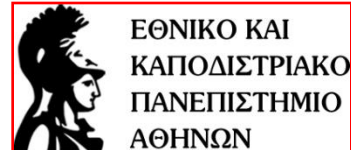


# Production of neutron-rich nuclei and studies of isospin transport in peripheral heavy-ion collisions below the Fermi energy

George A. Souliotis

Laboratory of Physical Chemistry, Department of Chemistry,  
National and Kapodistrian University of Athens, Athens 15771

1<sup>st</sup> Workshop of the Hellenic Institute of Nuclear Physics (HINP),  
University of Ioannina, Ioannina, September 7, 2012



# Overview of recent activities:

## Recent work :

- deep inelastic collisions below the Fermi energy:
- $^{86}\text{Kr}(25\text{MeV/nucleon}) + ^{64}\text{Ni}, ^{124}\text{Sn}$  PRL 91, 022701 (2003)
- $^{86}\text{Kr}(15\text{MeV/nucleon}) + ^{64}\text{Ni}, ^{124}\text{Sn}$  PRC 84, 064607 (2011)

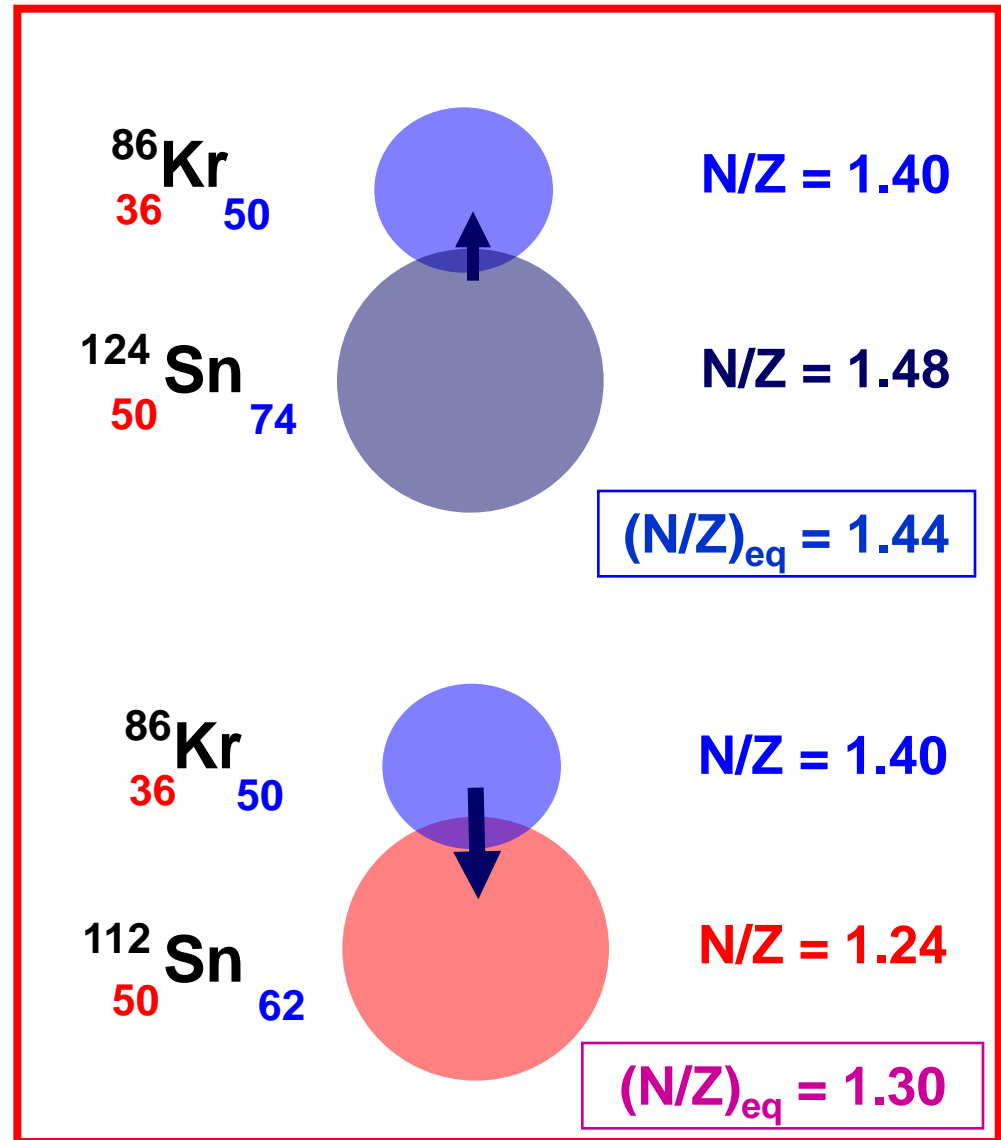
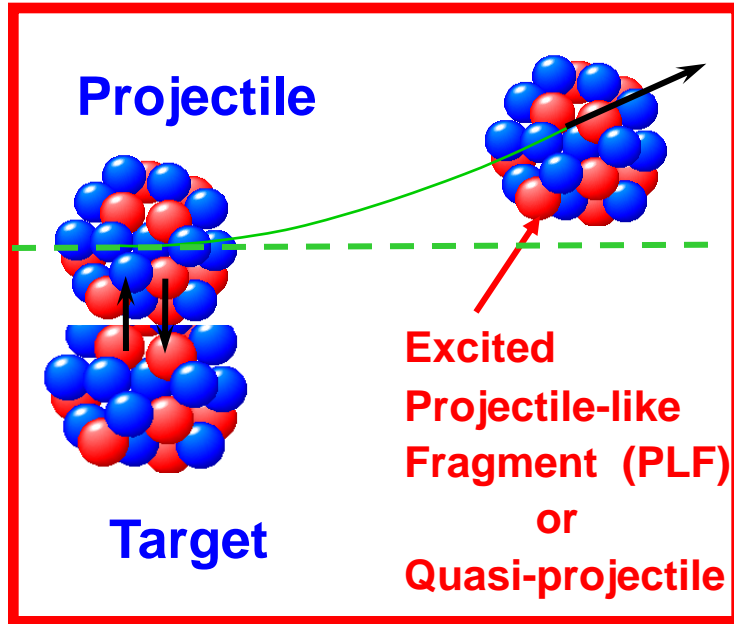
## Findings:

- Peripheral collisions: enhanced production of neutron-rich nuclei
- Heavy Residues as equation-of-state (EOS) probes:
  - Heavy-residue isoscaling PRC 73, 024606 (2006)
  - N/Z equilibration PLB 588, 35 (2004)

