Sensitivity of collective flow to the density dependence of the symmetry energy

Zach Kohley

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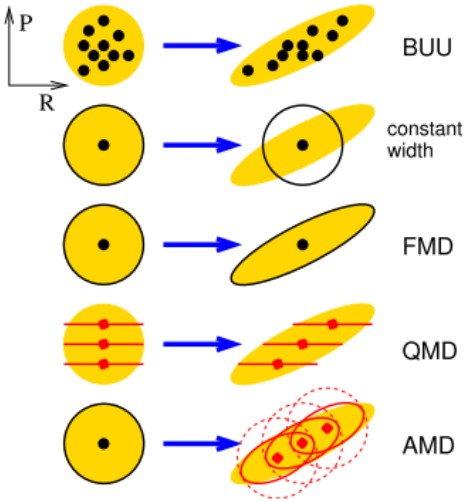
International Conference on Nuclear Symmetry Energy
and Reaction Mechanisms (ASY-EoS)
Siracusa, Sicily, Italy
Sept 4, 2012

Outline

- Motivation
- Experiment
- $E_{sym}(\rho)$ sensitivity of theoretical models to IMF flow
- MoNA Experiment
- Summary
- Acknowledgements



Ono and Randrup., EPJA30(2006)109

Motivation

Program of the ASY-EOS 2012
International Workshop on Nuclear Symmetry Energy and Reaction Mechanisms
(Venue: Provincia Regionale di Siracusa, Via Roma 31, Siracusa)
as of 17/08/2012

Tuesday 4th September, 2012

8:30-9:30 **Registration**

09:30-9:45 **Welcome**

Morning session (9:45-13:05)

09:45-10:15 Z. Chajecki (NSCL/MSU, East Lansing USA): **T.B.A** (25'+5')

10:15-10:35 E. De Filippo (INFN-Catania, Italy) : **Probing the symmetry energy at low density using observables from neck fragmentation mechanism** (17'+3')

10:35-10:55 P. Marini (GANIL, Caen, France) : **Extracting information on the symmetry energy by coupling the VAMOS spectrometer and the 4pi INDRA detector to reconstruct primary fragments** (17'+3')

10:55-11:15 P.C. Wigg (Department of Physics, University of Liverpool, UK) : **Nuclear Symmetry Energy in Ca+Ca Collisions** (17'+3')

11:15-11:45 **Coffee break**

11:45-12:05 A.M. Sanchez-Benitez (Department of Applied Physics, University of Huelva, Spain) : **Scattering of ^{8}He on ^{208}Pb at energies around the Coulomb barrier** (17'+3')

12:05-12:25 V. Scuderi (INFN-LNS, Catania, Italy) : **Elastic scattering and reaction mechanisms induced by light halo nuclei at the barrier** (17'+3')

12:25-12:45 P. Diaz Fernandez (Univ. Santiago de Compostela, Spain) : **An investigation into quasifree scattering of neutron-rich carbon and nitrogen nuclei around N=14** (17'+3')

12:45-13.05 M. Young (NSCL/MSU, East Lansing, USA) : **Measurement of emitted tritons and ^{3}He from ^{112,124}Sn+^{112,124}Sn collisions at Ebeam=50 and 120 MeV/nucleon** (17'+3')

Evening session (15:00–18:00)

15:00-15:30 A. Krasznahorkay (Inst. of Nucl. Res. - ATOMKI, Debrecen Hungary) : **Experimental investigation of the symmetry energy by studying giant resonances** (25'+5')

15:30-15.50 S. Hudan (Indiana University, USA) : **Tracking saddle-to-scission dynamics using N/Z in projectile breakup reactions** (17'+3')

15:50-16:10 Z. Basrak (R. Boskovic Institute, Croatia) : **Energy deposition in heavy-ion reactions at intemediate energies** (17'+3')

16:10-16:30 J. Winkelbauer (Michigan State University National Superconducting Cyclotron Laboratory, Lansing, USA) : **Precision Measurement of Isospin Diffusion in Sn+Sn Collisions** (17'+3')

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16:30-17:00 **Coffee break**

17:00-17:20 Z. Kohley (National Superconducting Cyclotron Laboratory, East Lansing, USA) :**Sensitivity of collective flow to the density dependence of the symmetry energy** (17'+3')

17:20-17:40 S. Yennello (Texas A&M University College Station, TX, USA) : **Asymmetry Dependence of the Nuclear Caloric Curve** (17'+3')

17:40-18:00 M. Veselsky (Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia) : **Symmetry energy and nucleon-nucleon cross sections** (17'+3')

Wednesday 05th September, 2012

Morning session (9:00-12:50)

09:00-09:30 L. Fabbietti (Excellence Cluster Universe, TUM Munich) : **Kaon properties in cold or dense nuclear matter** (25'+5')

09:30-09:50 P. Pawloski (IFJ-PAN, Krakow, Poland) : **Nuclear cluster formation in the participant zone of heavy-ion relativistic reactions"** (17'+3')

09:50-10:10 K. Gill (Goethe-Universitate, Frankfurt, Germany) : **Rare kaon signals from Au+Au collisions at HADES** (17'+3')

10:10-10:30 R. Bhattacharya (University of Calcutta, Kolkata, India) : **Tensor Interaction and its effect on Spin-orbit Splitting of Shell Model States** (17'+3')

10:30-11:00 **Coffee break**

11:00-12:00 J. Aichelin (Subatech, Nantes, France) and H.H. Wolter (University of Munich, Garching, Germany) : **Tandem session on Status of transport models in the search for the symmetry energy (at sub- and supra-saturation densities)** (50'+10')

12:00-12:30 D. Cozma (IFIN-HH, Bucharest, Romania) : **Constraints on the density dependence of the symmetry energy from elliptic flow data** (25'+5')

12:30-12:50 A. Le Fevre (GSI Helmholtzzentum Darmstadt) : **A new approach to detect hypernucleii and isotopes in the QMD phase space distribution at relativistic energies** (17'+3')

Evening session (15:00–18:00)

15:00-15:30 W. Reisdorf (GSI, Darmstadt, Germany) : **Heavy ion collisions (HIC) in the 1A GeV regime: how well can we join up to astrophysics?** (25'+5')

15:30-16:00 T. Nakamura (Tokyo Institute of Technology, Tokyo, Japan) : **Breakup Reactions of Exotic Nuclei at the large acceptance spectrometer SAMURAI at RIBF** (25'+5')

16:00-16.20 I. Vidana (University of Coimbra, Coimbra, Portugal) : **Nuclear symmetry energy and the r-mode instability of neutron stars** (17'+3')

16:20-16:50 **Coffee break**

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16:50-17:35 T. Isobe (Riken, Saitama, Japan) and A. McIntosh (Texas A&M University, College Station, USA): **Tandem session on SAMURAI TPC: A Time Projection Chamber to Study the Nuclear Symmetry Energy at RIKEN-RIBF with Rare Isotope Beams** (40'+5')

17:35-18:00 **Open discussion (round table)**

18:00 -20:00 **Visit to Siracusa**

21:00 **Social dinner**

Thursday 06th September, 2012

Morning session (9.00-13.00)

9:00-9:30 M.B. Tsang (Michigan State Univesrsity, East Lansing, USA): **T.B.A** (25'+5')

9:30-10:00 I. Martel (University of Huelva, Huelva, Spain) : **GASPHYDE particle detectors and the new superconducting linac facility LRF-Huelva** (25'+5')

10:00-10:20 H. Alvarez Pol (Univ. Santiago de Compostela, Spain) : **The CALIFA calorimeter in the versatile R3B setup** (17'+3')

