# Isospin diffusion in $^{58}$Ni-induced reactions at intermediate energies

E. Galichet[1] M. Colonna[2] B. Borderie[1]
M. F. Rivet[1]

[1] Institut de Physique Nucléaire, Orsay, France

[2] Laboratori Nazionali del Sud, Catania, Italy

23/08/2009 / IWND 2009 Shanghai

# Outline

1. Introduction
2. Experiment
3. Isospin diffusion
4. Isospin equilibration time
5. Conclusions

# Introduction

## EOS of asymmetric nuclear matter

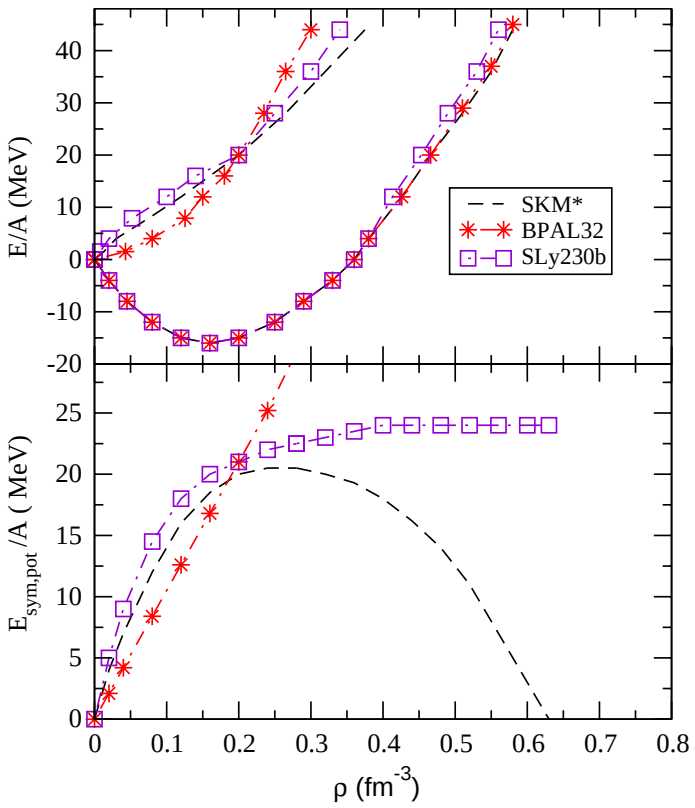
$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) \quad + \frac{E_{sym}}{A}(\rho) \times I^2$$

symmetric matter

with $I = \frac{\rho_n - \rho_p}{\rho} = \frac{N-Z}{A}$

The form of the symmetry term is still highly controversial.

# Introduction




*V. Baran et al., Phys. Rep. 410 (2005) 335.*

EOS using different effective interactions may present the same saturation properties for symmetric nuclear matter, but very different symmetry energy contributions.

# Introduction

- Isospin diffusion is one of the observables which should be sensitive to the symmetry energy.
  We studied isospin diffusion by looking at the isospin content of light products ($Z<5$) emitted in the forward part of phase space, as a function of the dissipation (or impact parameter).
- We need a model to derive information on the symmetry energy term of the EOS. We chose the BNV transport model.

# The Boltzmann-Nordheim-Vlasov model

The BNV transport equation describes the evolution of the one-body distribution function with Mean Field + 2-body collisions. It uses the test-particle prescription (here 50 tp/nucleon)

- Soft isoscalar EOS : $K_\infty$=200 MeV.
- 2 prescriptions for the symmetry energy :
  - asy-stiff $E_{sym}(\rho) = E_{sym}(\rho_0) \times (\rho/\rho_0)$
  - asy-soft $\propto (\rho/\rho_0)^{0.6}$
- free $\sigma_{NN}$ with its angular, energy and isospin dependences.

# The Boltzmann-Nordheim-Vlasov model

The BNV transport equation describes the evolution of the one-body distribution function with Mean Field + 2-body collisions. It uses the test-particle prescription (here 50 tp/nucleon)

- Soft isoscalar EOS : $K_\infty$=200 MeV.
- 2 prescriptions for the symmetry energy :
  - asy-stiff $E_{sym}(\rho) = E_{sym}(\rho_0) \times (\rho/\rho_0)$
  - asy-soft $\propto (\rho/\rho_0)^{0.6}$
- free $\sigma_{NN}$ with its angular, energy and isospin dependences.

# The Boltzmann-Nordheim-Vlasov model

The BNV transport equation describes the evolution of the one-body distribution function with Mean Field + 2-body collisions. It uses the test-particle prescription (here 50 tp/nucleon)

- Soft isoscalar EOS : $K_\infty$=200 MeV.
- 2 prescriptions for the symmetry energy :
  - asy-stiff $E_{sym}(\rho) = E_{sym}(\rho_0) \times (\rho/\rho_0)$
  - asy-soft $\propto (\rho/\rho_0)^{0.6}$
- free $\sigma_{NN}$ with its angular, energy and isospin dependences.

