Study of the isospin transport phenomena in the $^{58}Ni+^{58}Ni$ reaction at 32, 52 and 74 AMeV with the FAZIA-INDRA apparatus.

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Isospin transport phenomena

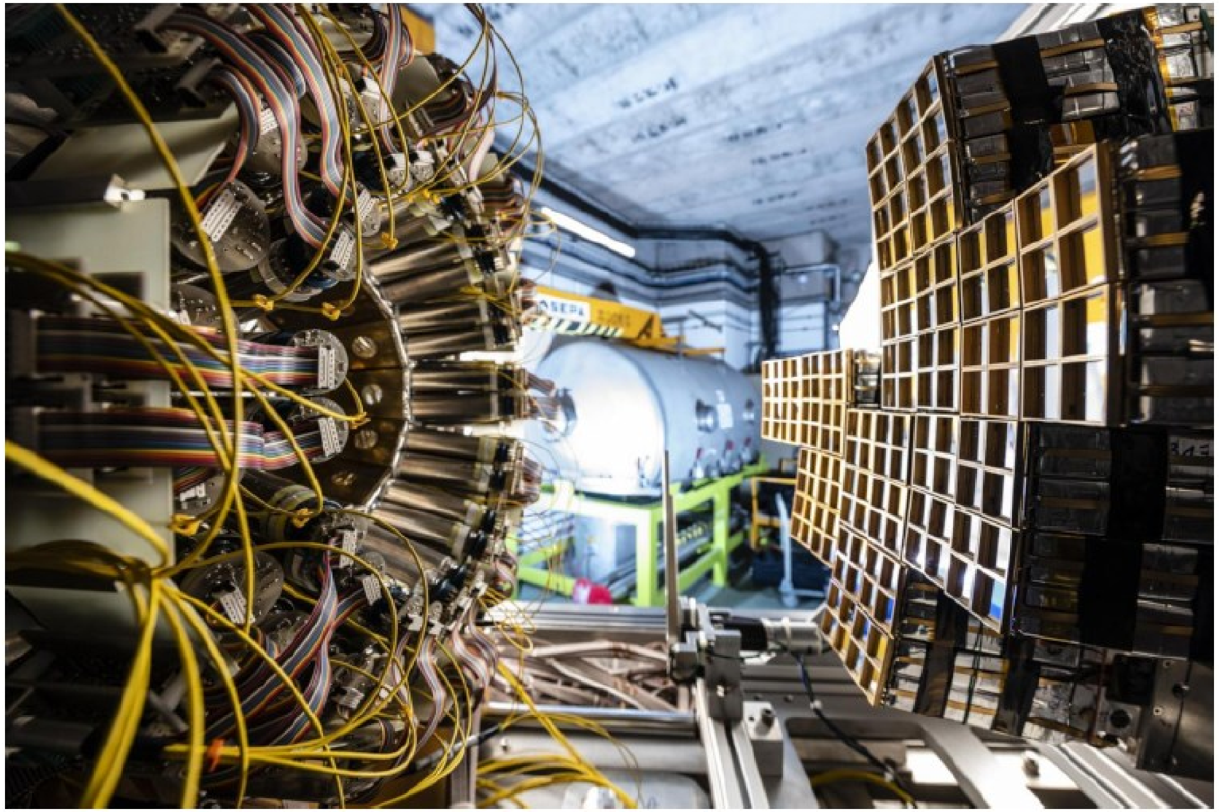
- The symmetry energy term of the NEoS governs the isospin transport phenomena, i.e. the nucleon exchange between projectile and target
- The isospin transport can be expressed as the difference between the neutron and proton currents between the two nuclei during the collision:

$$j_n - j_p \propto \frac{E_{sym}}{A}(\rho)\nabla\delta + \delta\frac{\partial\frac{E_{sym}}{A}(\rho)}{\partial\rho}\nabla\rho$$

  - **Isospin diffusion**: driven by an isospin gradient → QP-QT equilibration
  - **Isospin drift**: driven by a density gradient → neutron enrichment of the neck region