10:20-10:40 J. Lukasik (IFJ-PAN, Krakow, Poland) : **Pulse shape analysis for KRATTA modules** (17'+3')

10:40-11:00 I. Gasparic (TU Darmstadt/IRB Zagreb) : **The NeuLAND detector of the R3B collaboration** (17'+3')

11:00-11:30 **Coffee break**

11:30-12:00 B. Hong (Korea University, Seoul, Republic of Korea) : **New opportunity for nuclear symmetry energy using LAMPS in Korea rare isotope accelerator** (25'+5')

12:00-12:30 N. Herrmann (University of Heidelberg, Germany) : **Compressed baryonic matter: the CBM experiment at SIS100** (25'+5')

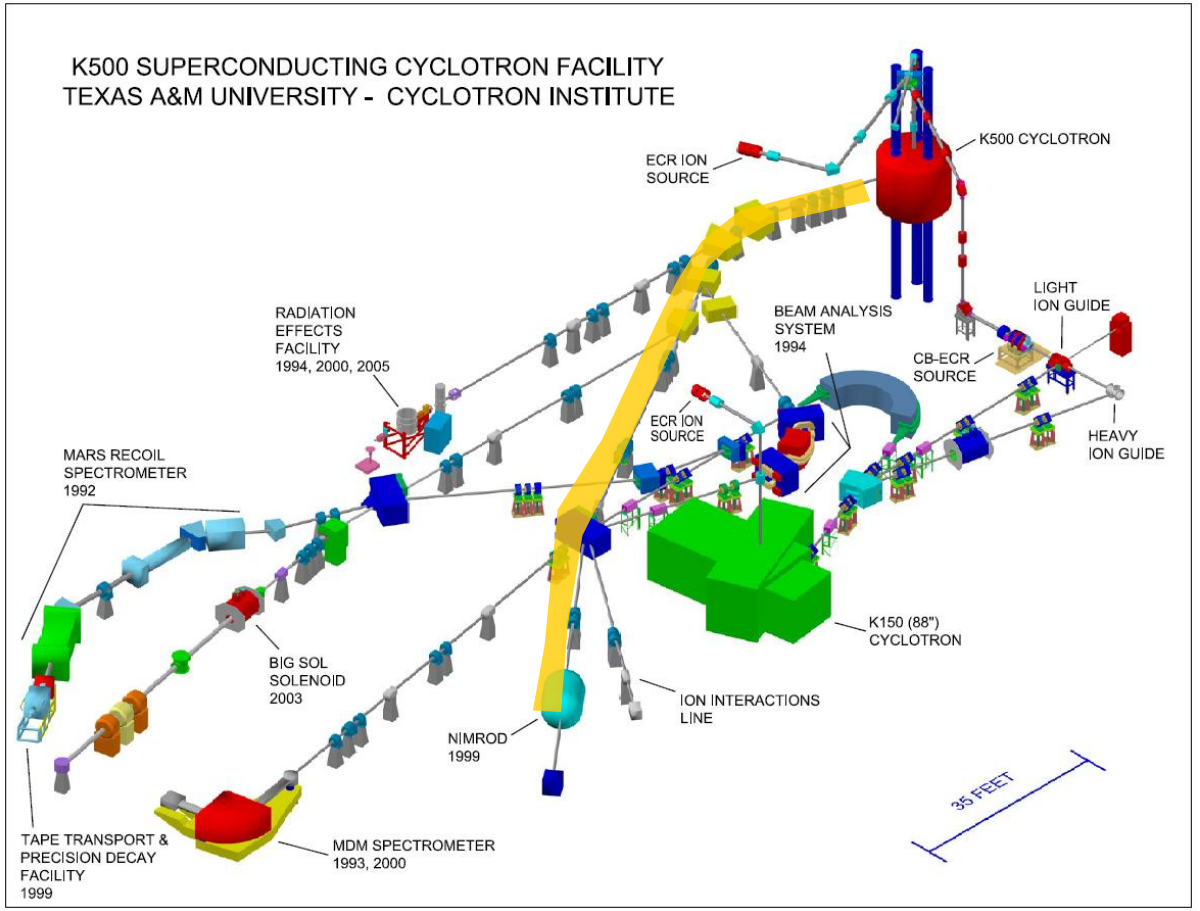
12:30-13:00: G. Batignani (INFN Sezione di Pisa, Italy) : **The SuperB Project** (25'+5')

The nuclear EoS and its isospin dependence are deeply embedded into many facets of nuclear science.