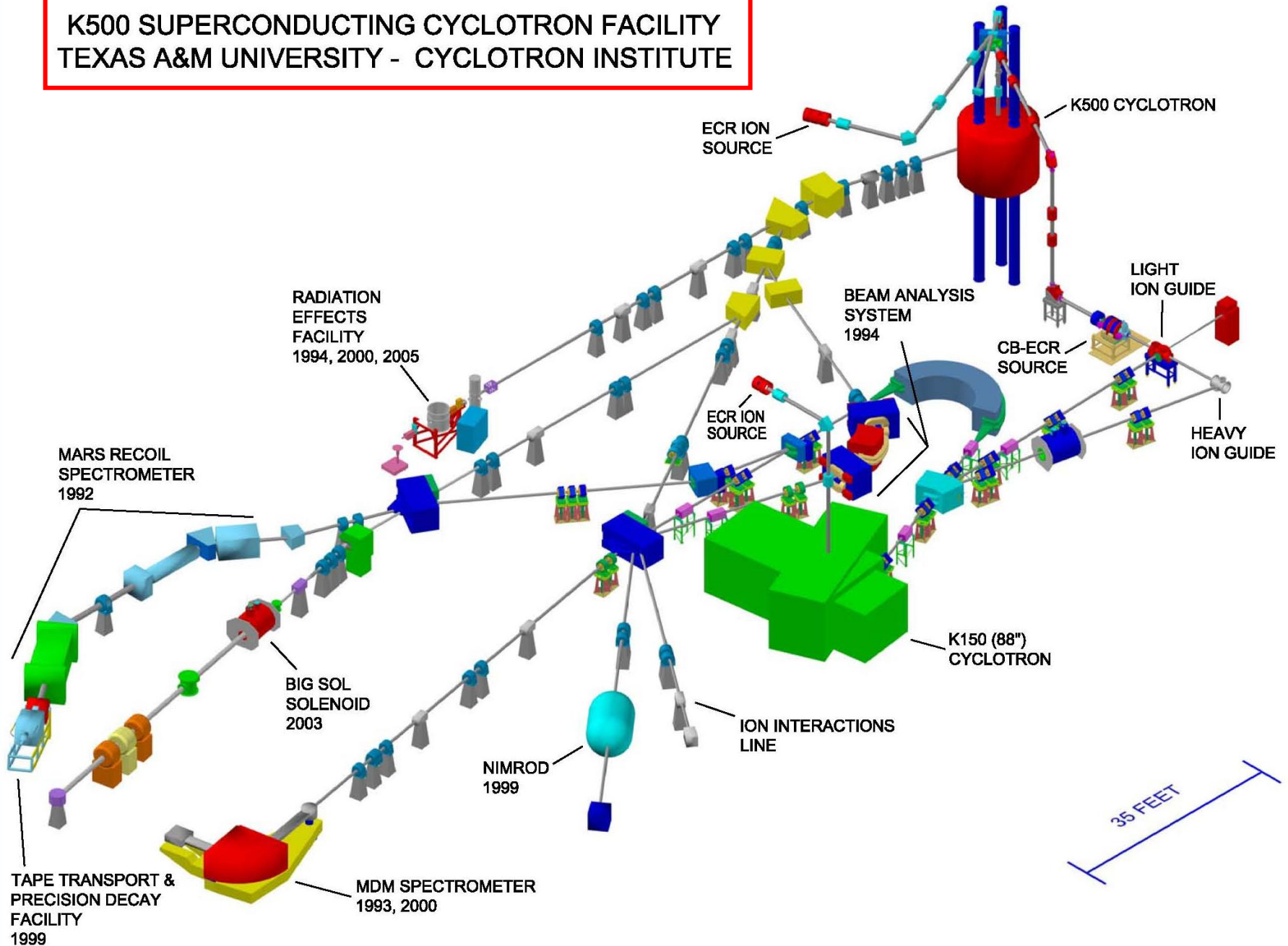
Present efforts: production of n-rich nuclei in 15 MeV/nucleon reactions

N/Z transport w.r.t. to TKEL (~ degree of dissipation)  
Comparisons with DIT, CoMD models.

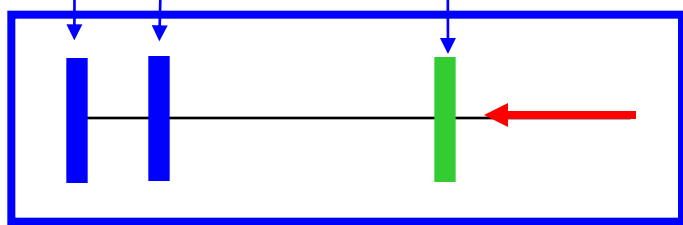
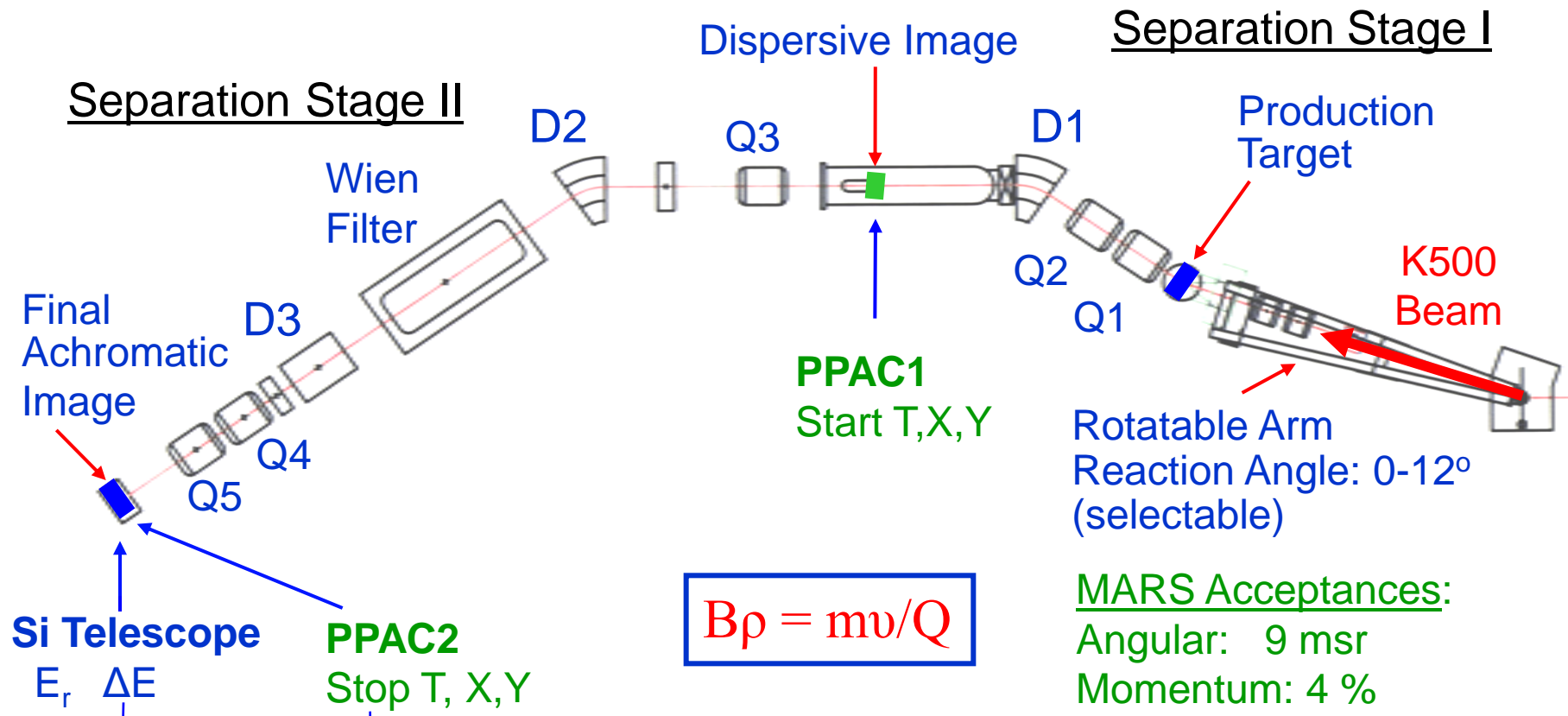
# The Process of N/Z Transport and Equilibration



