASSA: 9 telescope Si(IP)-Si(IP)-CsI(Tl)/PD array; $7° \leq \theta_{lab} \leq 58°$

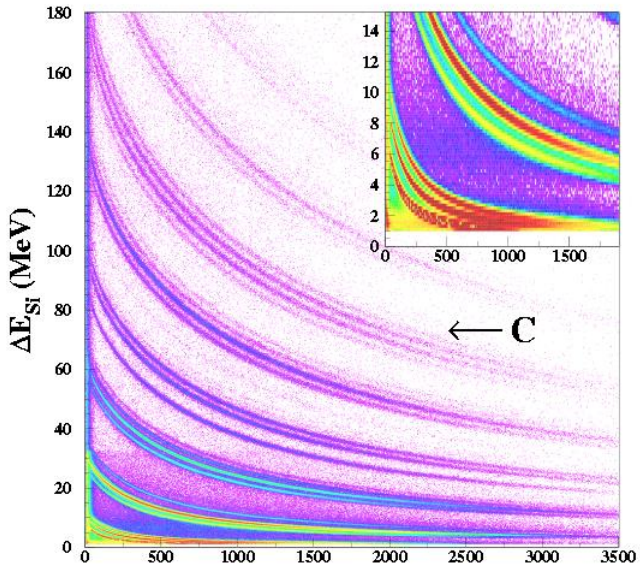
Si-CsI(Tl)/PD; $2.5° \leq \theta_{lab} \leq 4.5°$

LASSA



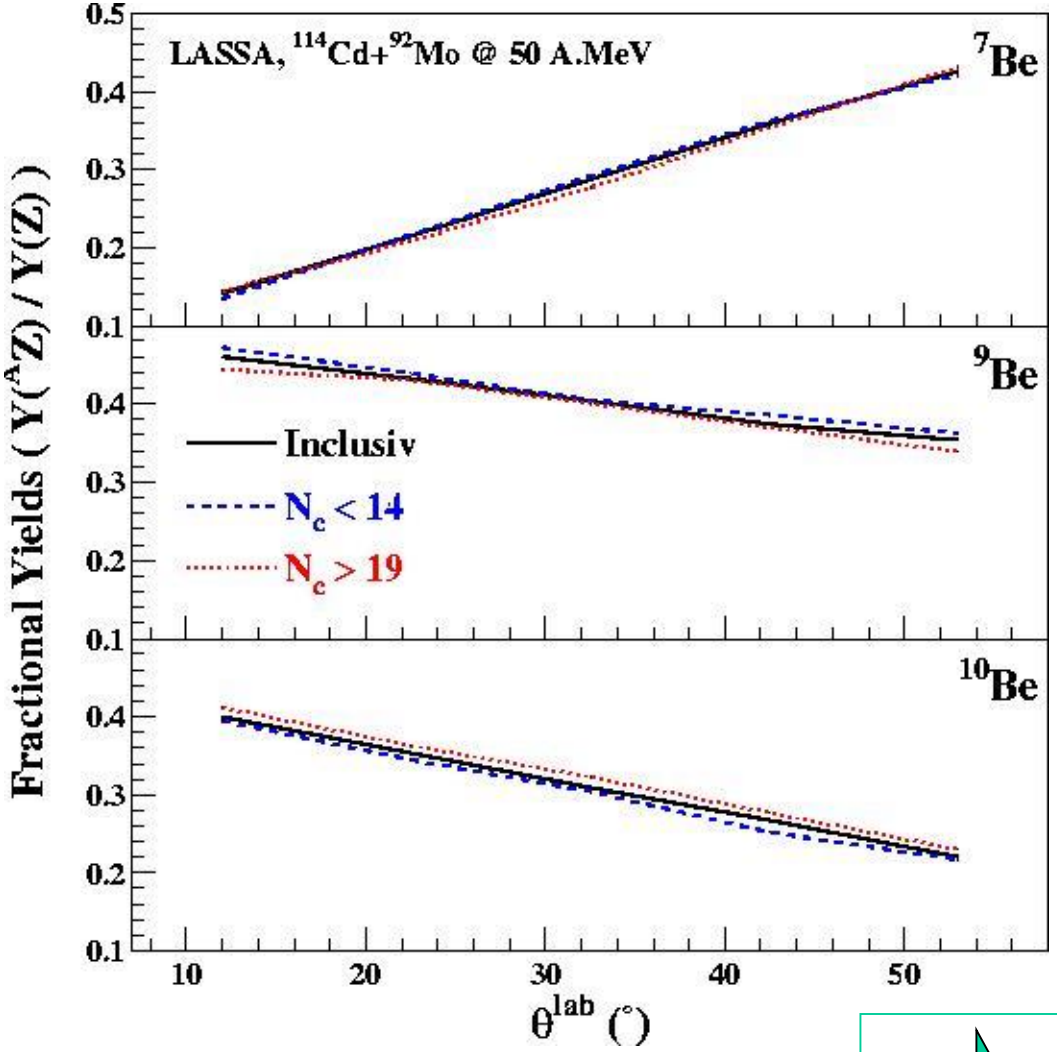
Miniball/Wall; Fast plastic/CsI(Tl); $2° \leq \theta_{lab} \leq 170°$