The INDRA-FAZIA apparatus

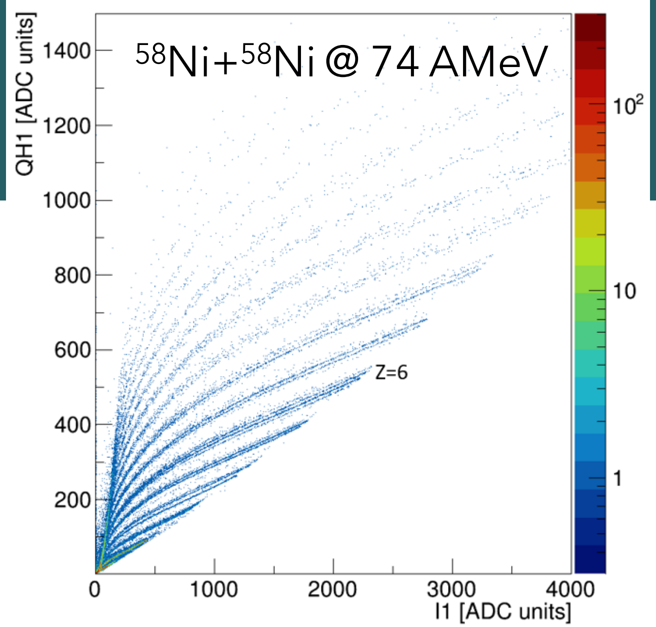
INDRA and FAZIA are multi-detector apparatuses for the detection of charged fragments produced in heavy ion collisions at Fermi energies.



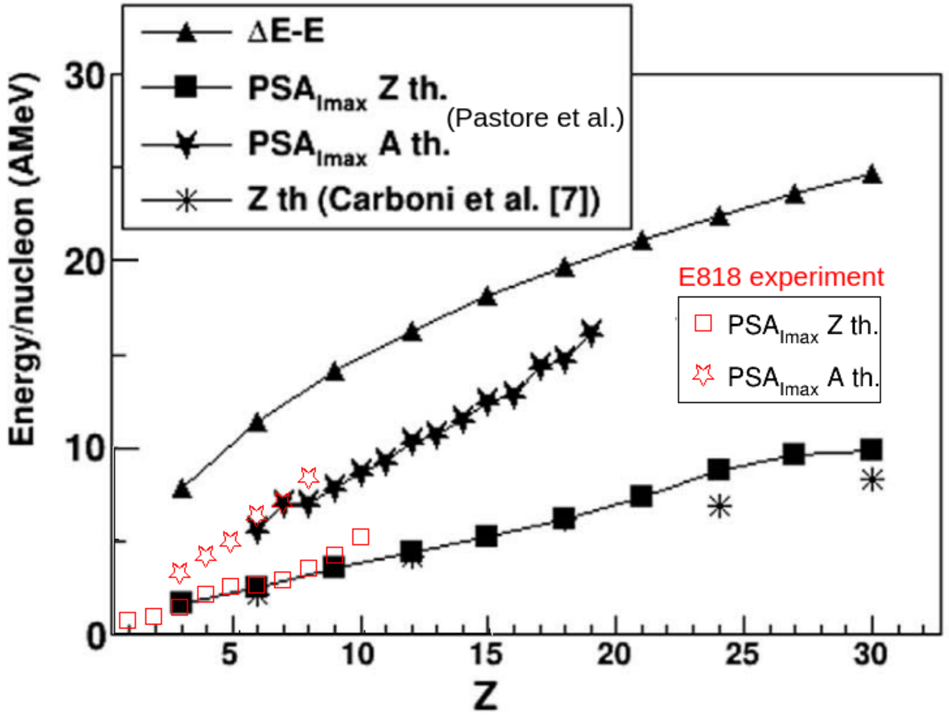
Since 2019, INDRA (rings 6-17) and FAZIA (12 blocks) have been coupled.