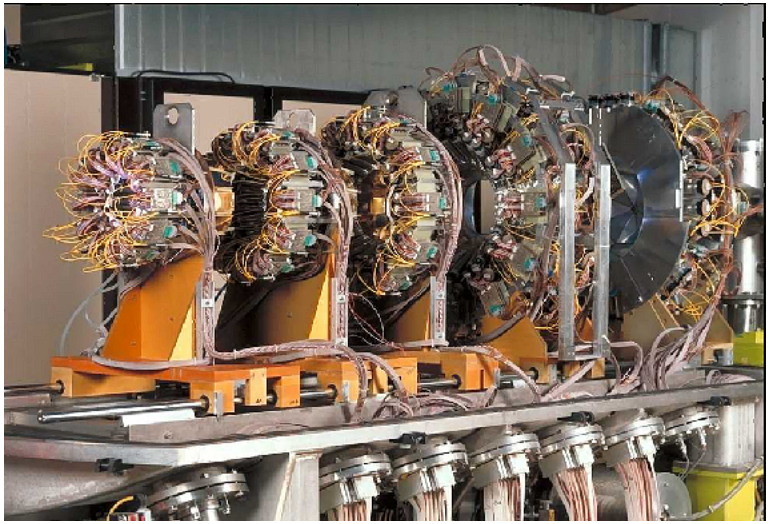
# The studied systems

Same projectile, two targets :

$^{58}$Ni + $^{58}$Ni
$^{58}$Ni + $^{197}$Au
at 52*A* and 74*A* MeV.

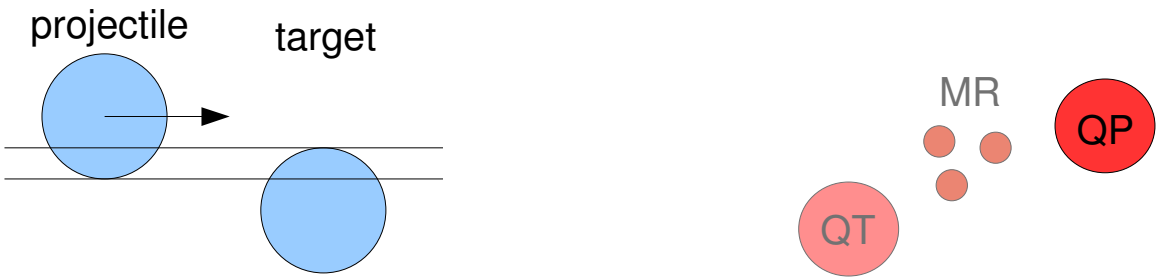
Expected Isospin effects on:
Ni+Ni - small, only preequilibrium emission.
Ni+Au - PE + isospin transport.

The experiment was performed at GANIL. The charged reaction products were detected by the 4$\pi$ INDRA array.



# Selections I

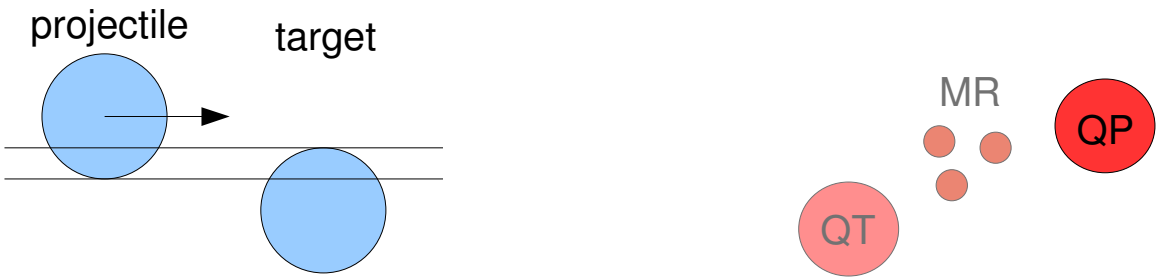
- We select semiperipheral collisions, with two main products in the exit channel (b$\sim$ 4 fm up to $b_{max}$).




- The hot QP and QT deexcite by emitting fragments (Z$\geq$5), particles (Z$\leq$4), leaving cold residues.

# Selections I

- We select semiperipheral collisions, with two main products in the exit channel (b$\sim$ 4 fm up to $b_{max}$).




- The hot QP and QT deexcite by emitting fragments (Z$\geq$5), particles (Z$\leq$4), leaving cold residues.

# Selections II

- We look at isospin in the forward part of the NN frame ($y > y_{proj}/2$). This eliminates the detection biases on the QT side, and, for the Ni+Au system, avoids considering products coming from the QT.
- We require "complete events" : $\sum_{fwdNN} Z_i \in [24 - 32]$.
- This does NOT isolate a "source" (equilibrated or not); in particular the selected light charged products originate from the quasi-projectile as well as from mid-rapidity (preequilibrium).