# K500 SUPERCONDUCTING CYCLOTRON FACILITY TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE



# MARS Recoil Separator and Setup for Heavy Rare Isotope Studies\*

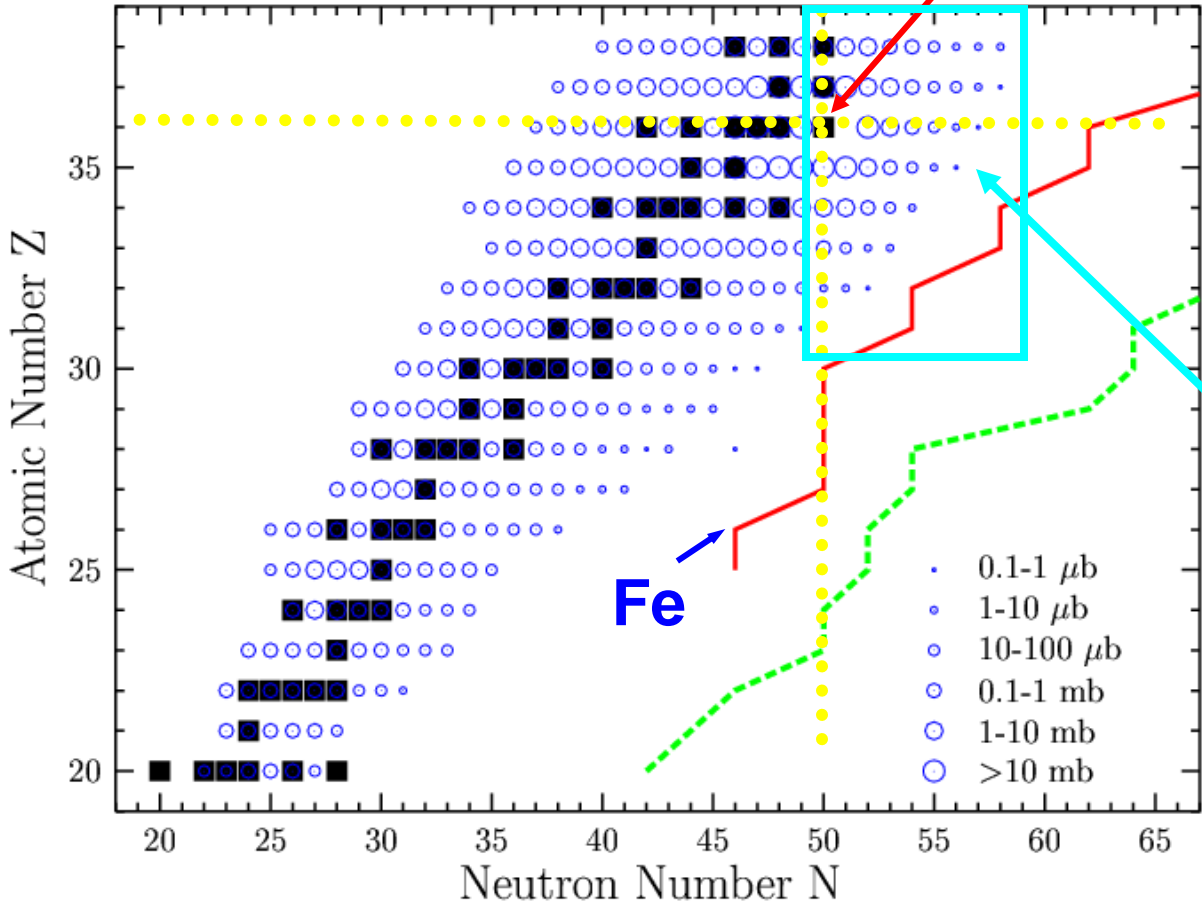


\*G. A. Souliotis et al.,  
Nucl. Instr. Methods B, 266, 4692 (2008)  
and references therein

# Rare Isotope Production at 15MeV/nucleon :

$^{86}\text{Kr}$  (15 MeV/nucleon) +  $^{64}\text{Ni}$

$^{86}\text{Kr}$   
36 50



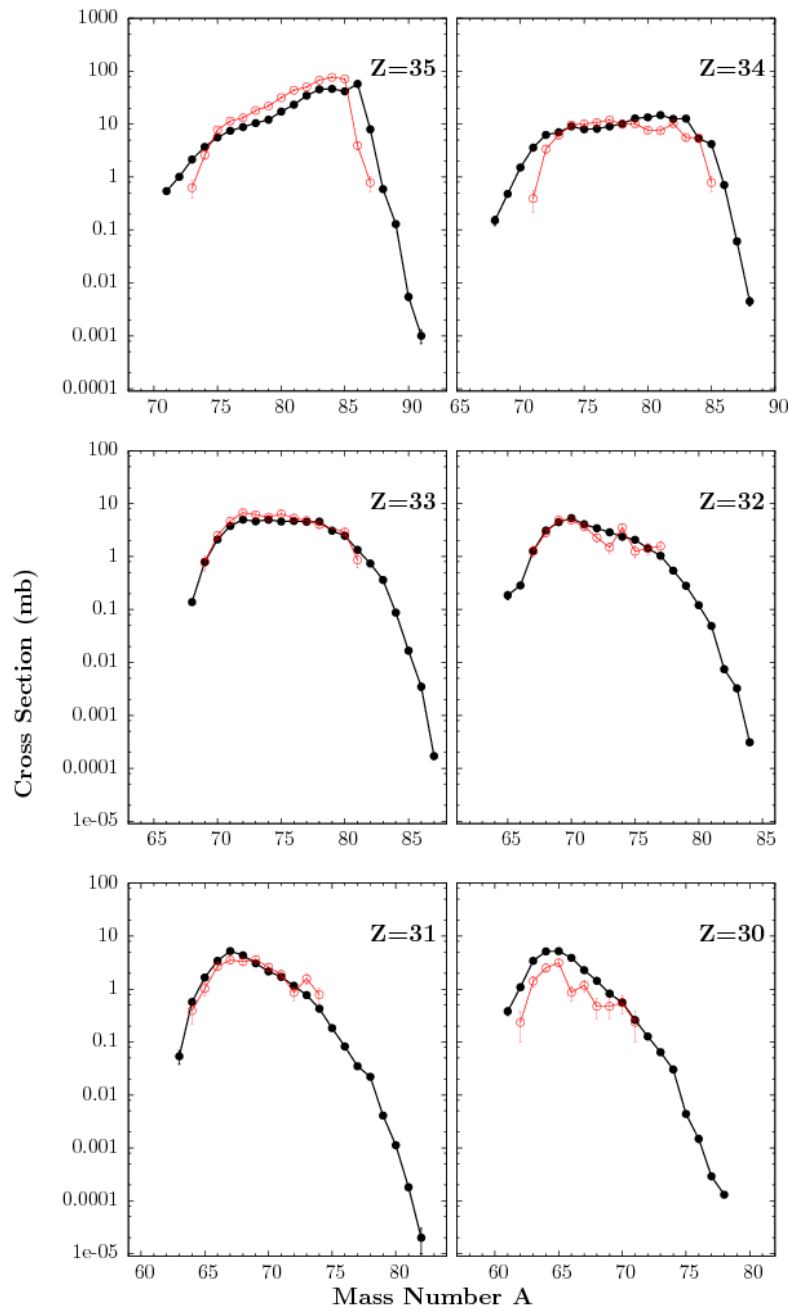
○ MARS Data:  
■ stable nuclei  
— r-process  
- - - n-drip line