- The large angular coverage of INDRA (14°-176°) allows the characterization of events.
- FAZIA, covering the forward polar angles (1.4°<θ<12.6°), provides an optimal (Z,A) identification of QP-like fragments

Energy thresholds for (Z,A) identification



The aim of using Pulse Shape Analysis on the first layer is to reduce the energy thresholds for (Z,A) identification with respect to the ΔE-E technique



G. Pastore et al., NIM A 860 (42), 2017

- Energy thresholds for atomic (■) and mass (★) number identification via PSA obtained using a single detector (ISO-FAZIA experiment in 2016).
- Average energy thresholds for atomic (□) and mass (☆) number identification via PSA obtained using ~ 100 detectors (E818 experiment in 2022).

→ The average energy thresholds are comparable with those obtained for a single detector.

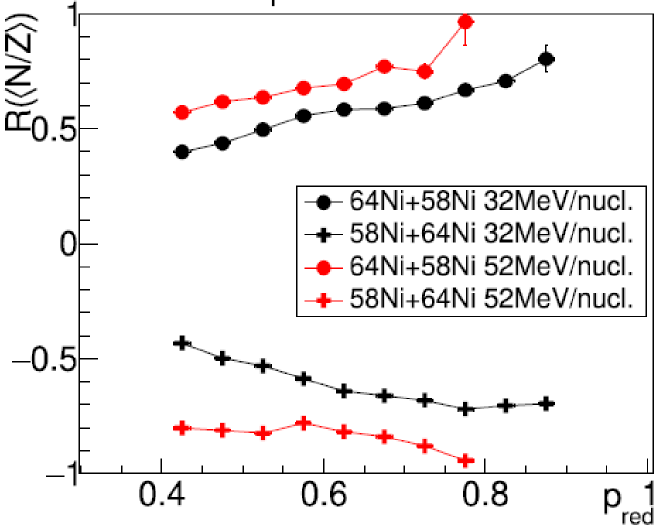
The ^{58}Ni+ ^{58}Ni reaction at 32, 52 and 74 AMeV

^{58}Ni+ ^{58}Ni at 32 and 52 AMeV

- E789 experiment (2019)
  - The four possible combinations of the two reaction partners ^{58}Ni and ^{64}Ni have been studied at two incident beam energies 32 and 52 AMeV.

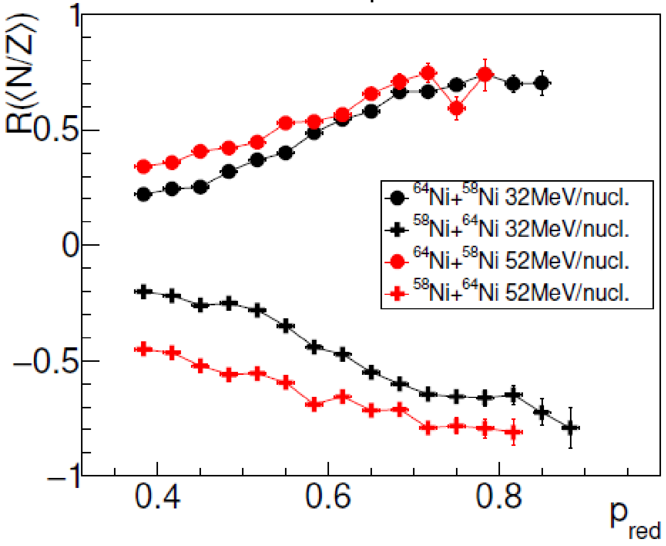
➢ The QP-QT isospin equilibration have been investigated using the isospin transport ratio (F. Rami et al., PRL 84, 1120 (2000)) finding a stronger equilibration at lower beam energy, as expected due to a longer interaction time.

QP evaporation channel



C. Ciampi et al., PRC 106, 024603 (2022)

QP breakup channel



C. Ciampi et al., arXiv:2308.15077 (2023)

The ^{58}Ni+ ^{58}Ni reaction at 32, 52 and 74 AMeV

^{58}Ni+^{58}Ni at 74 AMeV

- E818 experiment (2022)
  - Measurement of ^{36}Ar+^{58}Ni and ^{58}Ni+^{58}Ni collisions at 74 AMeV
  - Performed for a different specific physics case
  - The ^{58}Ni+^{58}Ni reaction at 74 AMeV can be also exploited for a comparison with the previous measurements at lower energies
    - Investigation of the isospin drift as a function of the beam energy, i.e. reasonably moving to shorter interaction time between projectile and target
  - Calibration and identification of the experimental data are almost complete