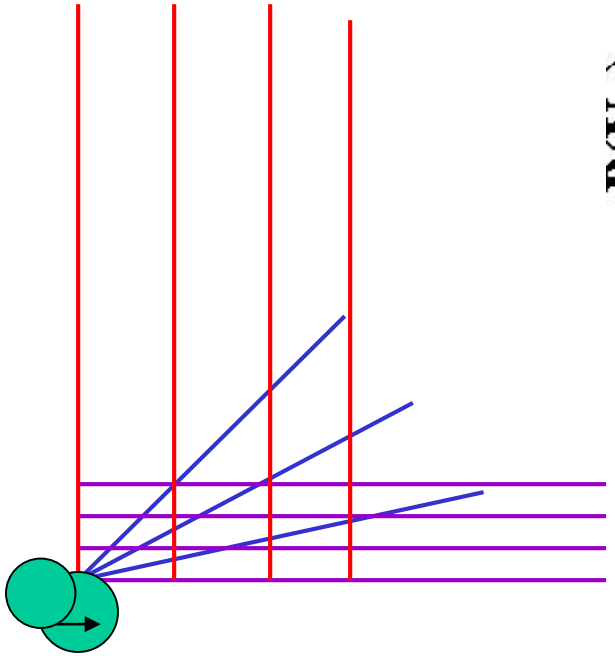
Reproducing Ramakrishnan

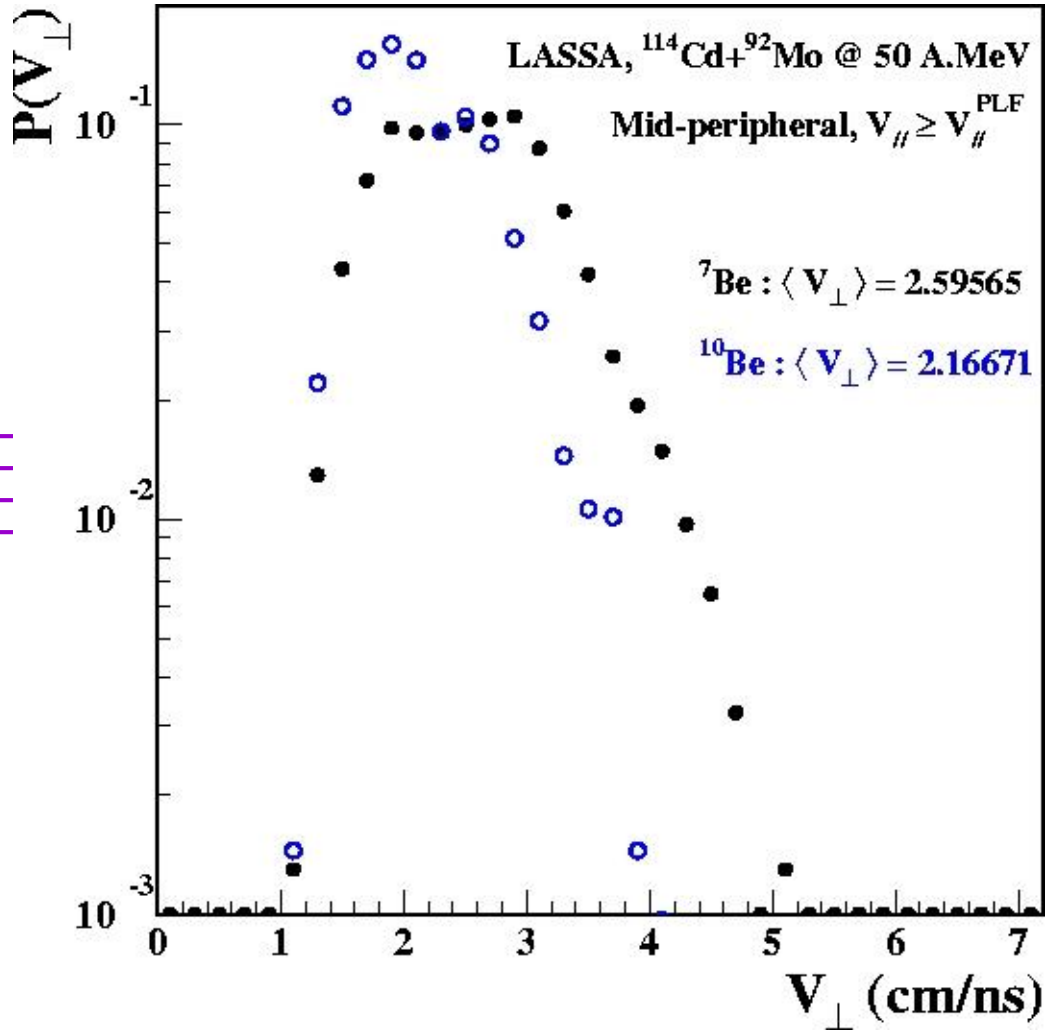
(neutron deficient isotopes dominate at central angles)