Neutron-pickup products

## Neutron-Rich Rare Isotopes near and above the Fe-Ni region

\*G. A. Souliotis et al., Phys. Rev. C 84 064607, 2011

(15 MeV/nucleon)  $^{86}\text{Kr} + ^{64}\text{Ni}$



## Heavy Residue Cross Sections: $^{86}\text{Kr}$ (15MeV/nucleon)+ $^{64}\text{Ni}$ \*

- **MARS data:** this work  
G. A. Souliotis et al., PRC 84, 064607 (2011)

----- **CoMD/SMM**

### MODELS:

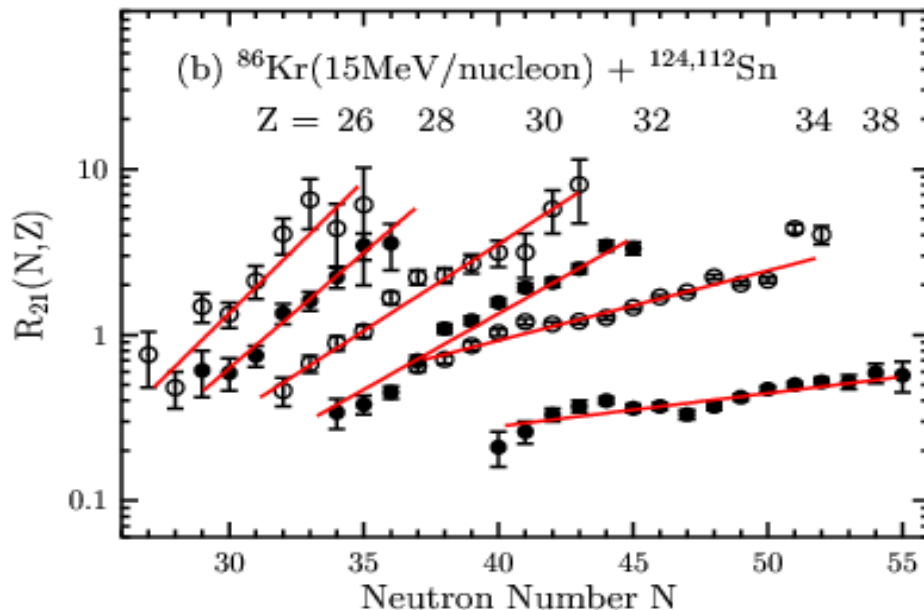
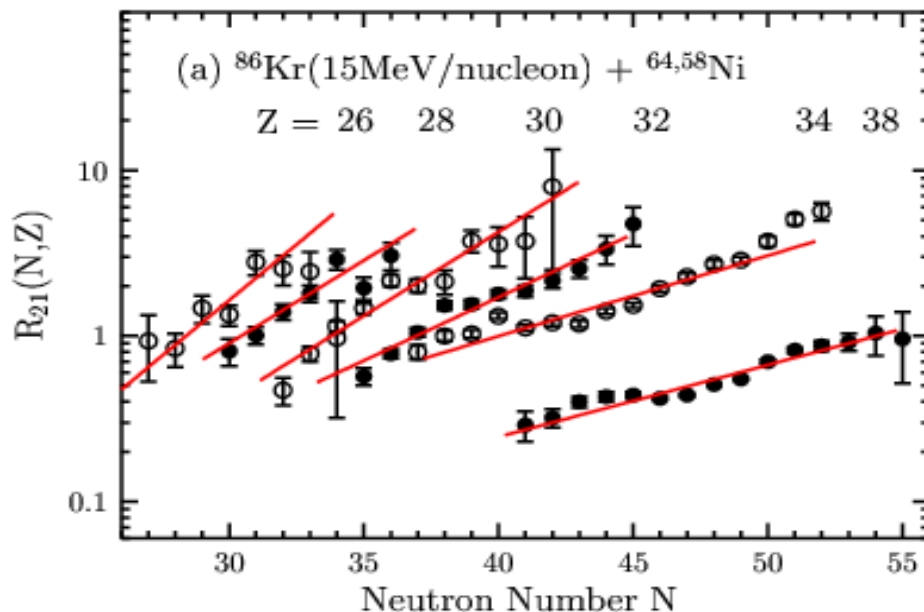
**CoMD:** Constraint Molecular Dynamics

**SMM:** Statistical Multifragmentation Model:

A. Botvina et al. Phys. Rev. C 65 044610 (2002)  
and Nucl. Phys. A 507, 649 (1990)

\* P. Fountas, G.A. Souliotis (work in progress)

# Scaling of Yield Ratios: 15MeV/nucleon data



$$R_{21}(N,Z) = Y_2/Y_1$$

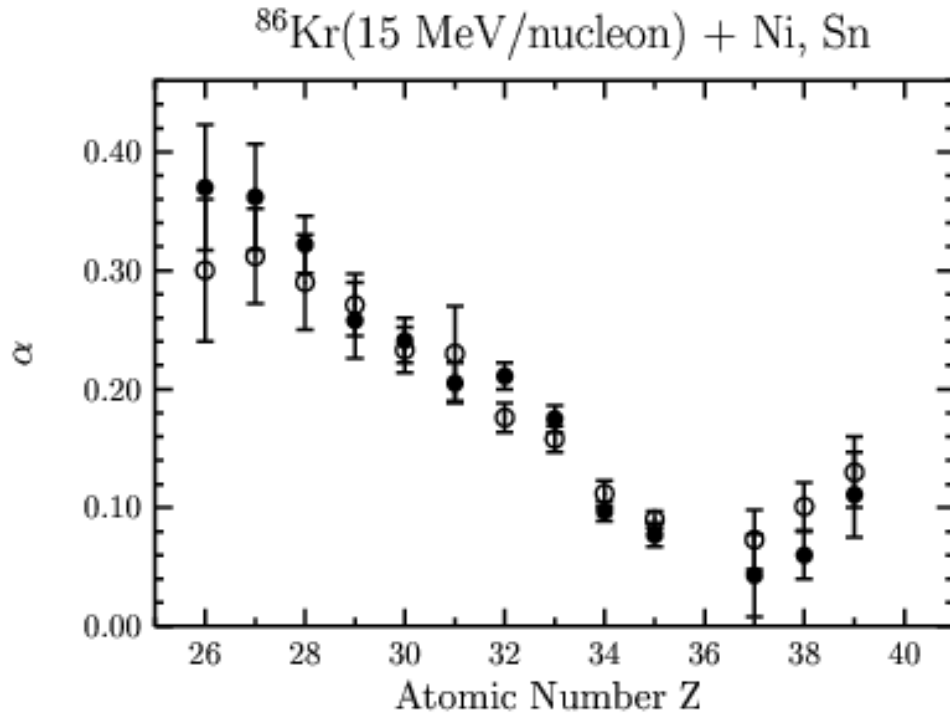
- $^{86}\text{Kr} + ^{64}\text{Ni}, ^{58}\text{Ni}$   
 data at  $4^\circ$  ( $\theta_{\text{gr}} = 6.0^\circ$ )

$$R_{21} = C \exp(\alpha N)$$

- $^{86}\text{Kr} + ^{124}\text{Sn}, ^{112}\text{Sn}$   
 data at  $7^\circ$  ( $\theta_{\text{gr}} = 9.0^\circ$ )