Experiment

Beam Energy: 35 MeV/u

Reactions: $^{70}Zn+^{70}Zn$, $^{64}Zn+^{64}Zn$, & $^{64}Ni+^{64}Ni$



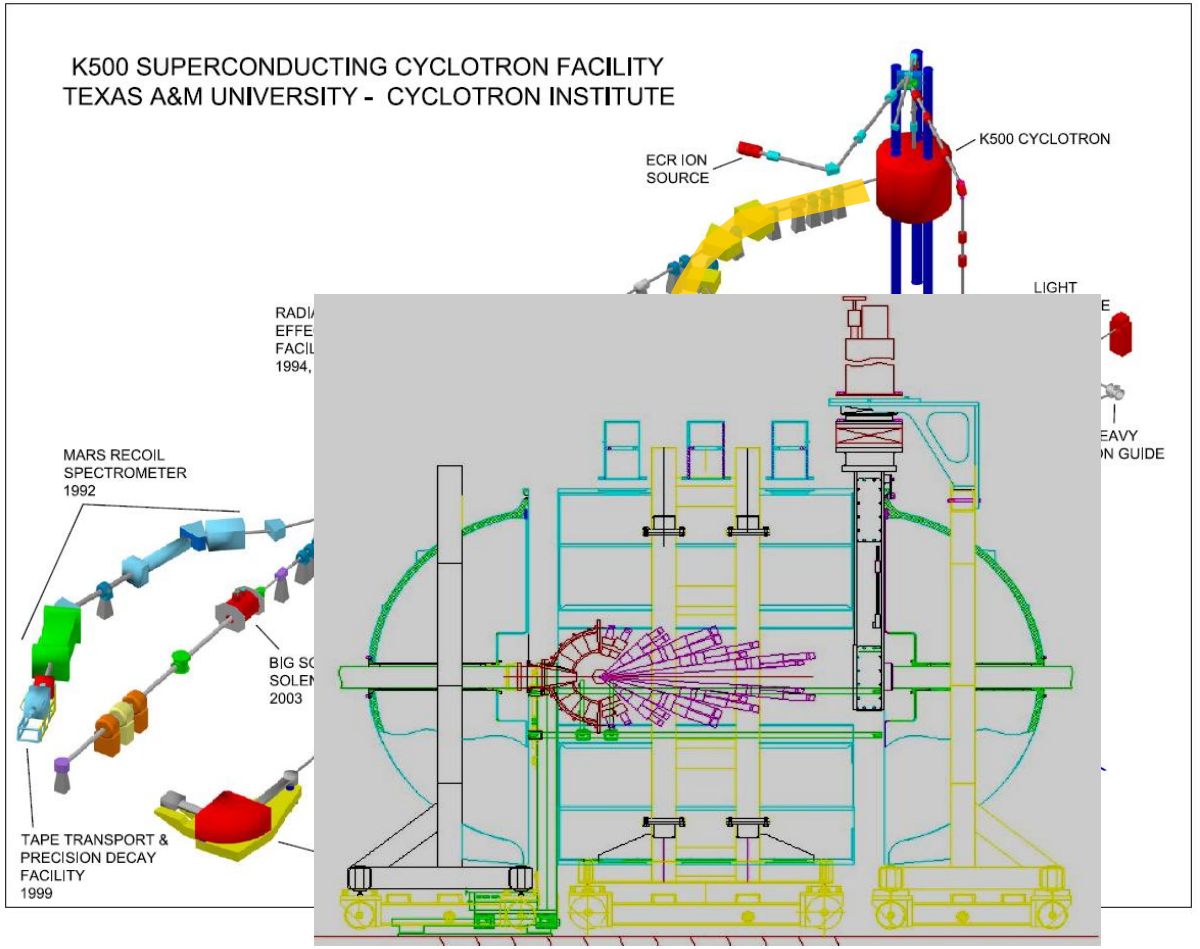
NIMROD-ISiS

- 14 Concentric Rings (ΔE-E)
- 3.6-167 degrees
- Neutron Ball

Experiment

Beam Energy: 35 MeV/u

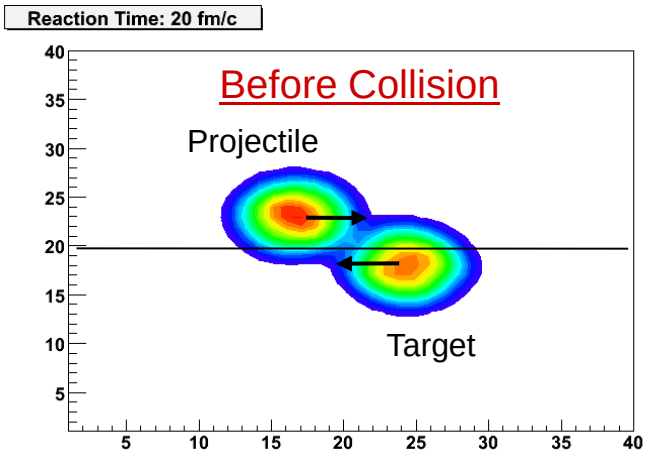
Reactions: $^{70}Zn+^{70}Zn$, $^{64}Zn+^{64}Zn$, & $^{64}Ni+^{64}Ni$

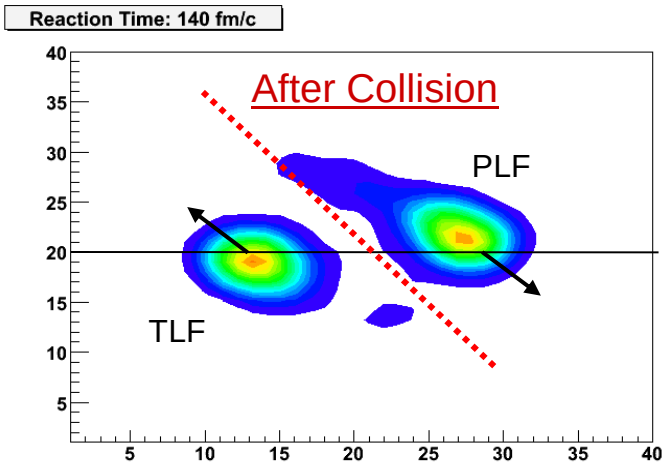


NIMROD-ISiS

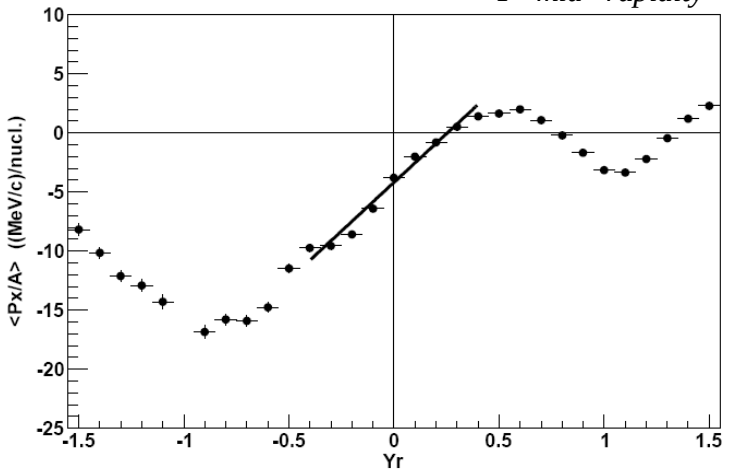
- 14 Concentric Rings (ΔE-E)
- 3.6-167 degrees
- Neutron Ball

Flow





$$F(MeV/c) = \left.\frac{\partial \langle P_x \rangle}{\partial Y_{red}}\right|_{Y=mid-rapidity}$$



Impact parameter selection from neutron-charged particle 2-D histograms.

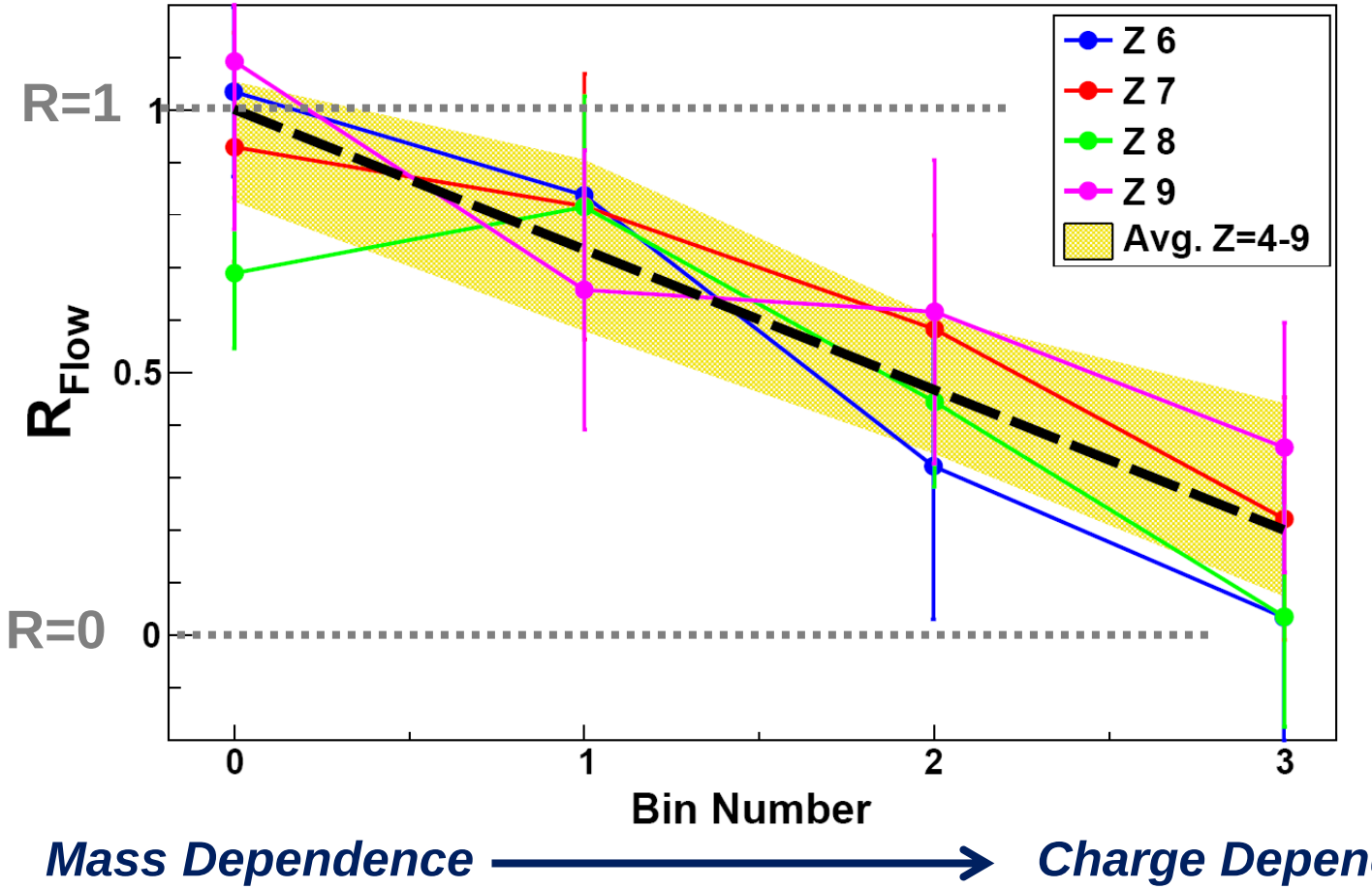
Rxn plane defined using azimuthal correlations method.