Hudan Clip

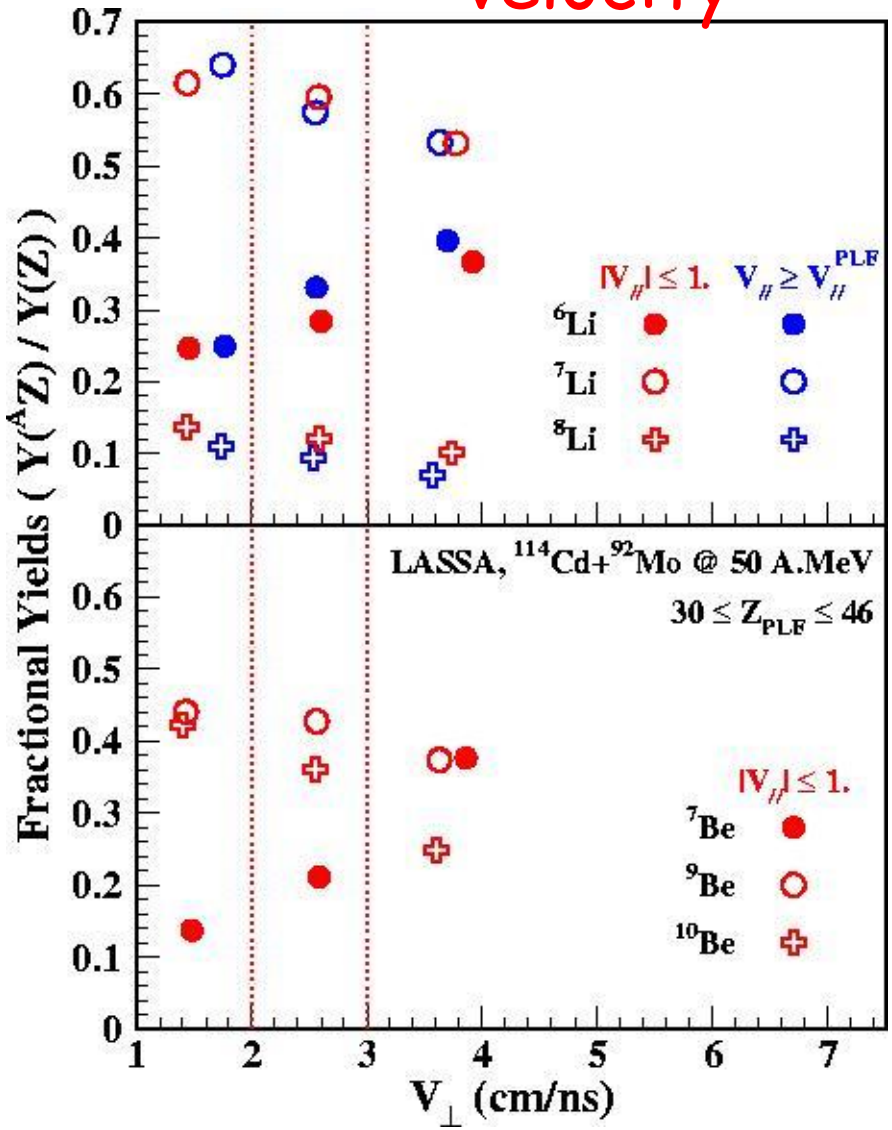
Perpendicular velocity spectra





Hudan Clip

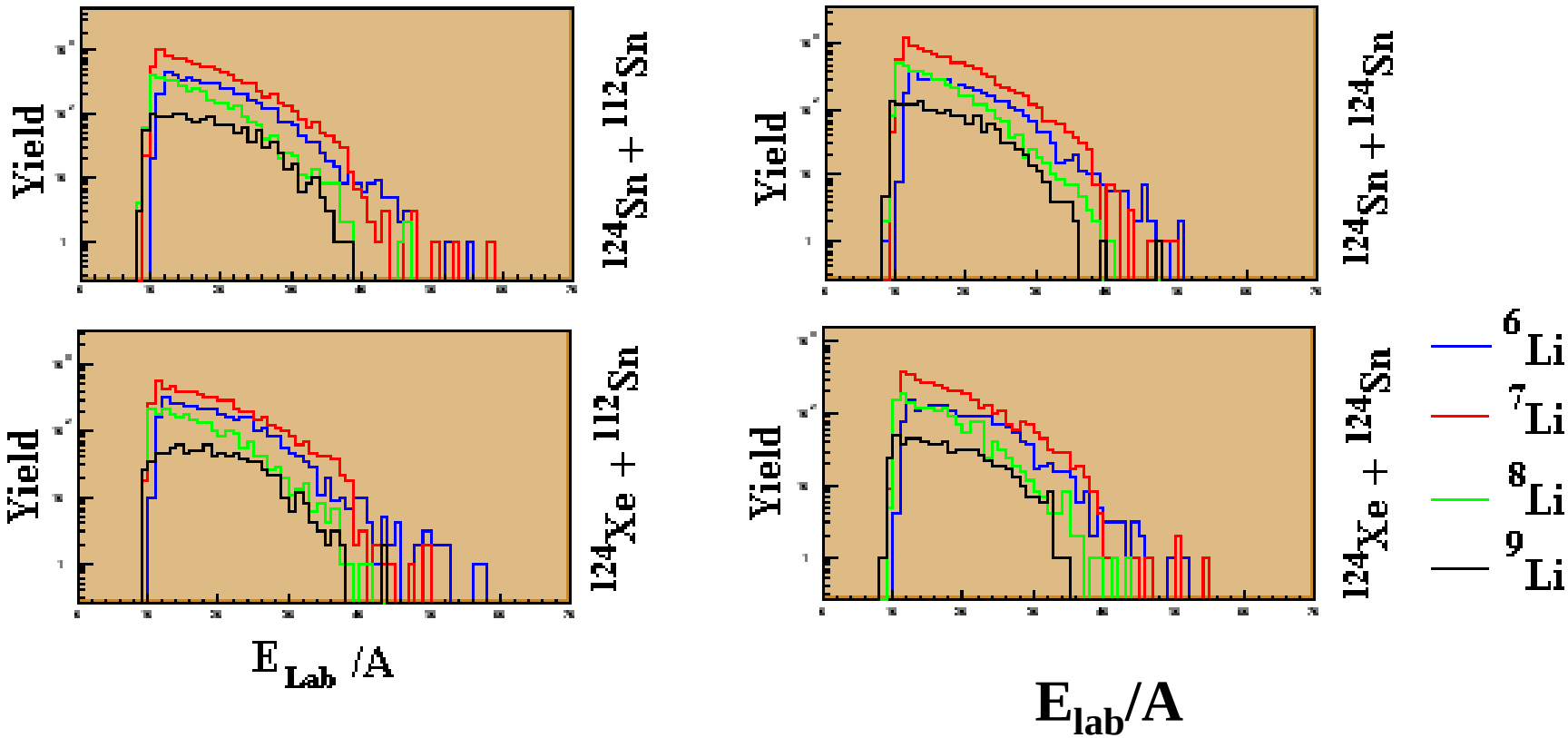
Fractional yield as function of perpendicular velocity