# Isoscaling Parameter $\alpha$ : 15MeV/u data



○  $^{86}\text{Kr} + ^{64}\text{Ni}, ^{58}\text{Ni}$  ( 4° data)

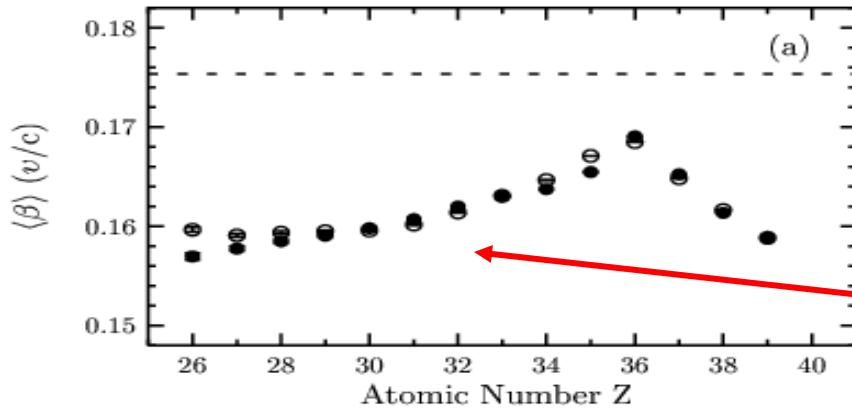
●  $^{86}\text{Kr} + ^{124}\text{Sn}, ^{112}\text{Sn}$  (7° data)

$$R_{21} = C \exp ( \alpha N )$$

$$\alpha = 4 C_{\text{sym}}/T \left( \left( \frac{Z}{A} \right)_1^2 - \left( \frac{Z}{A} \right)_2^2 \right)$$

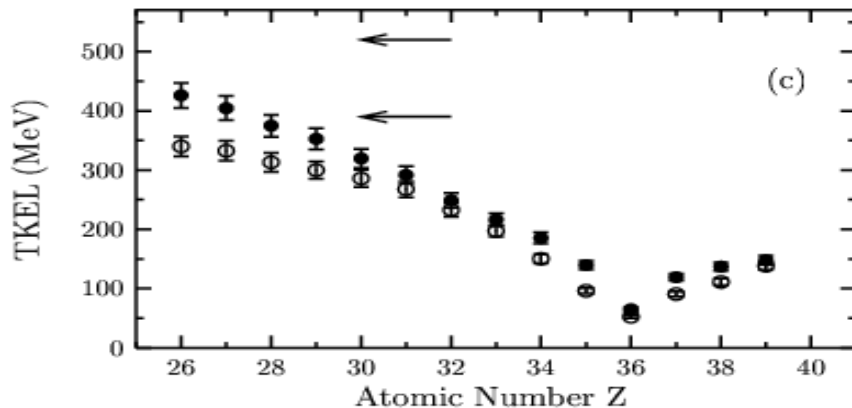
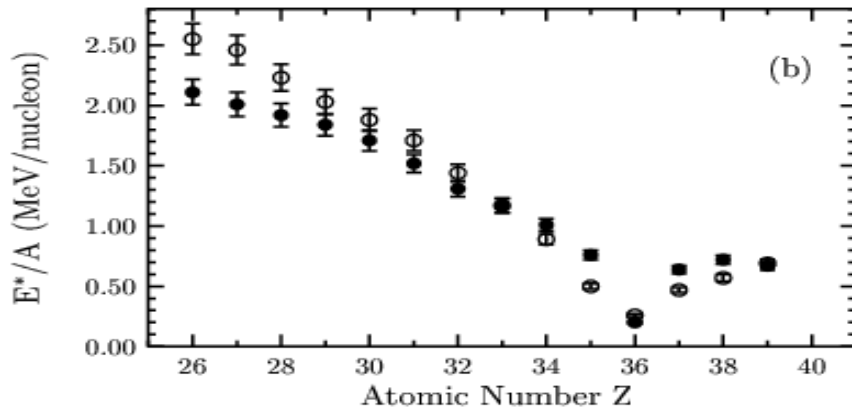
Quasi-projectiles 1: n-poor      2:nrich

# Velocity, $E^*$ , TKEL vs $Z$ correlations: 15MeV/u data

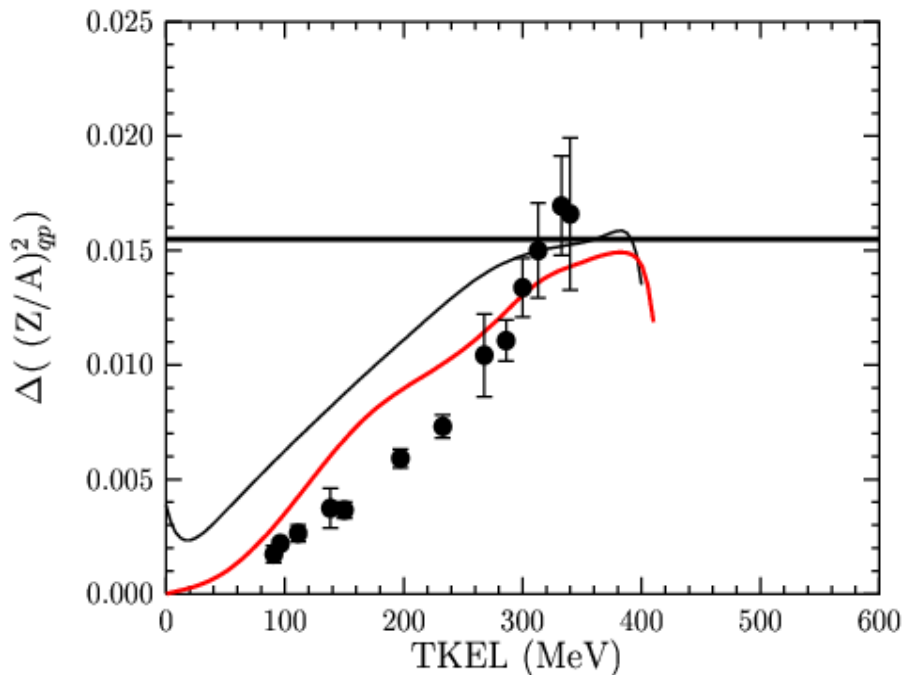
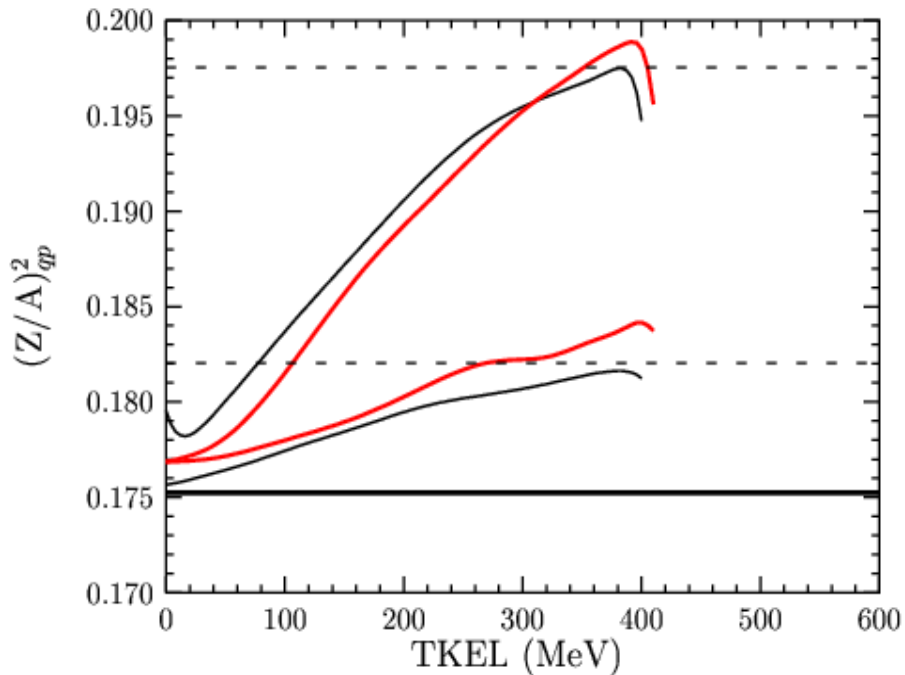