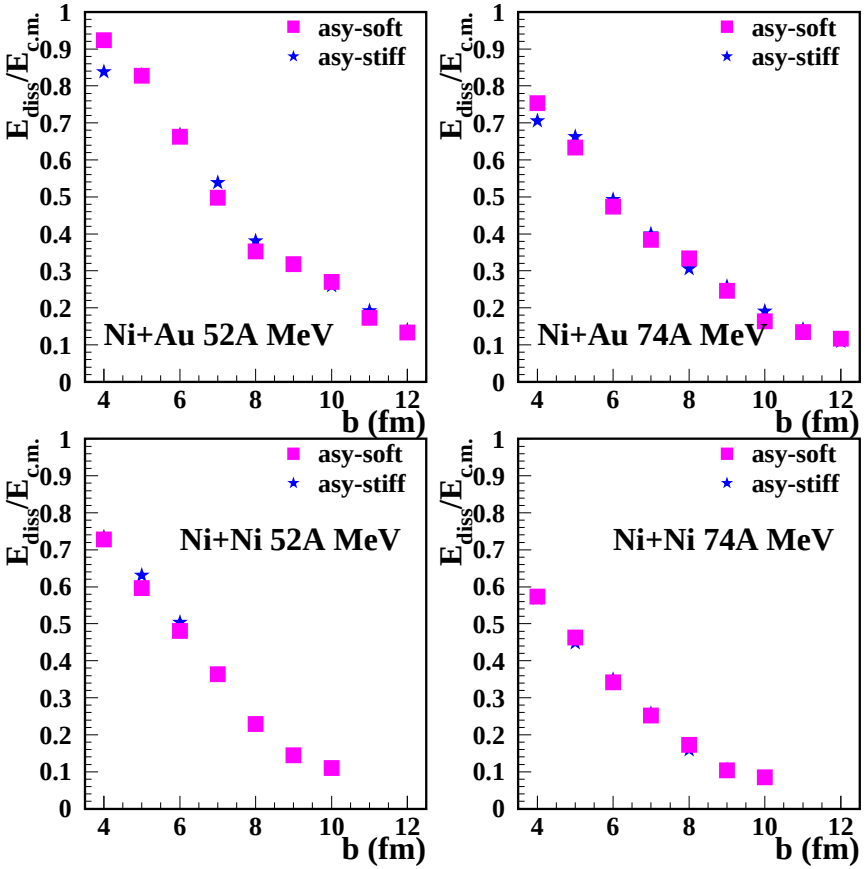
# Selections II

- We look at isospin in the forward part of the NN frame ($y > y_{proj}/2$). This eliminates the detection biases on the QT side, and, for the Ni+Au system, avoids considering products coming from the QT.
- We require "complete events" : $\sum_{fwdNN} Z_i \in [24 - 32]$.
- This does NOT isolate a "source" (equilibrated or not); in particular the selected light charged products originate from the quasi-projectile as well as from mid-rapidity (preequilibrium).

# Selections II

- We look at isospin in the forward part of the NN frame ($y > y_{proj}/2$). This eliminates the detection biases on the QT side, and, for the Ni+Au system, avoids considering products coming from the QT.
- We require "complete events" : $\sum_{fwdNN} Z_i \in [24 - 32]$.
- This does NOT isolate a "source" (equilibrated or not); in particular the selected light charged products originate from the quasi-projectile as well as from mid-rapidity (preequilibrium).

# The sorting variable: the energy dissipation




$$E_{diss} = E_{c.m.} - \frac{1}{2}\mu V_{rel}^2$$

with

$$V_{rel} = V_{QP}^{rec} \times \frac{A_{tot}}{A_{target}}$$

$V_{QP}^{rec}$ obtained from selected fragments

BNV shows that this variable gives a good measure of the impact parameter.

# The experimental isospin variable: $< N >/< Z >)_{CP}$

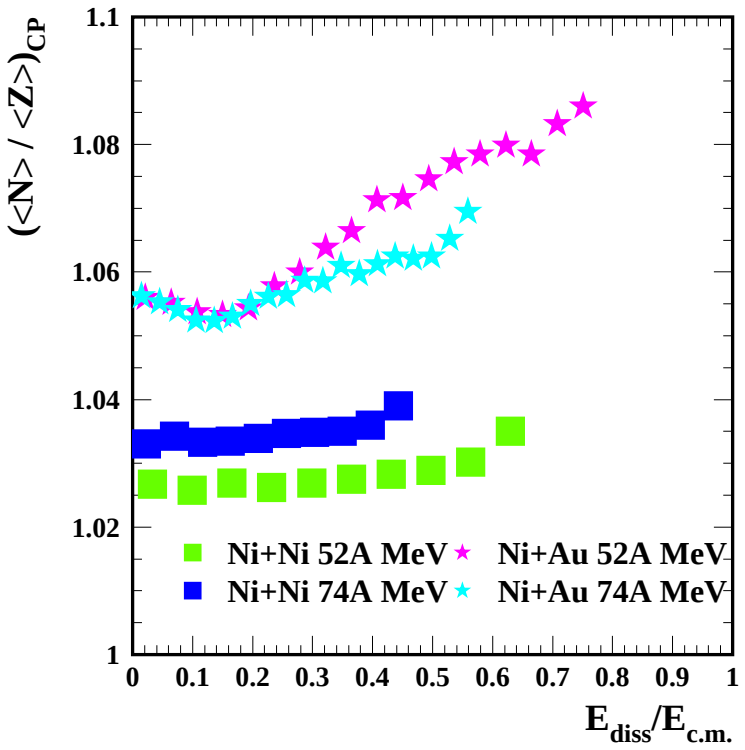
**Definition**

$$(< N > / < Z >)_{CP} = \sum_{N_{evts}} \sum_{\nu} N_{\nu} / \sum_{N_{evts}} \sum_{\nu} P_{\nu}$$

$N_\nu$ and $P_\nu$ are respectively the numbers of neutrons and protons bound in particle $\nu$, forward emitted in the NN frame.
$\nu$ = $d$, $t$, $^3$He, $\alpha$, $^6$He, $^6$Li, $^7$Li, $^8$Li, $^9$Li, $^7$Be, $^9$Be, $^{10}$Be
free protons are excluded, as neutrons are not measured.