Hudan Clip

Spectral Comparison for Z = 3 Isotopes (change in slope trend for heaviest isotope?)

^{124}Xe, ^{124}Sn + $^{112,124}Sn$



Shetty poster

isotopic energy spectra (preequilibrium effects)

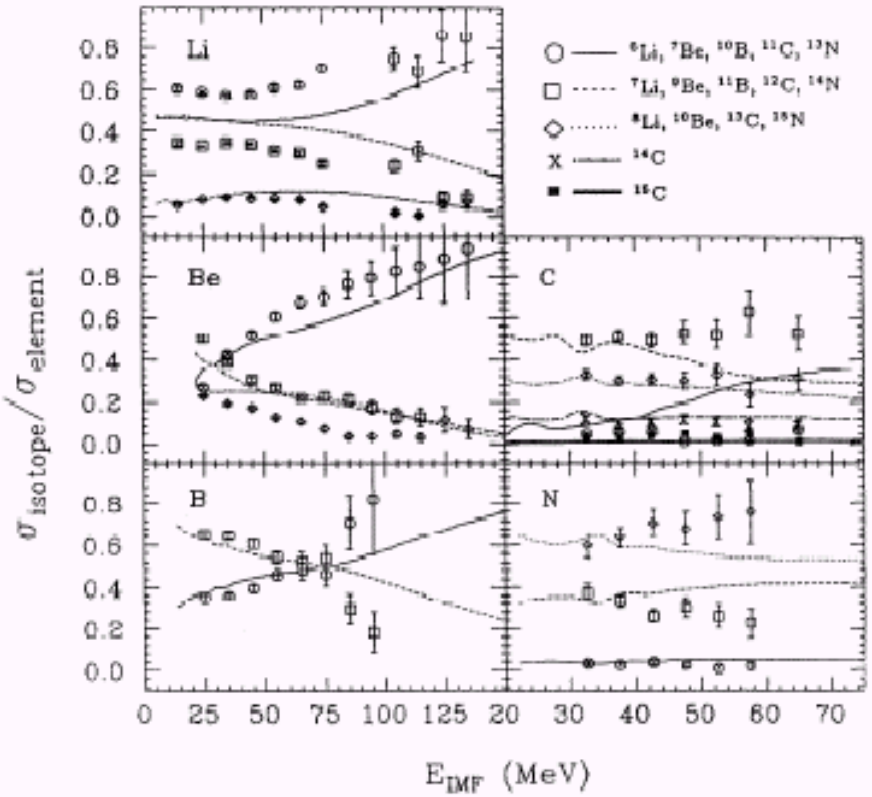


FIG. 5. Ratio of individual isotopic yields to total element yield for Li, Be, B, C, and N fragments observed at 15° as a function of IMF energy. Lines are the result of an accreting-source calculations [13], as identified in the figure. Nuclides are identified by key at upper right.