The AMD+GEMINI simulations

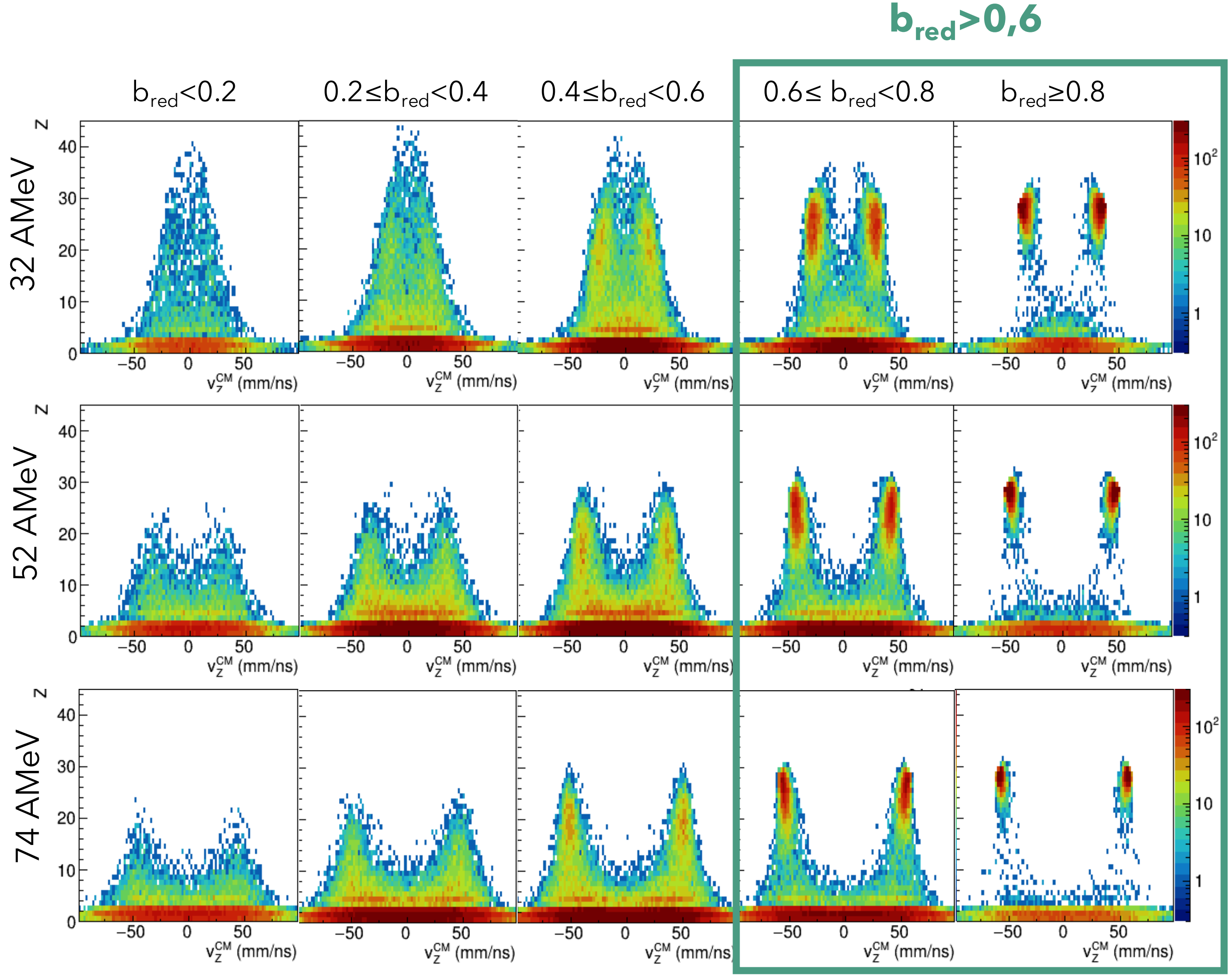
The simulation of the reactions at Fermi energies is performed in two steps:

- Dynamical Phase:
  - AMD (Antisymmetrized Molecular Dynamics):
    - $\sim$ 20000 primary events
    - asy-stiff parametrization
    - stopped at 500 fm/c
    - the impact parameter follows a triangular distribution (from 0 up to $b_{grazing}$)

- Statistical phase:
  - GEMINI:
    - de-excitation of primary fragments
    - 100 secondary events for each primary event

Characteristics of the primary fragments

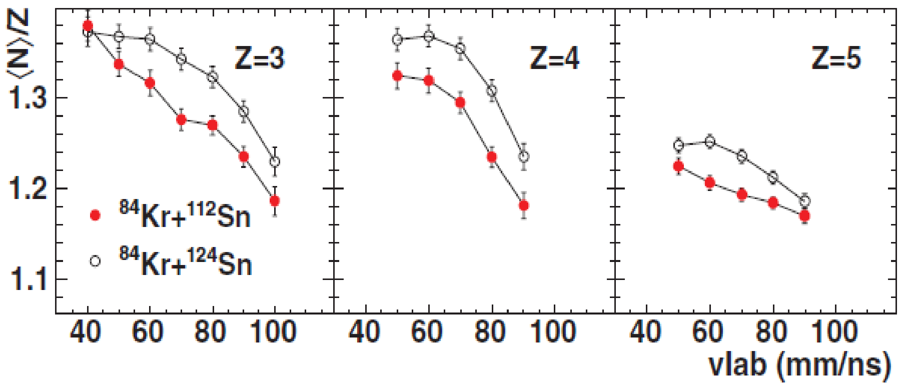
- Z vs v_z^{cm} for different centrality bins ($b_{red}=b/b_{grazing}$)
  - Peripheral collisions:
    - in all cases the exit channel is binary characterized by two big fragments, the QP and the QT, and some LCPs and IMFs
  - Central collisions:
    - at 32 AMeV some heavy fragments are produced in a sort of incomplete fusion
    - at 52 and 74 AMeV the binary character persist but there is an enhanced of lighter fragments consistent with multifragmentation and vaporization process.



Isospin drift

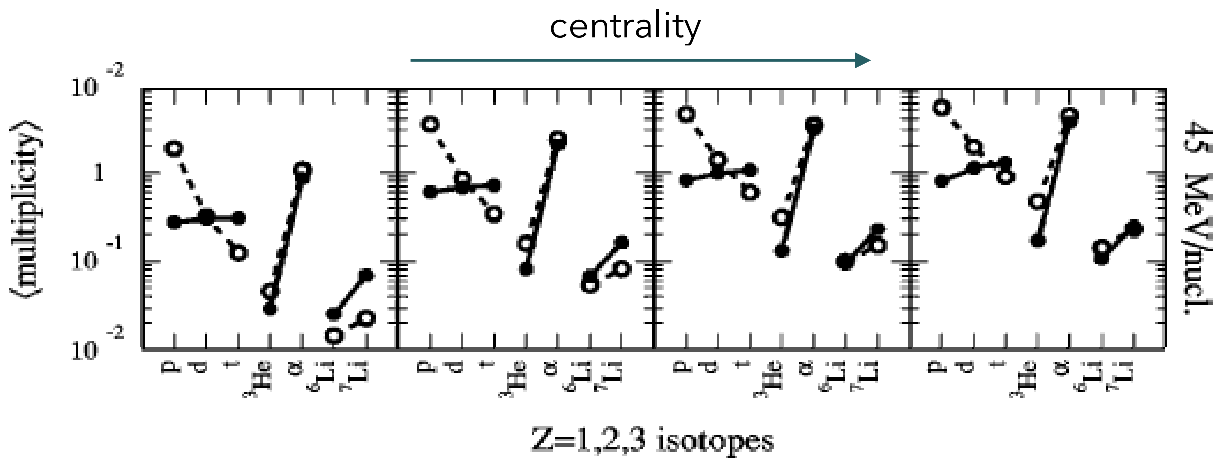
- A well-known experimental observation in peripheral and semiperipheral collisions is the neutron enrichment of the midvelocity emissions
- The isospin content of the lighter fragments is usually studied as a function of their emitted pattern