- $^{86}\text{Kr}+^{64}\text{Ni}, ^{58}\text{Ni}$  (4° data)
- $^{86}\text{Kr}+^{124}\text{Sn}, ^{112}\text{Sn}$  (7° data)

$v_{\min} E^*/A \sim 2.0-2.5 \text{ MeV}$



$^{86}\text{Kr}(15\text{MeV/nucleon}) + ^{64,58}\text{Ni}$



**Residues:  $^{86}\text{Kr}$  (15 MeV/u) +  $^{64,58}\text{Ni}$**

**$^{86}\text{Kr} + ^{58}\text{Ni}$**

----- **DIT**  
 ----- **CoMD (linear)**

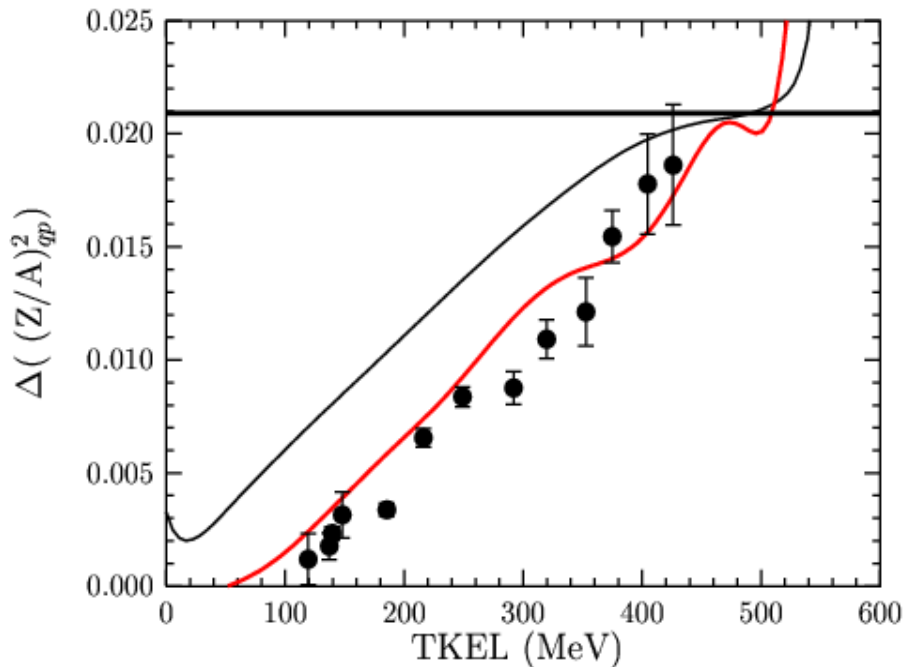
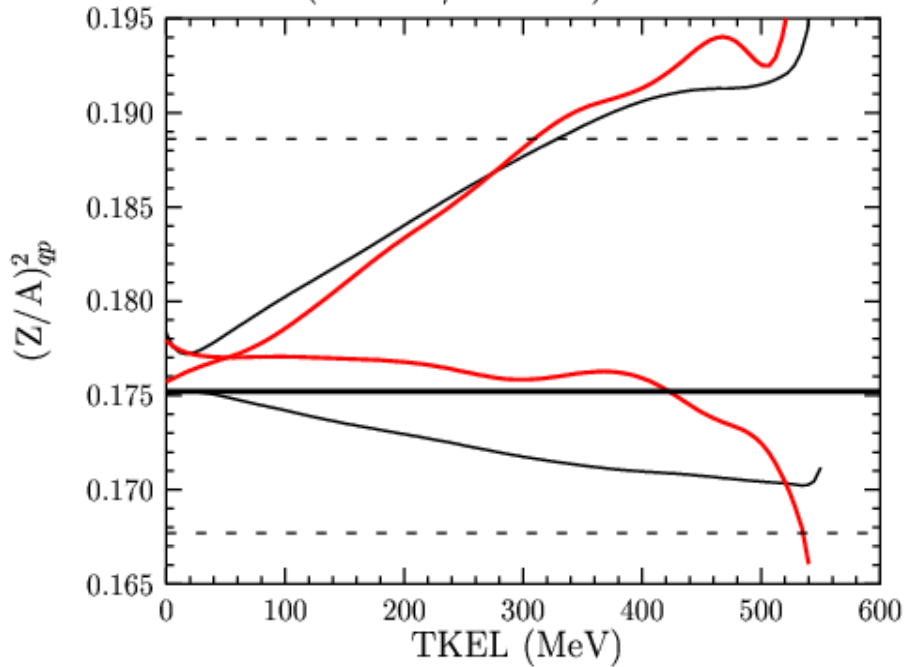
**$^{86}\text{Kr} + ^{64}\text{Ni}$**

- MARS Isoscaling data\*

$$\Delta(Z/A)^2 = (Z/A)^2_1 - (Z/A)^2_2 = \mathbf{a T / (4 C_{\text{sym}})}$$

**MODELS:**  
**DIT:** Deep Inelastic Transfer:  
 L. Tassan-Got, Nucl. Phys. A 524, 121 (1991)  
**CoMD:** Constraint Molecular Dynamics