W.K. Wilson et al., Phys. Rev. C **45,** 738, (1992).

LCP Flow & Emission
Kohley *et al.* PRC **83**, 044601 (2011)

IMF flow

$$R_{\mathrm{flow}} = \frac{\overline{\langle Px \rangle}_{64}\mathrm{Zn} - \overline{\langle Px \rangle}_{70}\mathrm{Zn}}{\overline{\langle Px \rangle}_{64}\mathrm{Ni} - \overline{\langle Px \rangle}_{70}\mathrm{Zn}}$$



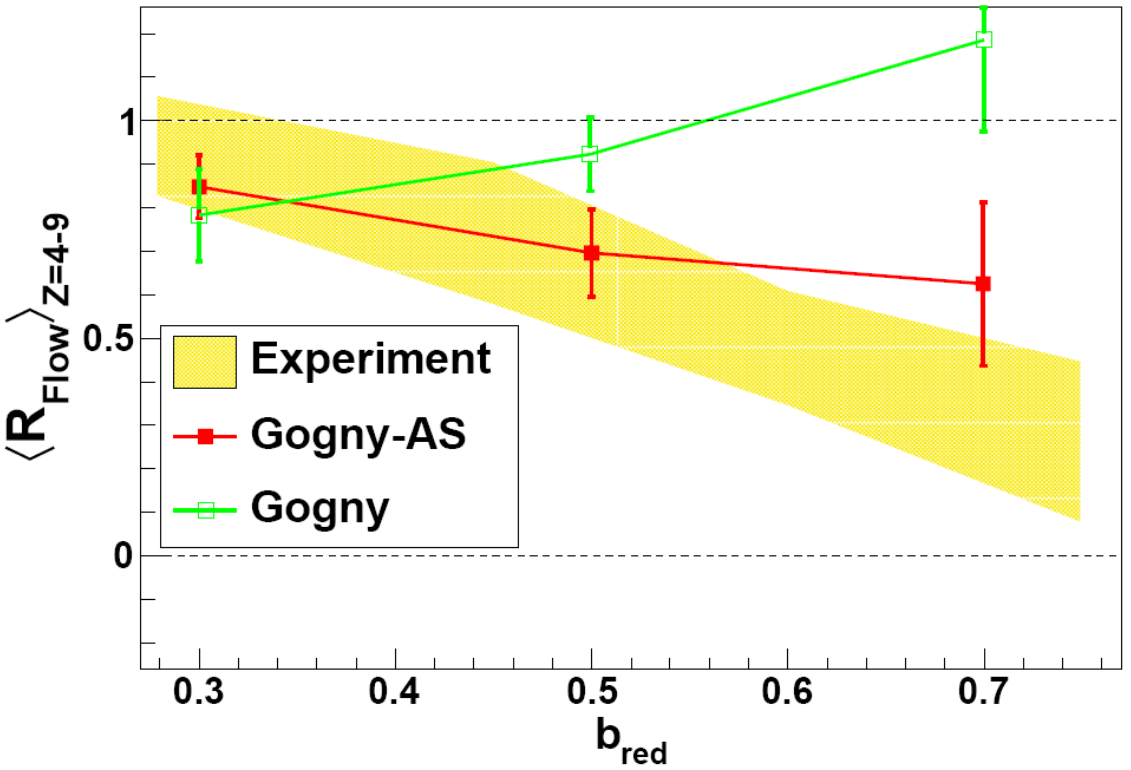
Mass Dependence → ***Charge Dependence***

Kohley *et al.*, PRC **82**, 064601 (2010)

IMF flow

$$R_{\text{flow}} = \frac{\langle P_x \rangle_{^{64}\text{Zn}} - \langle P_x \rangle_{^{70}\text{Zn}}}{\langle P_x \rangle_{^{64}\text{Ni}} - \langle P_x \rangle_{^{70}\text{Zn}}}$$

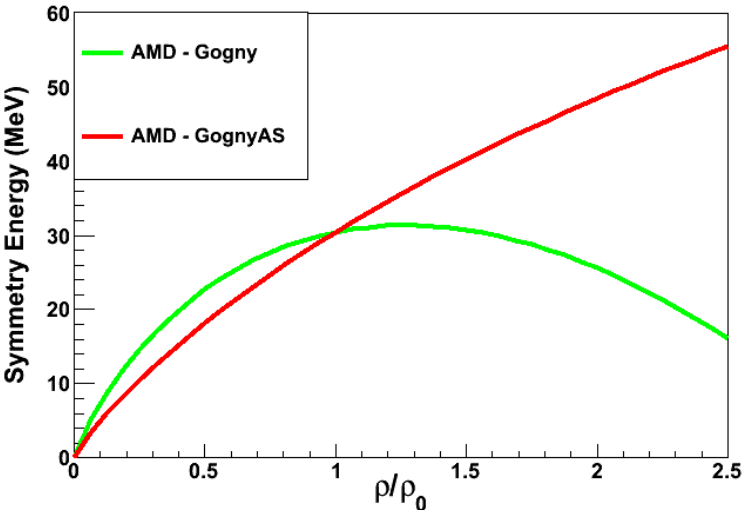
Average Z=4-9



Kohley *et al.*, PRC **82**, 064601 (2010)

Antisymmetrized Molecular Dynamics (AMD)

A. Ono and H. Horiuchi, Prog. Part. Nucl. Phys. ***53,*** *501, (2004).*



Sensitivity of simulations

Stochastic Mean-Field Model
SMF
(Colonna, Rizzo, Baran, Di Toro…)

-Rooted in BLE

$$\frac{df}{dt} = \frac{\partial}{\partial t} f - \{H[f], f\} = I_{coll}[f] + \delta I[f]$$

- should provide accurate description of one-body dynamics
- uses test particle method to solve BLE
- "stochastic" nature of the collisions (last term in eq. above) is included through agitation of spatial density.
- Mean-field (no nn-interaction) do not get natural production of light clusters.

- 100 test particles per nucleon
- Ran for 220 fm/c and phase-space coalescence applied.

Constrained Molecular Dynamics
CoMD-II
(Papa, Bonasera)

- Improvement beyond typical QMD simulations.
- Constrains the occupation density to fulfill Pauli principle.

$$\overline{f_i} \leq 1 \quad (\text{for all } i),$$

$$\overline{f_i} \equiv \sum_j \delta_{\tau_i,\tau_j}\delta_{s_i,s_j}\int_{h^3} f_j(\mathbf{r},\mathbf{p})d^3r d^3p.$$

- Advantage is good description of Pauli blocking with N^2 computational increase in comparison to N^4 (AMD)
- Special care to conserve total angular momentum.