- <N>/Z vs v_{lab}



Adapted from S. Barlini et al., PRC 87, 054607 (2013)

- multiplicities for the midvelocity (●) and evaporative (○) components

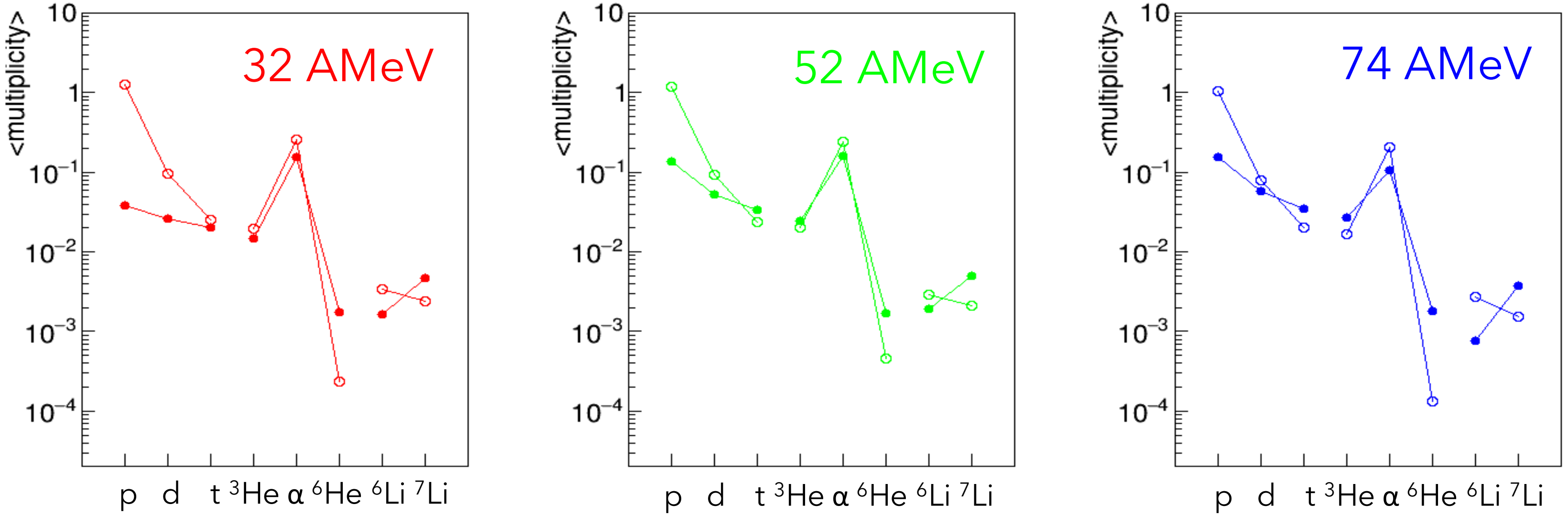


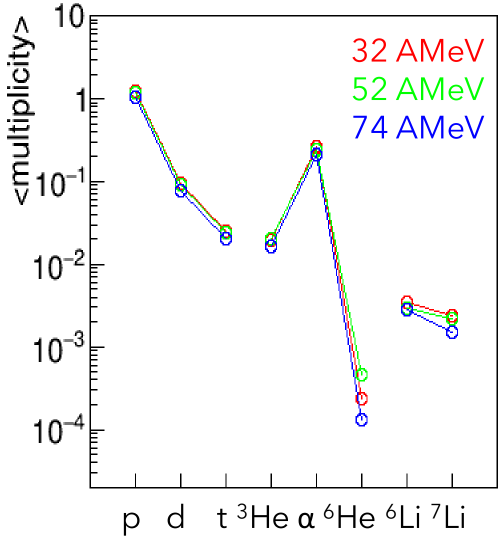
Adapted from E.Plagnol et al., PRC 61(1999) 014606

Isospin drift

Analysis of the secondary fragments in 4π: selection of the QP evaporation channel

- Average multiplicities per event of p, d, t, ^{3}He, α, ^{6}He, ^{6}Li, ^{7}Li
  - o Evaporative component
  - ● Midvelocity component