E. Renshaw, Phys. Rev. C **44**, 2618-2624 (1991)

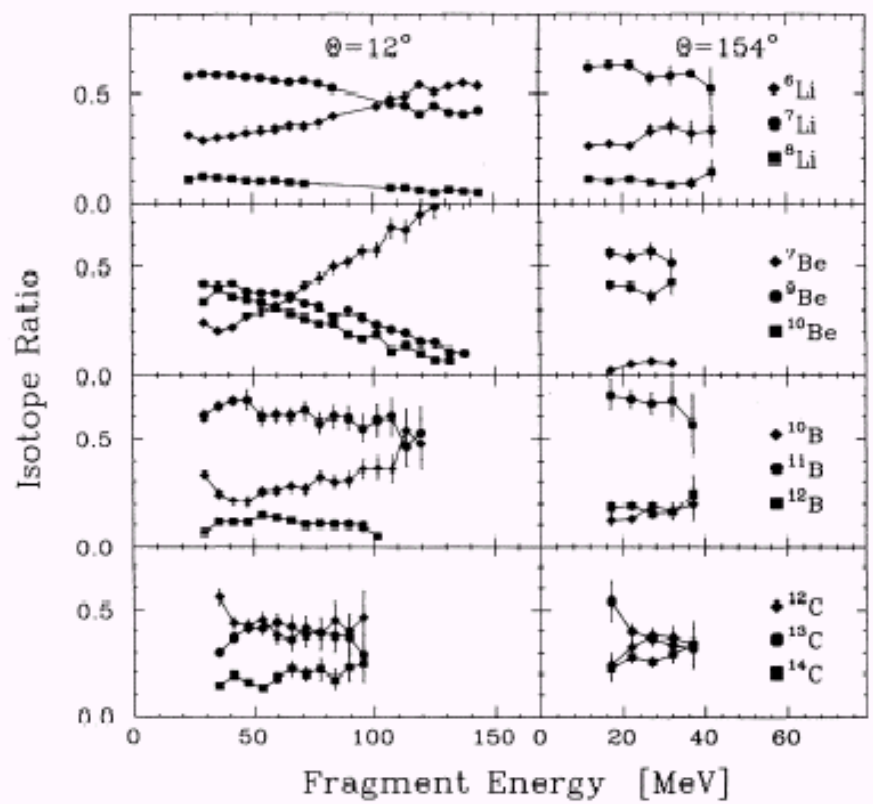
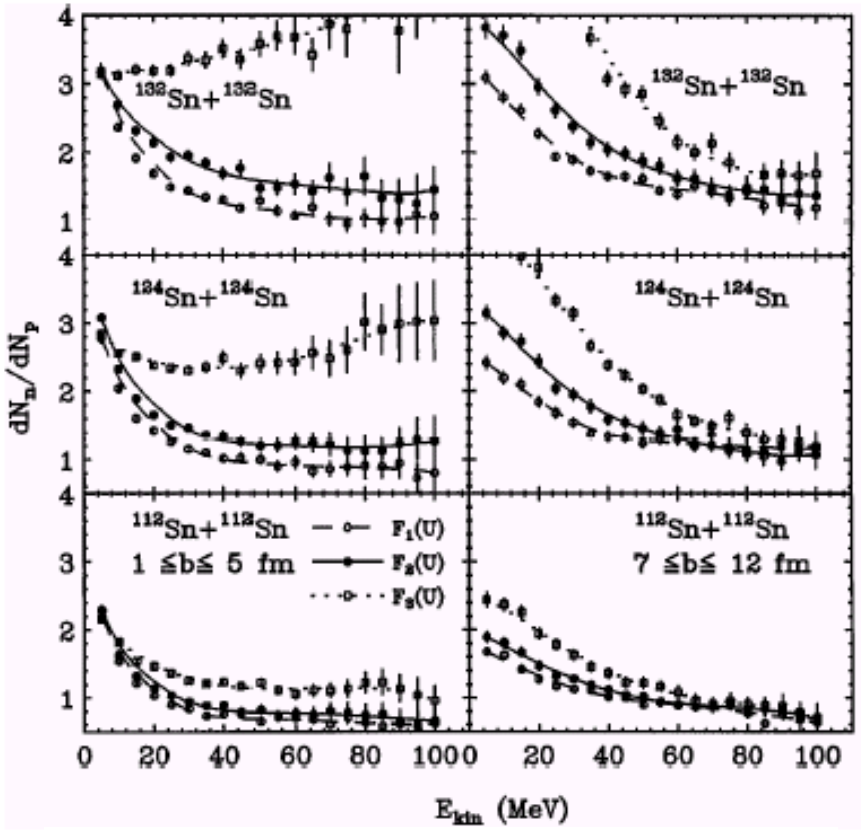


FIG. 6. Isotope ratios [fraction of given isotope to total elemental yield, $\sigma(Z,A)/\sigma(Z)$] as a function of IMF kinetic energy for Li, Be, B, and C ejectiles from ^{124}Sn target. Left column is for data at 12°; right column for data at 154°.