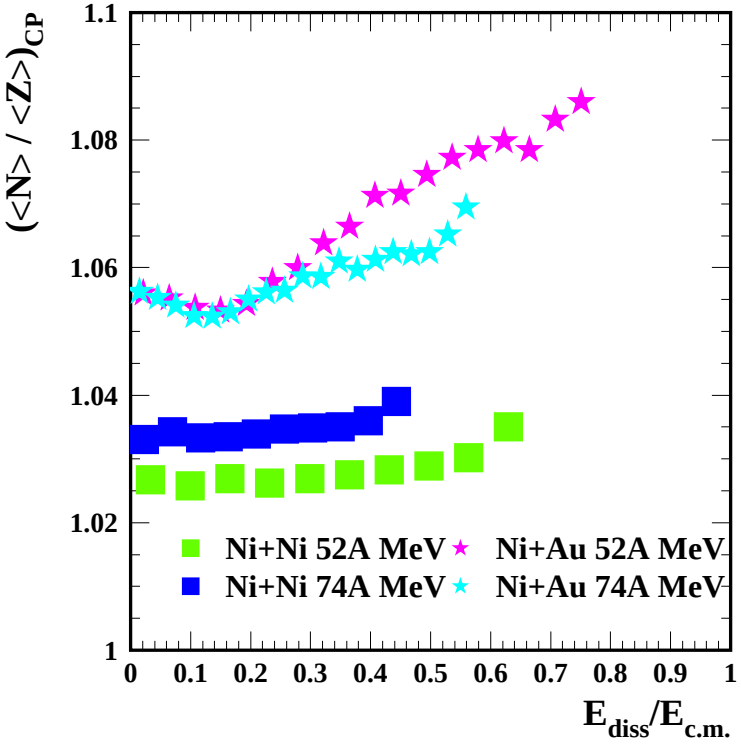
# Experimental results

E. Galichet et al., Phys. Rev. C 79 064614



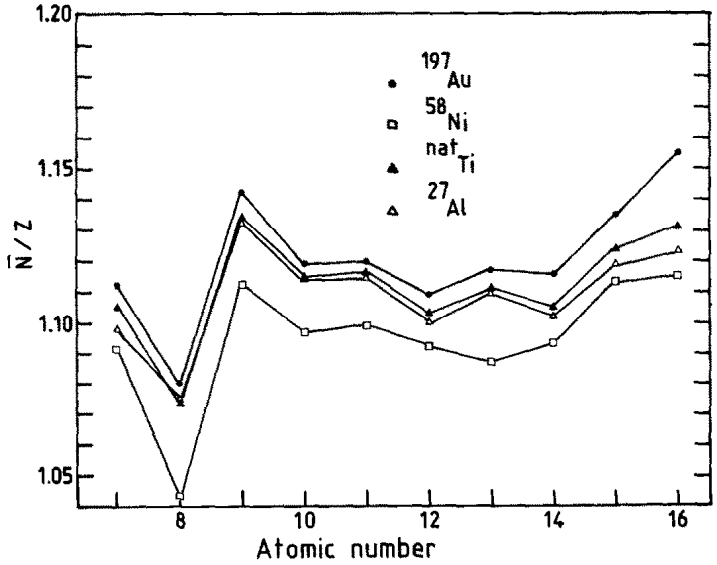
# Experimental results

E. Galichet et al., Phys. Rev. C 79 064614




QP residues from $^{40}$Ar + X @ 44 MeV/nucleon

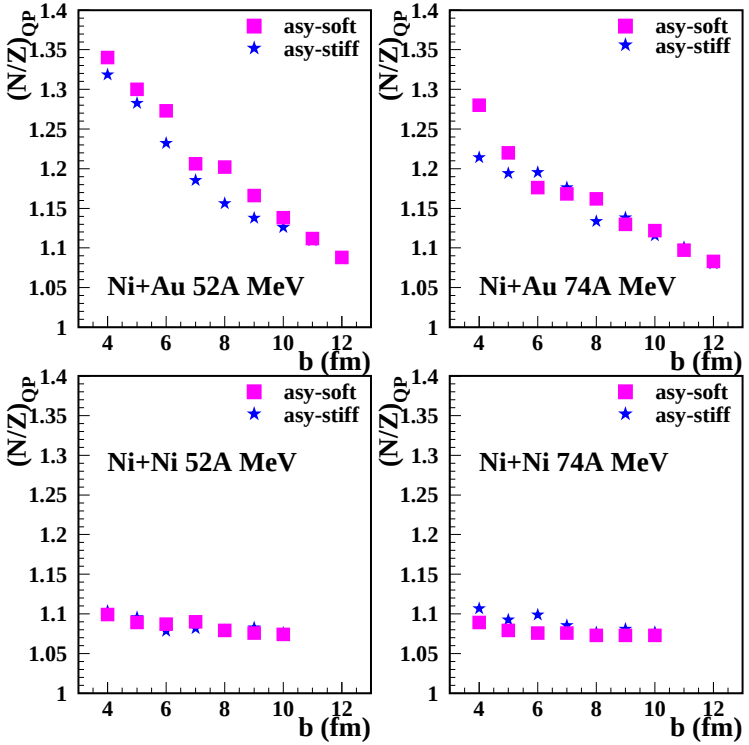
Dayras et al. NPA460 (1986)



# The ideal isospin variable: $< N >/< Z >)_{QP}$

## sorting with b

BNV results : N/Z of QP* when QP, QT re-separate.