$^{86}\text{Kr}(15\text{MeV/nucleon}) + ^{124,112}\text{Sn}$



**Residues:  $^{86}\text{Kr} (15 \text{ MeV/u}) + ^{124,112}\text{Sn}$**

**$^{86}\text{Kr} + ^{112}\text{Sn}$**

----- **DIT**

----- **CoMD (linear)**

**$^{86}\text{Kr} + ^{124}\text{Sn}$**

- MARS Isoscaling data\*

$$\Delta(Z/A)^2 = (Z/A)^2_1 - (Z/A)^2_2 = a T / (4 C_{\text{sym}})$$

**MODELS:**

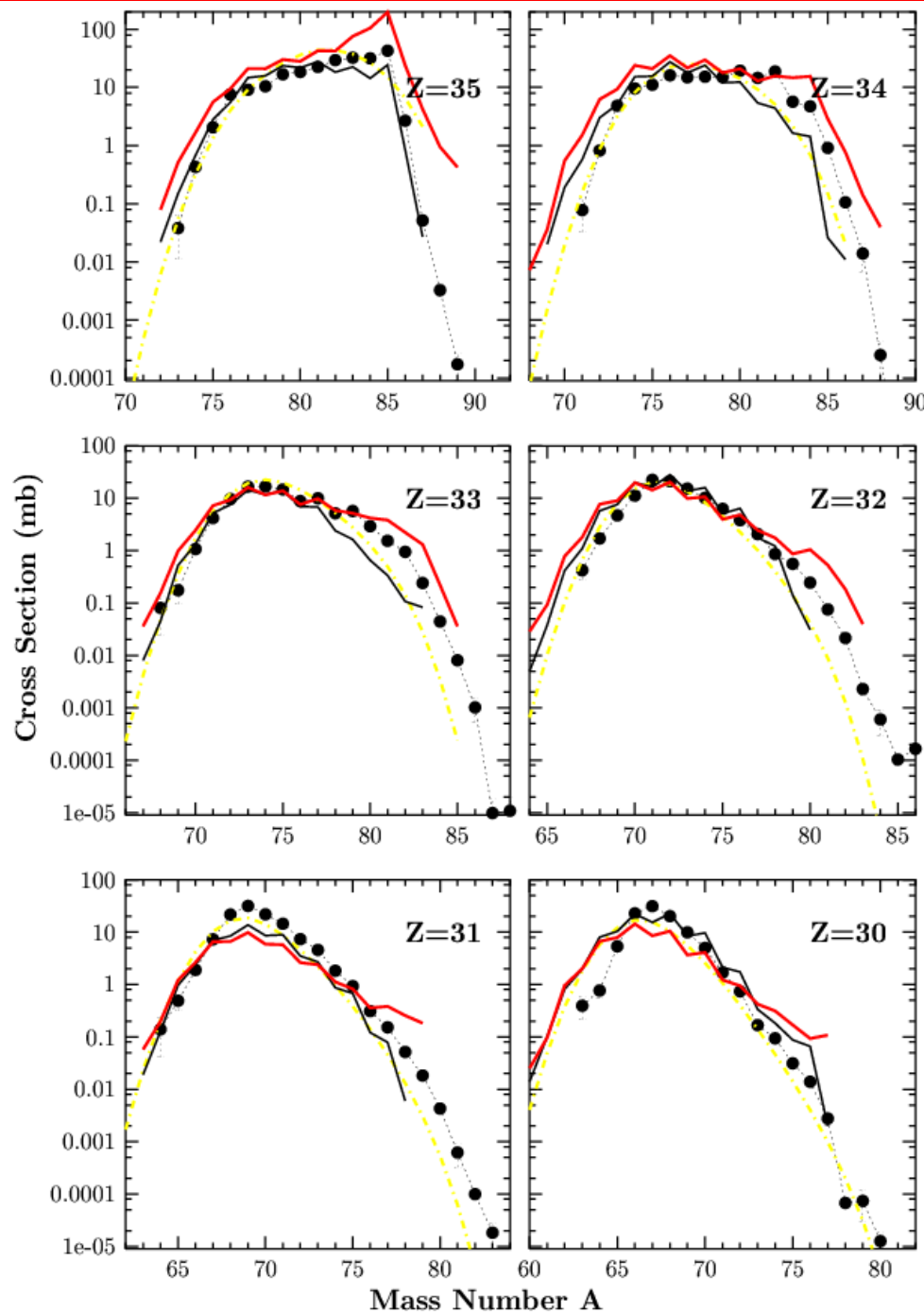
**DIT:** Deep Inelastic Transfer:

L. Tassan-Got, Nucl. Phys. A 524, 121 (1991)

**CoMD:** Constraint Molecular Dynamics

# Heavy Residue Cross Sections: $^{86}\text{Kr}$ (25MeV/u) + $^{64}\text{Ni}$

- **MARS data:**  
G.A. Souliotis et al.  
PLB 543, 163 (2002)



----- EPAX

———— DIT/GEMINI

----- CoMD/GEMINI (asy-stiff)

## MODELS:

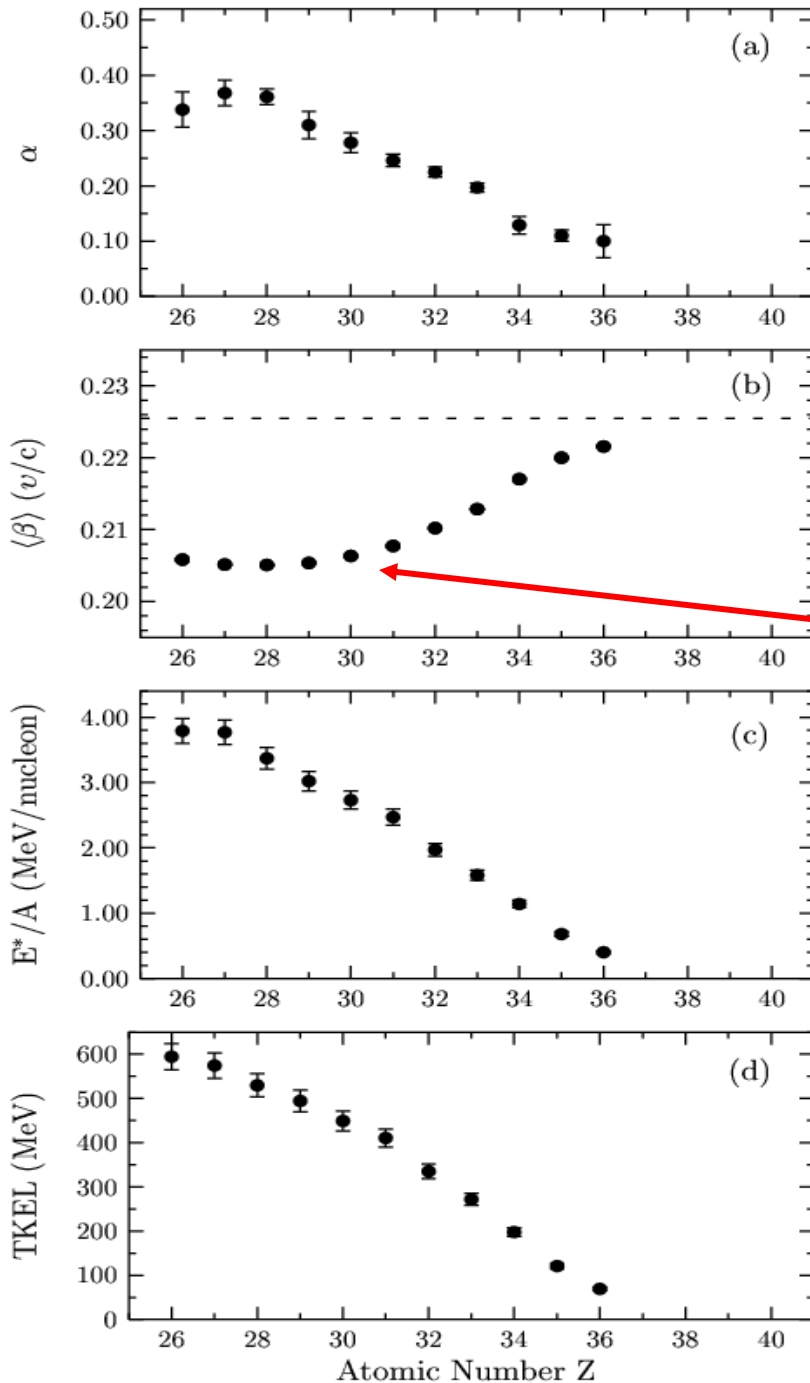
**DIT:** Deep Inelastic Transfer:  
L. Tassan-Got, Nucl. Phys. A 524, 121 (1991)