- Fast computation allows for time evolution till 3000 fm/c
- System decays dynamically.
- Gemini++ still applied but has very minimal effect.

Antisymmetrized Molecular Dynamics: AMD-DS
(Ono)

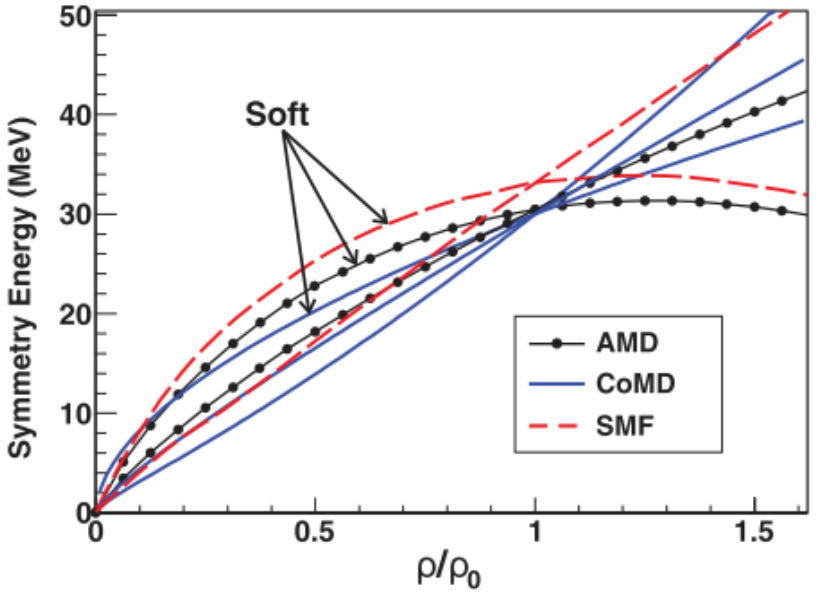
- Wavefunction for a reaction with A nucleons represented by a Slater determinant of Gaussian wave packets,

$$\Phi(Z) = det\left[exp\left\{-\nu\left(\mathbf{r}_j - \frac{\mathbf{Z}_i}{\sqrt{\nu}}\right)^2 + \frac{1}{2}\mathbf{Z}_i^2\right\}\chi_{\alpha i}(j)\right]$$

- Fermionic nature of nucleus is respected at all times.
- Many improvements to reproduce the clustering observed in experiments. AMD, AMD-V, AMD-DS and now AMD + clust.

- Main issue is computationally expensive.
- Was coupled to statistical decay Gemini++ after 300 fm/c.

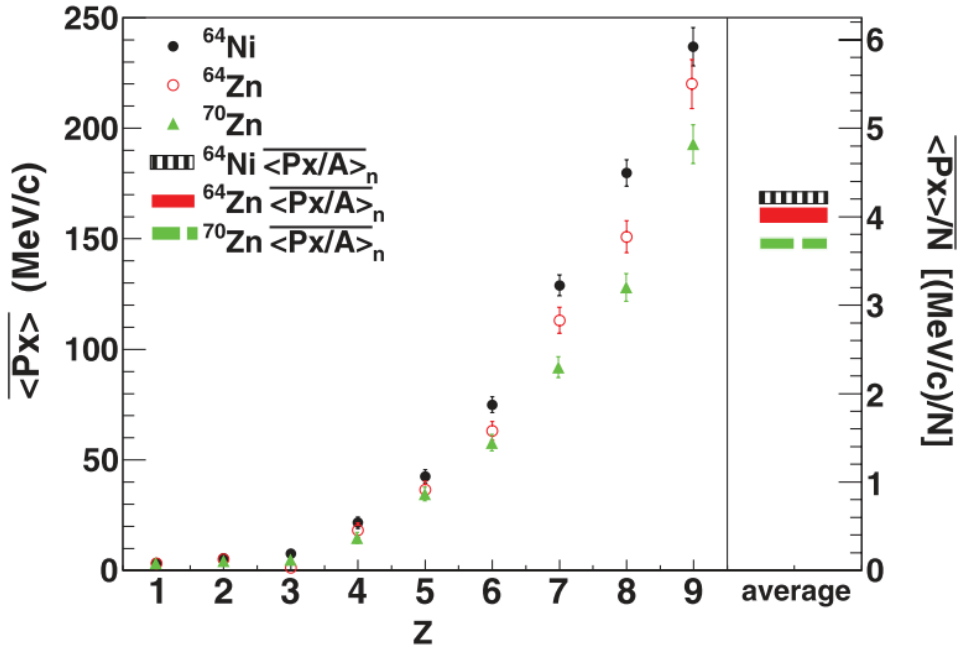
Sensitivity of simulations

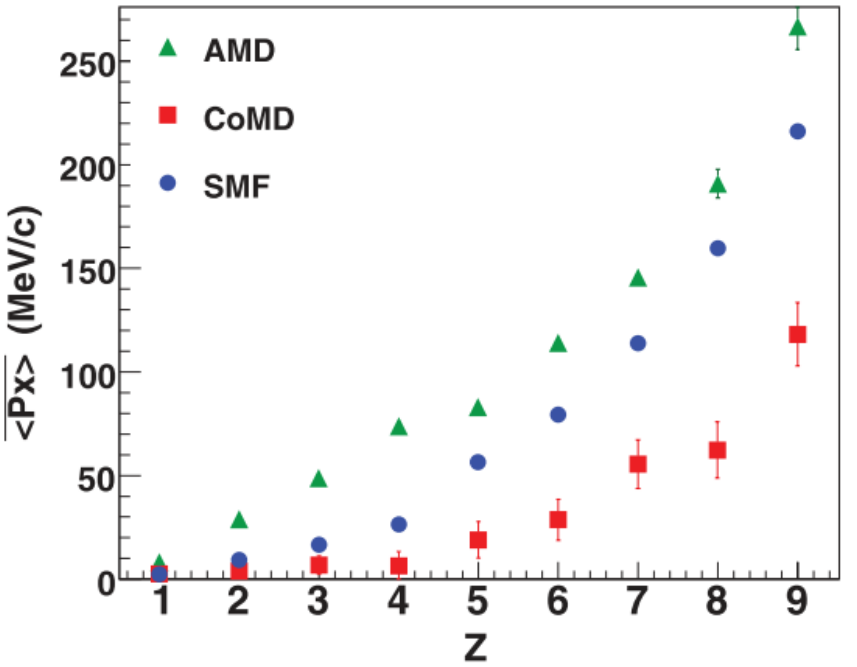


Simulation	Form	$E_{sym}(\rho_\circ)$	L (MeV)
AMD	Stiff	30.5	65
	Soft	30.5	21
SMF	Stiff	33	95
	Soft	33	19
CoMD	Superstiff	30	105
	Stiff	30	78
	Soft	30	51

Kohley *et al.*, PRC **85**, 064605 (2012)