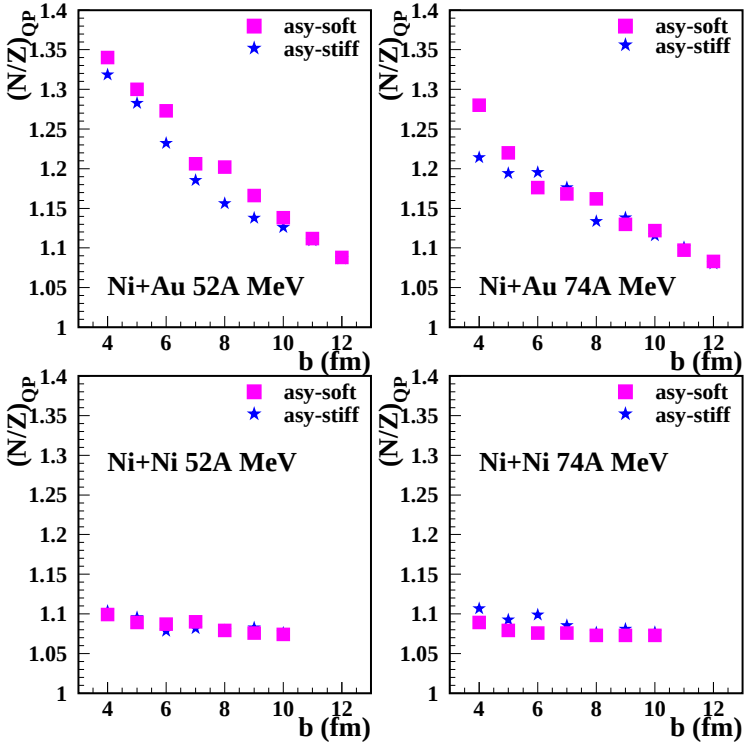



- Small increase for Ni+Ni, stronger with asy-stiff (more preequilibrium *p* emission)
- Ni+Au: N/Z higher for asy-soft, more dissipative. N/Z diffusion related to degree of dissipation and driving force provided by $E_{sym}$

# The ideal isospin variable: $< N >/< Z >)_{QP}$

## sorting with b

BNV results : N/Z of QP* when QP, QT re-separate.

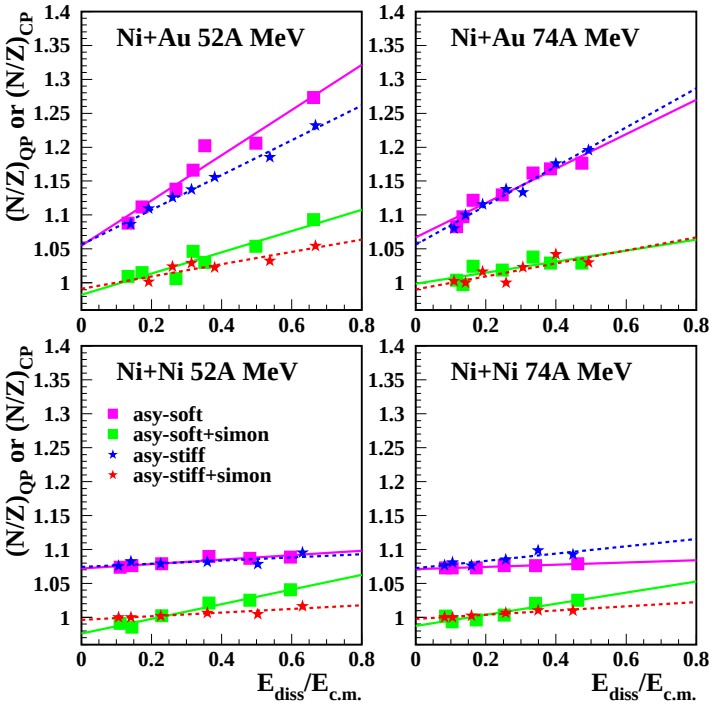



- Small increase for Ni+Ni, stronger with asy-stiff (more preequilibrium *p* emission)
- Ni+Au: N/Z higher for asy-soft, more dissipative. N/Z diffusion related to degree of dissipation and driving force provided by $E_{sym}$

# The ideal isospin variable

## sorting with $E_{diss}$ - effect of deexcitation

QP* de-excited with the help of the SIMON code.




Same trends as with b.

De-excitation -> $(< N > / < Z >)_{CP}$ smaller than $< N > / < Z >)_{QP}$ and has smaller slopes.

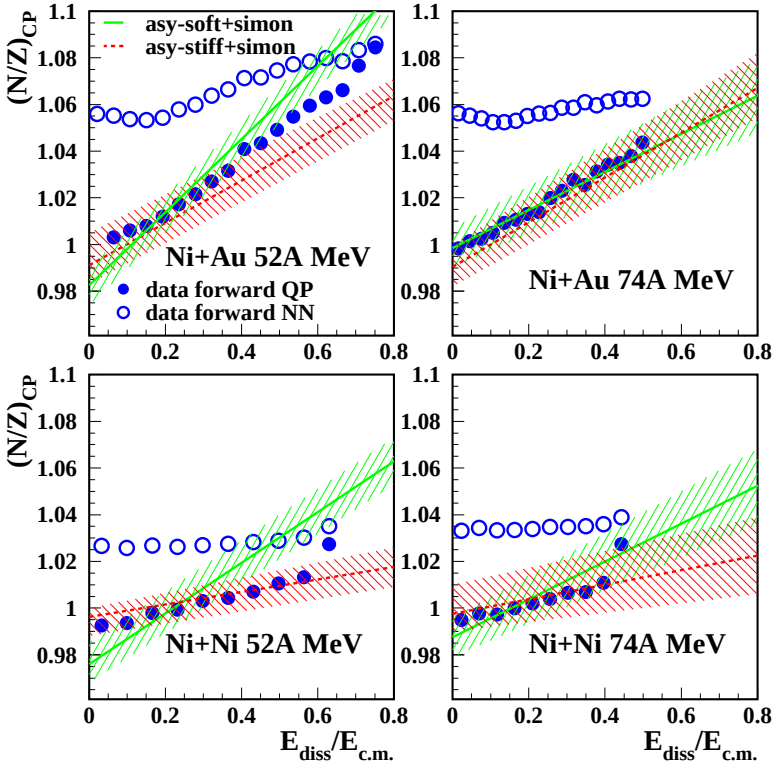
Differences with asy-EOS still present, even increased at 52A MeV (due to larger E* with asy-soft -> more emission of n-rich nuclei)

# How to compare BNV results and data?

In BNV we cannot "identify" MR fragments/particles. We can construct $< N >/< Z >)_{CP}$ only with the deexcitation products of the QP.
Experimentally we thus re-calculate $< N >/< Z >)_{CP}$ only with particles forward emitted in the QP frame.