J. Brzychczyk, Phys. Rev. C **47**, 1553-1562 (1993)

Energy Spectra As a Probe Of Symmetry Potential

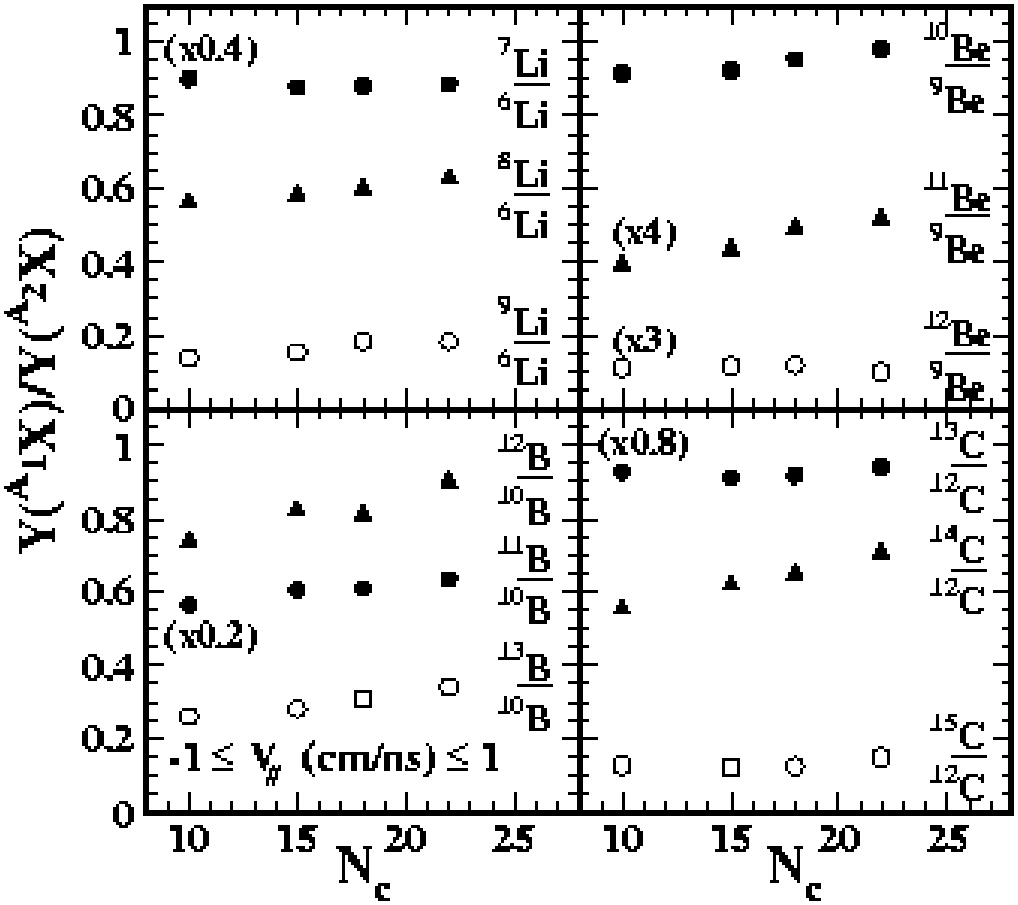


The ratio of pre-equilibrium neutrons to protons as a function of nucleon kinetic energy for central (upper panel) and peripheral (lower panel) collisions calculated with the Coulomb and symmetry potentials.