Sensitivity of simulations

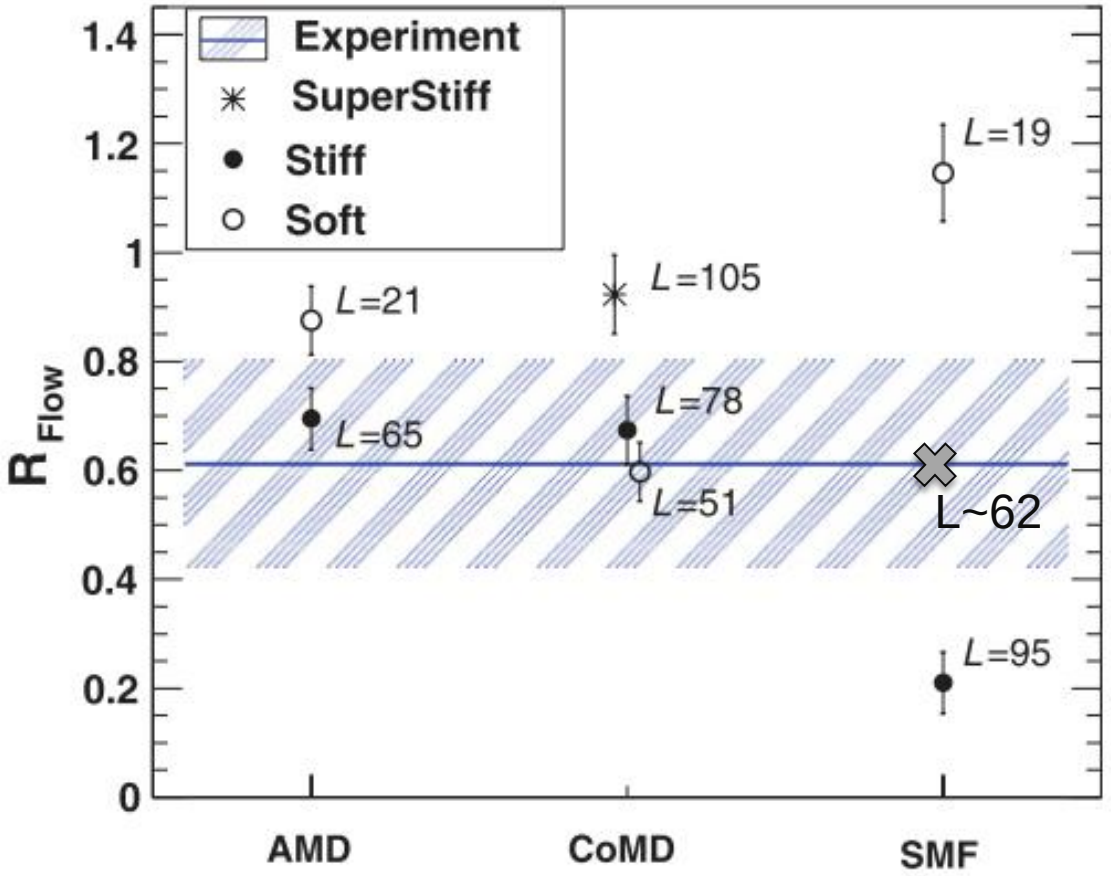




$$R_{\text{flow}} = \frac{\overline{\langle Px \rangle}_{^{64}\text{Zn}} - \overline{\langle Px \rangle}_{^{70}\text{Zn}}}{\overline{\langle Px \rangle}_{^{64}\text{Ni}} - \overline{\langle Px \rangle}_{^{70}\text{Zn}}} = 0.61 \text{ +/- } 0.14$$

Kohley *et al.*, PRC **85**, 064605 (2012)

Sensitivity of simulations



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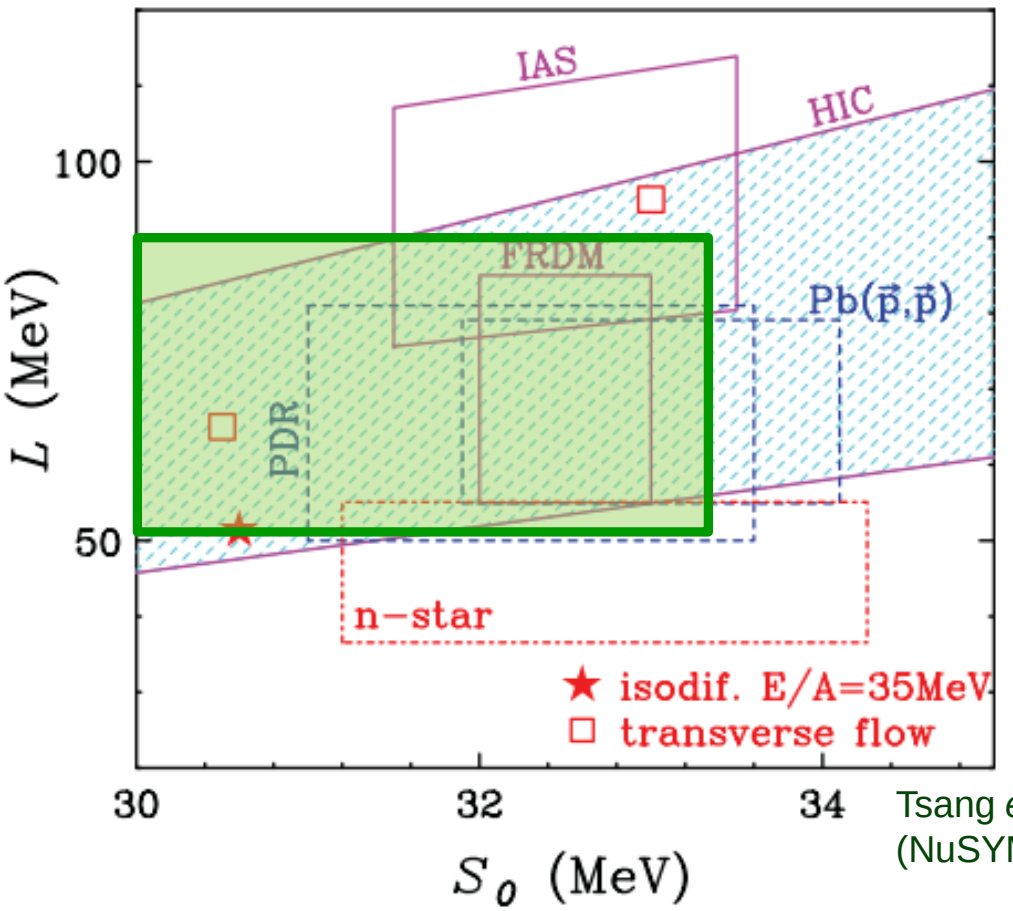
Kohley *et al.*, PRC **85**, 064605 (2012)

Sensitivity of simulations



Tsang *et al.*, PRC **86**, 015803 (2012)
(NuSYM 2011 Paper)

WAIT… The significance of the agreement is outweighed by the differences in the sensitivity of the models to *L*.

Sensitivity of simulations

PHYSICAL REVIEW C **84**, 054603 (2011)

Influence of transport variables on isospin transport ratios

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National Superconducting Cyclotron Laboratory, Physics and Astronomy Department, and Joint Institute of Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA

P. Danielewicz§
National Superconducting Cyclotron Laboratory and Physics and Astronomy Department, Michigan State University, East Lansing, Michigan 48824, USA

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China Institute of Atomic Energy, P.O. Box 275 (10), Beijing 102413, P.R. China
(Received 18 July 2011; published 3 November 2011)

PHYSICAL REVIEW C **85**, 024602 (2012)

Influence of in-medium NN cross sections, symmetry potential, and impact parameter on isospin observables

Yingxun Zhang (张英逊),[1,2] D. D. S. Coupland,[3] P. Danielewicz,[2,3] Zhuxia Li (李祝霞),[1] Hang Liu (刘航),[4] Fei Lu (卢 飞),[2,5] W. G. Lynch (連致標),[2,3] and M. B. Tsang (曾敏兒)[2,3]

PHYSICAL REVIEW C **76**, 024611 (2007)