# Comparison with BNV data

E. Galichet et al., Phys. Rev. C 79 064615



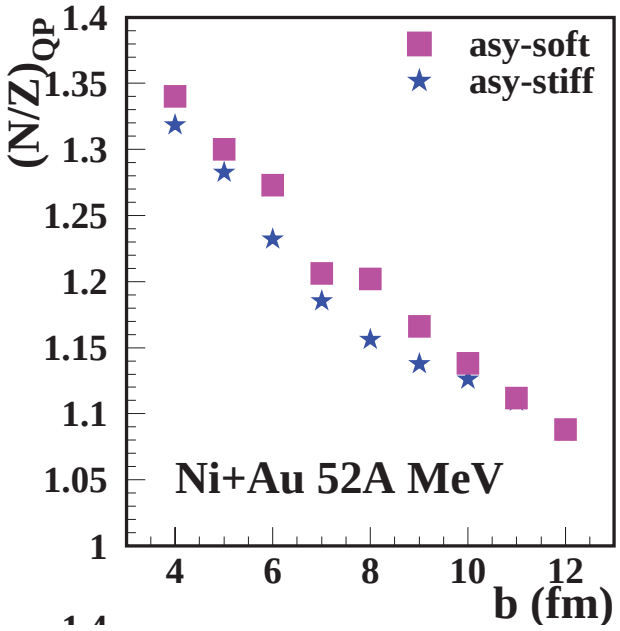

When considering the 4 systems

A better overall agreement is obtained with the asy-stiff EOS,

in which the symmetry energy varies linearly with the density.

# Isospin equilibration in Ni + Au at 52*A* MeV ?

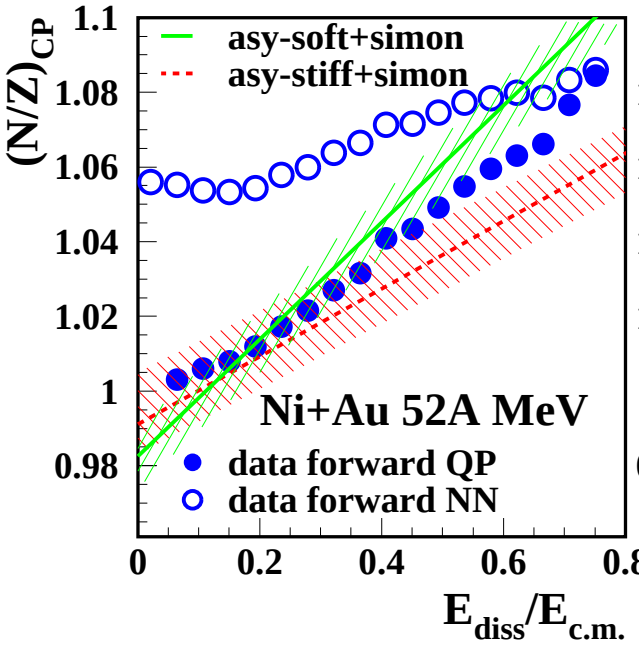
## BNV model




For b=4 fm and asy-soft, the isospin equilibration (N/Z=1.38) is quasi-reached when QP and QT re-separate at time t=130 fm/*c*. About 80% of the energy has been dissipated.

# Isospin equilibration in Ni + Au at 52*A* MeV ?

## Experiment




The values of $< N >/< Z >)_{CP}$ forward of the NN velocity (dominated by MR particles, more n-rich) and forward in the QP frame (QP evaporation) become equal at high dissipation ($E_{diss}/E_{c.m.} \sim 0.7$); this is a good indication of N/Z equilibration of the system.

# Other estimate: $^{64}$Zn + $^{197}$Au @ 47$A$ MeV

TAMU group PRC72 (2005), PRC 75 (2007)

- *The agreement between the thermal slope parameter (from a 3-source fit) and the chemical temperature, $T_{HHe}$, for the IV source, provides a strong indication that . . . chemical equilibrium has been achieved, at least locally, at the time of maximum $T_{HHe}$.*
- For the system $^{64}$Zn + $^{197}$Au @47 MeV/nucleon, similar to ours*, the time is $\tau_{maxT}$ = 115 fm/$c$, in reasonable agreement with our finding.

  * The time $\tau_{maxT}$, determined with the help of AMD calculations, depends on the masses and energy of the incident nuclei.

# Other estimate: $^{64}$Zn + $^{197}$Au @ 47$A$ MeV

TAMU group PRC72 (2005), PRC 75 (2007)

- *The agreement between the thermal slope parameter (from a 3-source fit) and the chemical temperature, $T_{HHe}$, for the IV source, provides a strong indication that . . . chemical equilibrium has been achieved, at least locally, at the time of maximum $T_{HHe}$.*
- For the system $^{64}$Zn + $^{197}$Au @47 MeV/nucleon, similar to ours*, the time is $\tau_{maxT}$ = 115 fm/$c$, in reasonable agreement with our finding.