**GEMINI:** Binary decay code:  
R. Charity, Nucl. Phys. A483 391 (1988)

**CoMD:** Constraint Molecular Dynamics

# $\alpha$ , Velocity, $E^*$ , TKEL vs Z correlations: 25MeV/u data

●  $^{86}\text{Kr} + ^{124}\text{Sn}$  (and  $^{112}\text{Sn}$ ) ( $4^\circ$  data)



$v_{\min}$   $E^*/A \sim 3.0$  MeV

TKELmax = 1037 MeV

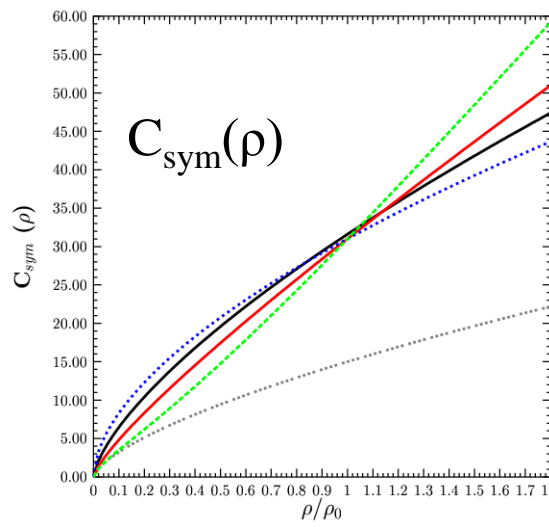
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avz\_iso\_25krsn\_tex.fit  
avz\_iso\_25krsn\_figure.tex => \*.ps

$^{86}\text{Kr}(25\text{MeV/nucleon}) + ^{124,112}\text{Sn}$

**Residues:  $^{86}\text{Kr} (25 \text{ MeV/u}) + ^{124,112}\text{Sn}$**

**$^{86}\text{Kr} + ^{112}\text{Sn}$**

**$^{86}\text{Kr} + ^{124}\text{Sn}$**

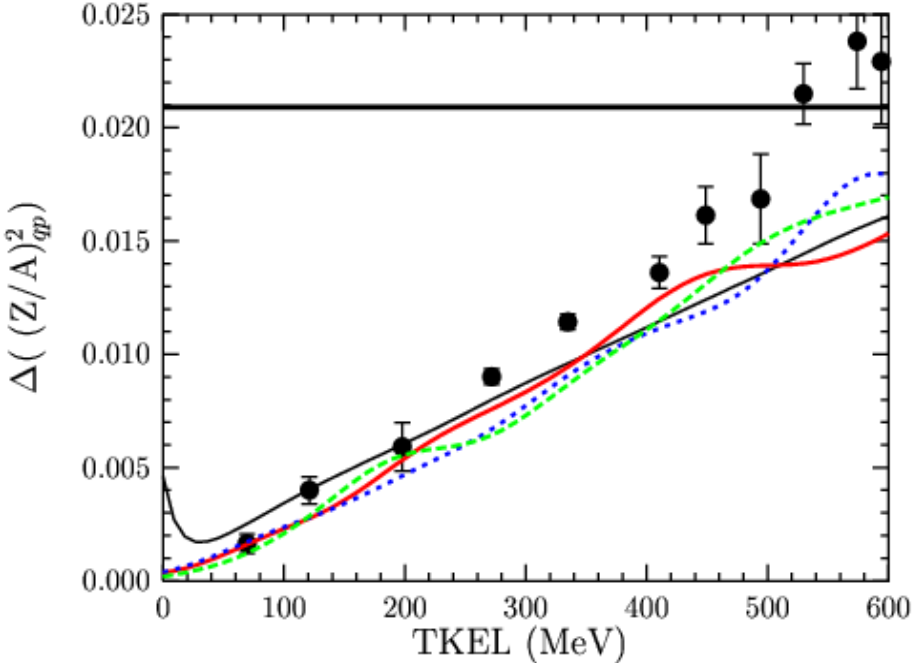
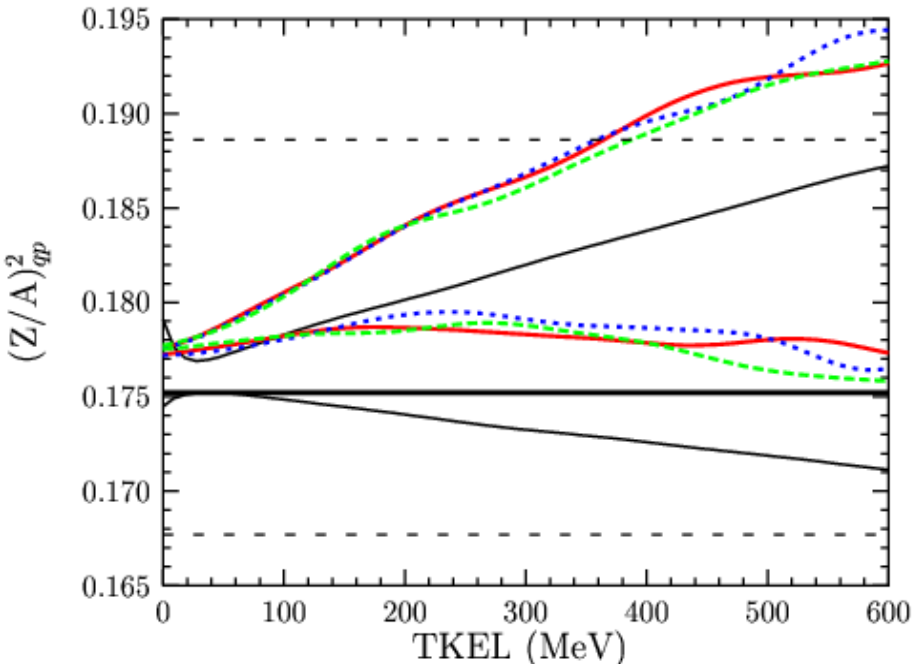


----- **DIT**

- **CoMD (linear)**
- **CoMD (a-soft)**
- **CoMD (a-stiff)**
- **CoMD (Vsym = 0)**

• MARS Isoscaling data\*

$$\Delta(Z/A)^2 = (Z/A)^2_1 - (Z/A)^2_2 = \mathbf{a T / (4 C_{sym} )}$$



GS files in "kr02" : anal\_mars\_kr\_apr02  
 azel1\_krsn\_tex.fit  
 azel1\_krsn\_figure.tex => \*.ps  
 in "kr07" saved as : azel1\_25krsn\_figure.eps

# Summary and Conclusions

- Production of neutron-rich nuclei in peripheral collisions  
Study of the mechanism of N/Z transport and equilibration.  
Extract properties of the effective nucleon-nucleon interaction, especially  $C_{\text{sym}}(\rho)$
- Microscopic calculations of peripheral collisions with CoMD

## Plans for future work:

- Detailed comparisons with theoretical codes (DIT, CoMD, TDHF)
- Experimental study of peripheral reactions at energy  $\sim 10\text{-}20$  MeV/nucleon  
Beams:  $^{70}\text{Zn}$ ,  $^{82}\text{Se}$  and with heavy targets:  $^{208}\text{Pb}$ ,  $^{238}\text{U}$  (look  $\sim \theta_{\text{gr}}$ )

**Extension of experimental studies using neutron-rich RIBs from TAMU RIB Upgrade\*, SPIRAL-II at GANIL and other facilities**

\* TAMU Cyclotron Upgrade, see : <http://cyclotron.tamu.edu>



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## Collaborators

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Z. Kohley, D.V. Shetty, B. Stein, S.J. Yennello

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