B.A. Li, PRL 78, 1544 (1997)

Isotope ratios as function of centrality

$^{114}Cd + ^{98}Mo$; 50MeV/nuc



H. Xu Phys. Rev. C **65**, 061602 (2002)

$^{124,136}Xe + ^{112,124}Sn$ 55MeV/nucleon

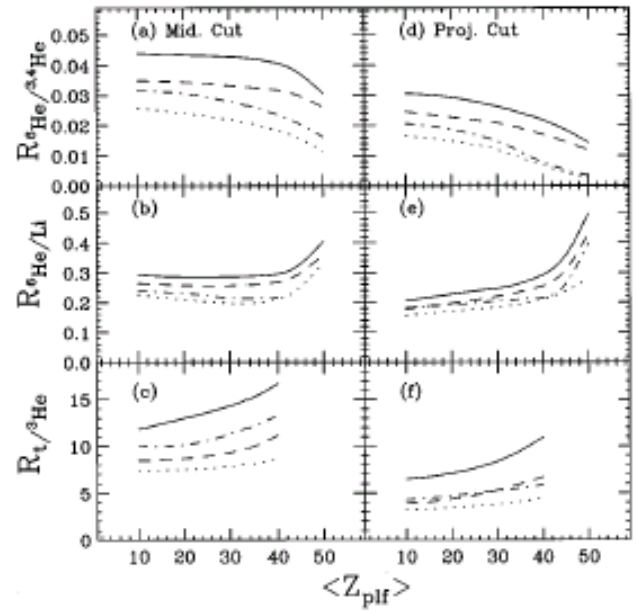
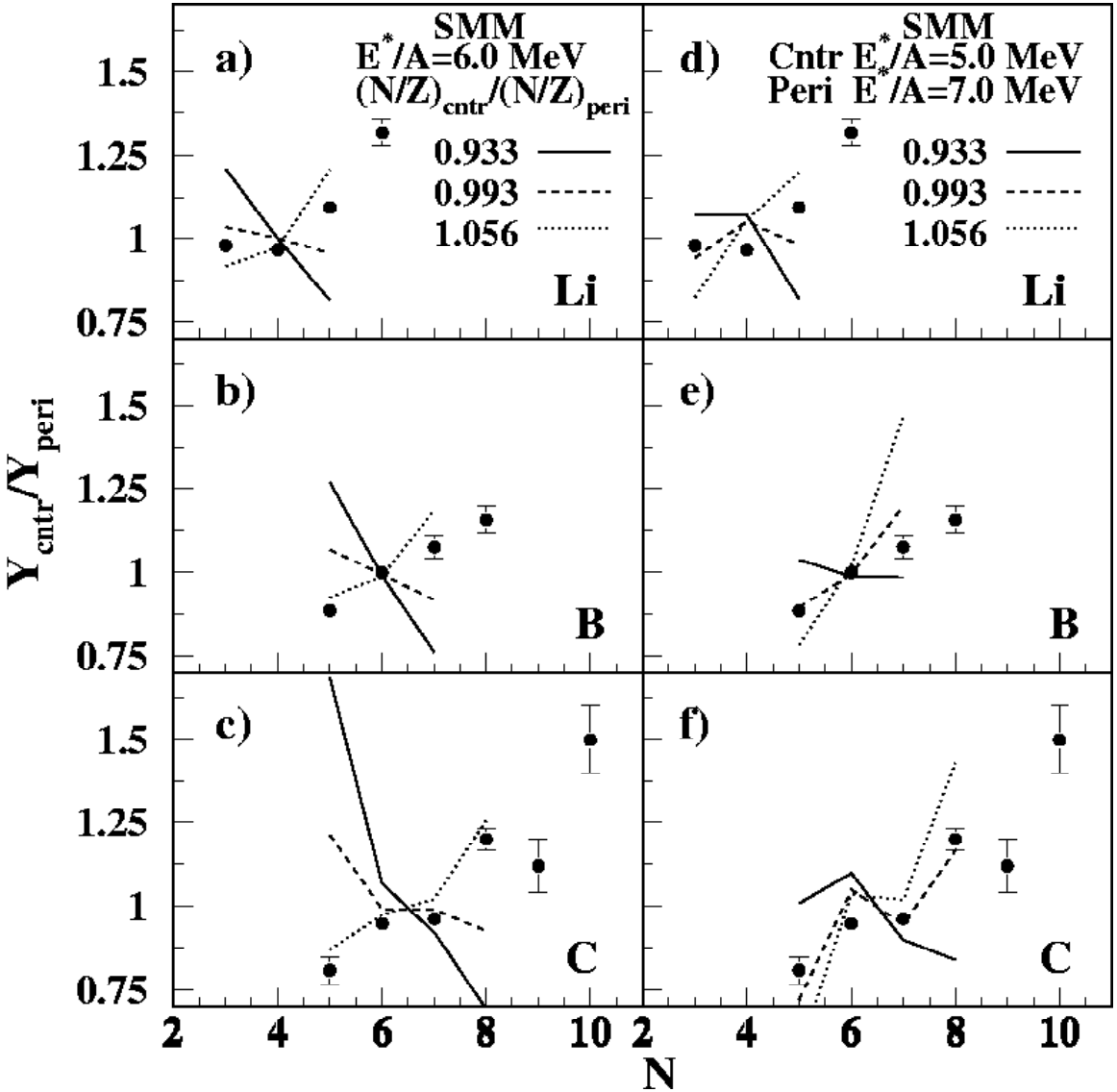