  * The time $\tau_{maxT}$, determined with the help of AMD calculations, depends on the masses and energy of the incident nuclei.

# Use of imbalance ratio

J.Rizzo et al., Nucl. Phys. A806 (2008) 79

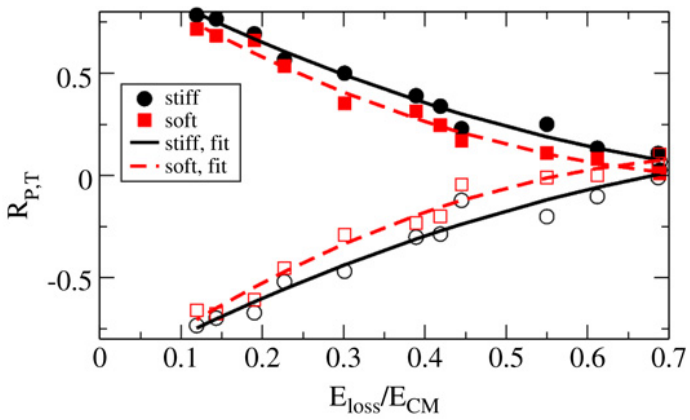
Study of isospin transport/equilibration with the Imbalance ratio:
$R^{x}_{P,T} = \frac{2(x^{M} - x^{eq})}{(x^{H} - x^{L})}$ with $x^{eq} = (x^{H} + x^{L})/2$

x is an isospin sensitive quantity.
H and L refer to symmetric reactions between n-rich and n-poor systems, M to the mixed reaction.

# Imbalance ratio vs dissipation

## BNV model

Reactions Sn+Sn @35A and 50A MeV.
H=124; L=112



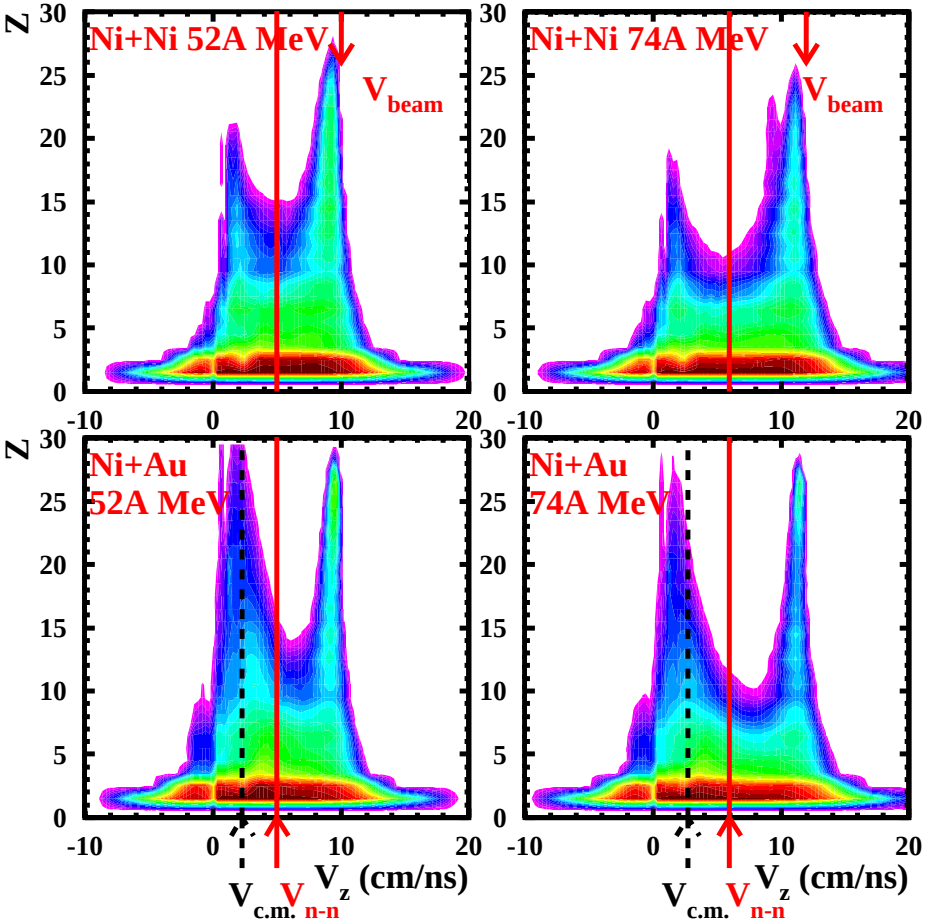

$x = I = (N - Z)/(N + Z)$

$R^I$ depends on
1- the strength of $E_{sym}$
2- the interaction time
Assuming
$I^M_{P,T} = I^{eq} + (I^{H,L} - I^{eq})e^{-t/\tau}$
then $R^I_{P,T} = \pm e^{-t/\tau}$.
isospin equilibrium for:
$\mathrm{E_{loss}/E_{c.m.}} \sim 0.6$ for asy-soft
$\mathrm{E_{loss}/E_{c.m.}} \sim 0.7$ for asy-stiff