Comparison of multifragmentation dynamical models

J. Rizzo,[1,2] M. Colonna,[1,2] and A. Ono[3]
[1]*LNS-INFN, I-95123 Catania, Italy*
[2]*Physics and Astronomy Department, University of Catania, Italy*
[3]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
(Received 18 September 2006; published 27 August 2007)

PHYSICAL REVIEW C **82**, 054613 (2010)

Fragmentation paths in dynamical models

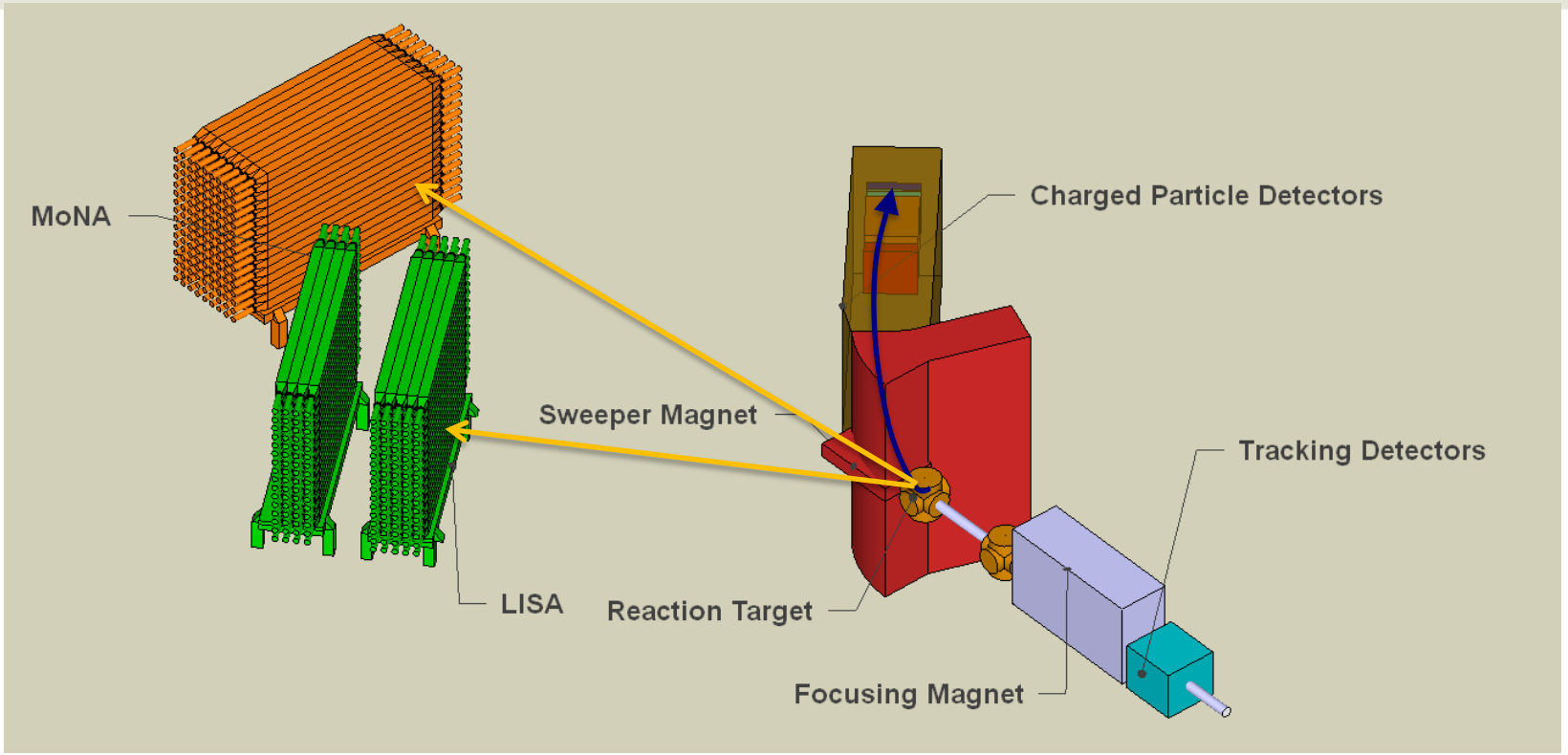
M. Colonna,[1] A. Ono,[2] and J. Rizzo[1]
[1]*Laboratori Nazionali del Sud–Istituto Nazionale Fisica Nucleare, I-95123 Catania, Italy*
[2]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
(Received 28 April 2010; revised manuscript received 5 October 2010; published 18 November 2010)

Sensitivity of simulations

Adjust variables for pBUU and ImQMD05:
- In-medium cross section
- MI vs. MD interaction
- Impact parameter

Compare SMF and AMD fragmentation
-One-body vs. many-body correlations
- "in the energy range discussed here (50 MeV/u), the fragmentation path is extremely sensitive the interplay between one- and many-body effects. Changing the relative weight of these effects leads to a rather different outcome."