FIG. 9. The relative yield of ^{6}He to ^{3,4}He, ^{6}He to Li, and t to ^{3}He are shown for the four systems for several gates on Z_{PLF}. (a), (b), and (c) display the ratios for the midvelocity region, 0 cm/ns $< V_{\parallel}$(c.m.)$<$ 2.0 cm/ns, while (d), (e), and (f) display the ratios for the projectile region, 3.0 cm/ns $< V_{\parallel}$(c.m.)$<$ 7.0 cm/ns for (d) and (e) and 4 cm/ns for section (f). (The range had to be reduced for the last ratio due to the limitations imposed by the rather low t punch through energy.)

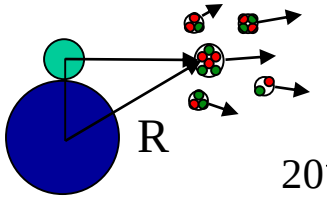
Dempsey et al, PRC 54, 1710(1996)

Enhanced neutron richness in central versus peripheral collisions

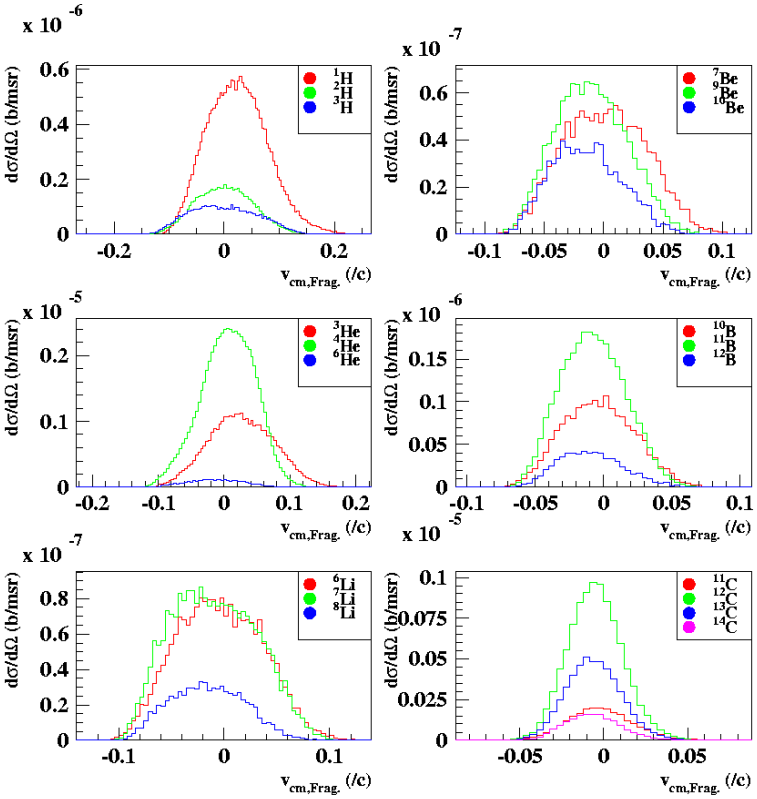


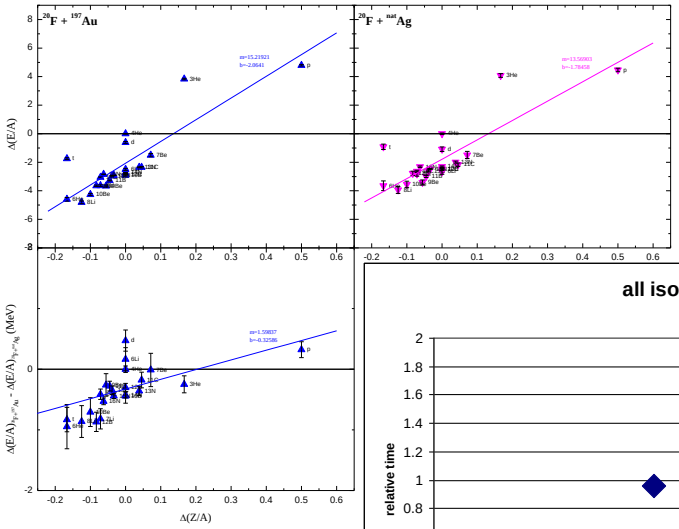
H. Xu Phys. Rev. C **65**, 061602 (2002)

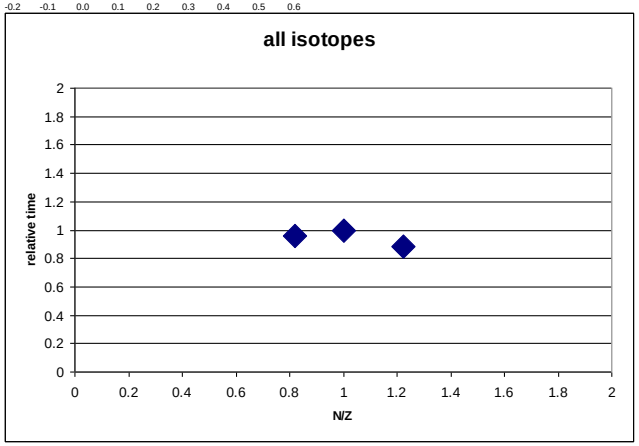
In the spirit of the Gordon Conf…

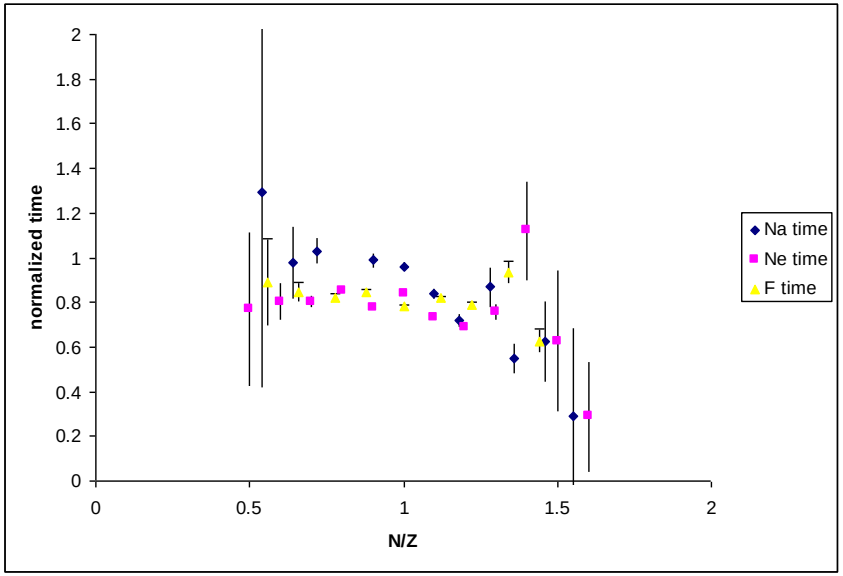


^{20}F,^{20}Ne, ^{20}Na + Au
32 MeV/nucleon









Summary

- Fragment Isospin can tell us about
  - Equilibration
  - Source composition – distribution of isospin
- DIT mechanism can be used to create systems with a diversity of isospin
- Isotopic energy spectra are important to understanding the sources of these fragments

The following people were responsible for bringing you the unpublished data shown in this presentation…*

- B. Davin, R. Alfaro, H. Xu, L. Beaulieu, Y. Larochelle, T. Lefort, R. Yanez, S. Hudan, A. L. Caraley, R. T. de Souza, T. X. Liu, X. D. Liu, W. G. Lynch, R. Shomin, W. P. Tan, M. B. Tsang, A. Vander Molen, A. Wagner,i H. F. Xi, C. K. Gelbke, R. J. Charity, L. G. Sobotka, A.S. Botvina, D. Rowland, D. Shetty, M. Veselsky, G. Souliotis, E. Martin, A. Keksis, E. Winchester,A. Ruangma G. Charbarian, L. Trache, K. Hagel, T. Keutgen, M. Murray, J.B. Natowitz, L. Qin, R. Wada, M. Cinausero, D. Fabris, E. Fioretto, M. Lunardon, G. Nebbia, G. Prete, V. Rizzi, G. Viesti, J. Cibor, Z. Majka, R. Alfarro, A. Martinez-Davalos, A. Menchaca-Rocha

- DOE, NSF, Welch Foundation

*However they should not be held accountable for the actual presentation