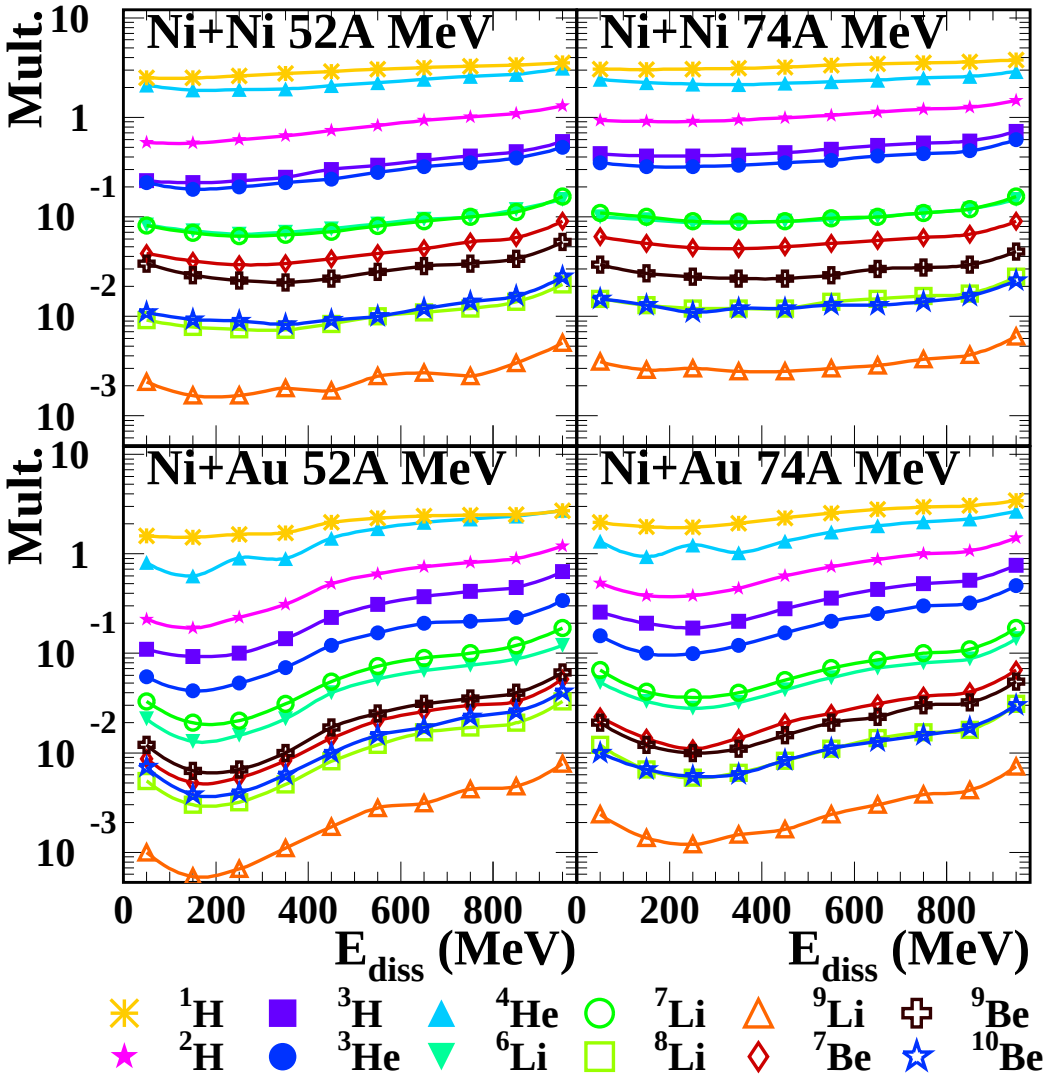
# Conclusions

1. $< N >/< Z >)_{CP}$ is a good probe of isospin diffusion for Ni+Au.
2. In dynamical simulations differences between asy-EOS are present, and persist after secondary decay.
3. A better global agreement for the 4 studied cases is obtained in the asy-stiff case ($E_{sym}(\rho) \propto (\rho/\rho_0)$).
4. Isospin equilibration is observed experimentally. The associated time is estimated at 130 $\pm$ 10 fm/$c$ at energies around 50 MeV/nucleon.

THANK YOU for your attention.


Ni+Ni 52A MeV
V beam
Ni+Ni 74A MeV
V beam
Ni+Au 52A MeV
Ni+Au 74A MeV
Z
V z (cm/ns)
V c.m.
V n-n

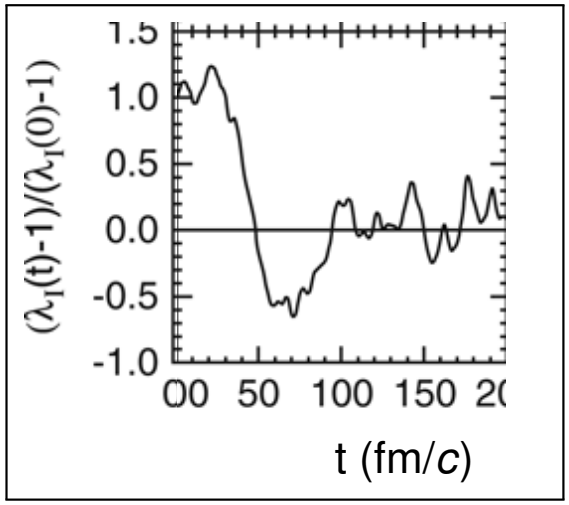
# Multiplicities



# Theoretical prediction

Bao-An Li and C. M. Ko PRC57 (1998)

$^{40}$Ca + $^{124}$Sn 50 MeV/nucleon; b = 1 fm; N/Z = 1.343.




Define:
$\lambda_i(t) = (n/p)_{y>0}/(n/p)_{y<0}$

Isospin equilibrium $\tau_I$:
$(\lambda_i(t) - 1)/(\lambda_i(0) - 1) = 0.01$

In the paper the authors give
$\tau_I \sim 50$ fm/$c$.