MoNA-LISA Experiment



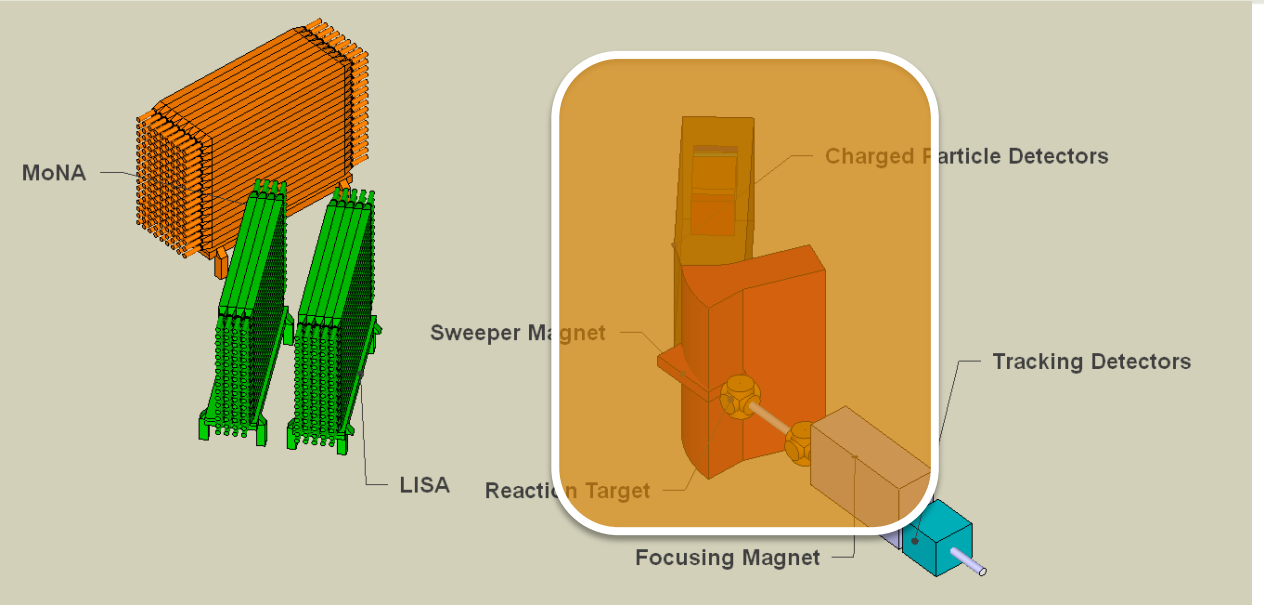
Thoennessen

Yennello
Bonasera

Tsang
Lynch

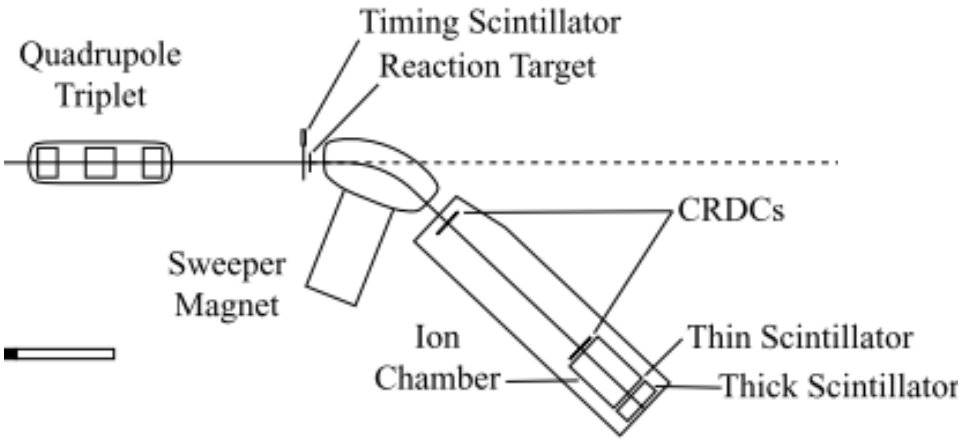
Develop new program:
Measuring projectile-like fragments (PLFs) in coincidence with neutrons.

MoNA-LISA Experiment



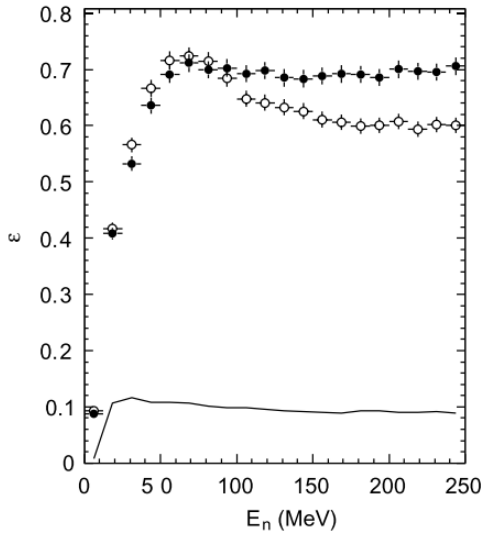
Sweeper Magnet:

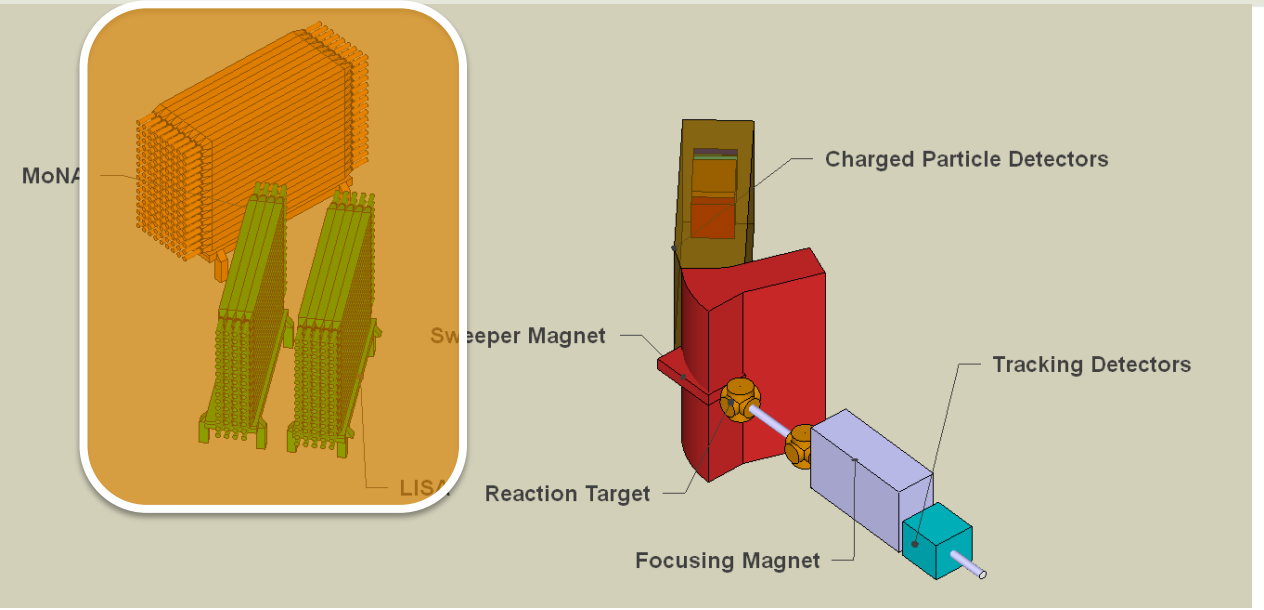
- 4 Tm, bends fragments ~43º
- Large acceptance; +/- 8% Bρ
- CRDCs for tracking (Mass, Energy)
- CsI Hodoscope



Z_{PLF} to define impact parameter

MoNA-LISA Experiment

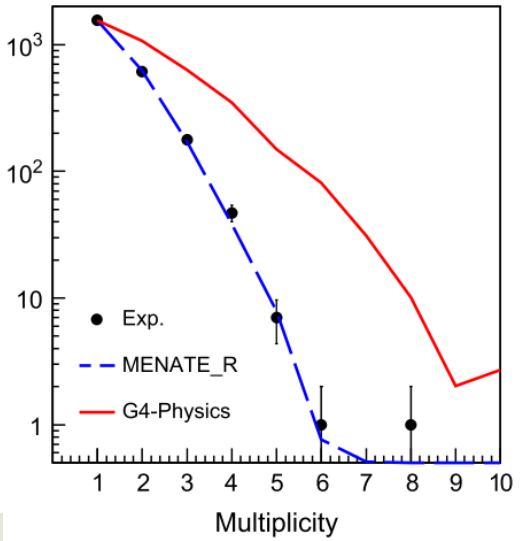


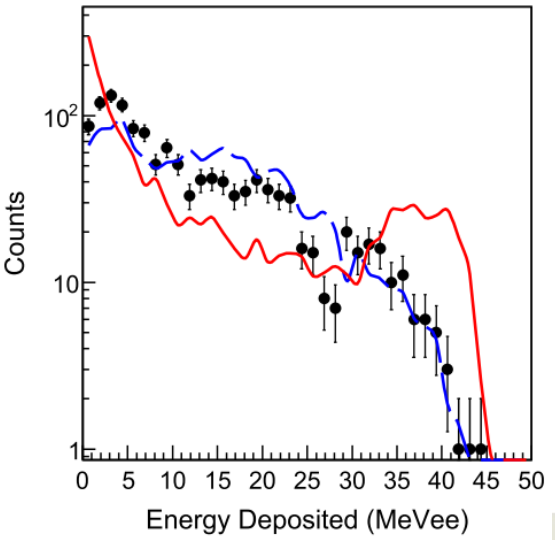


For accepted experiment coverage in lab from 0-45°

$^{17}C(-p)\rightarrow{}^{16}B\rightarrow{}^{15}B+n$

Kohley *et al.*, NIMA **682**, 59 (2012)





Summary

- IMF flows useful probes of EoS (~linear form E_{sym})

- Sensitivity of $E_{sym}(\rho)$ dependence on treatment of reaction dynamics.
- Constrain “weight” one-body vs. many-body effects

- New program to use MoNA-Sweeper for reaction studies.

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

Theory
SMF: Maria Colonna
CoMD: Aldo Bonasera
AMD: Roy Wada and A. Ono