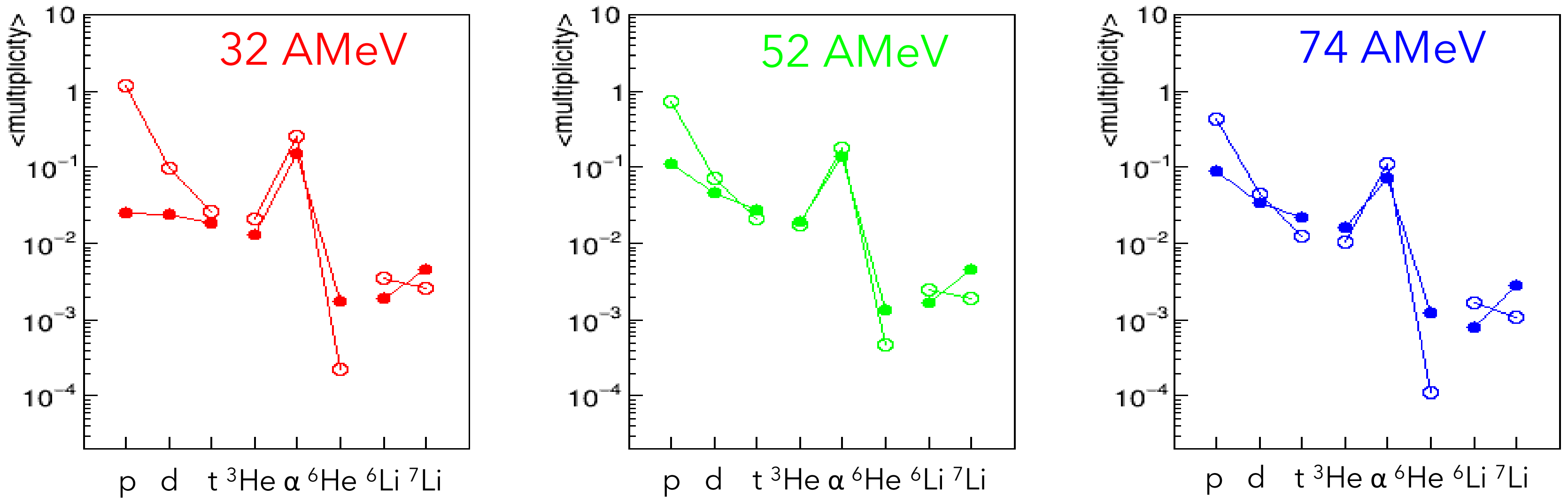


- ➢ The evaporative component is quite similar → similar QP sources in terms of excitation energy
- ➢ A neutron enrichment of the midvelocity component with respect to QP emissions is predicted.

Isospin drift

Analysis of the secondary fragments filtered: selection of the QP evaporation channel

- Average multiplicities per event of p, d, t, ^{3}He, α, ^{6}He, ^{6}Li, ^{7}Li
  - o Evaporation component
  - ● Midvelocity component



- ➢ The evaporative component is quite similar → similar QP sources in terms of excitation energy
- ➢ A neutron enrichment of the midvelocity component with respect to QP emissions is predicted.
- ➢ The neutron enrichment of the midvelocity component is still predicted in the filtered data

Conclusions and future perspectives

- Conclusions
  - The analysis of the AMD+GEMINI simulations
    - Observation of a neutron enrichment of the midvelocity component that can be interpreted as an evidence of isospin drift.

- Future perspectives
  - Investigation on the forthcoming experimental data of E818 will allow to explore the isospin transport process as a function of the beam energy and to test model predictions
    - Investigation of the isospin drift: challenge to employ various sensitive robust observable
    - Investigation of different reaction channels: the QP evaporation and the QP break up

Thank you

Backup slides

Nuclear Equation of State

Heavy ion collisions at intermediate energies allow to collect information on the Nuclear Equation of State (NEoS)

- NEoS: energy per nucleon as a function of
  - nuclear density $\rho = \rho_n + \rho_p$
  - isospin asymmetry $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$
- Expand around δ=0 → separate symmetric and asymmetric term

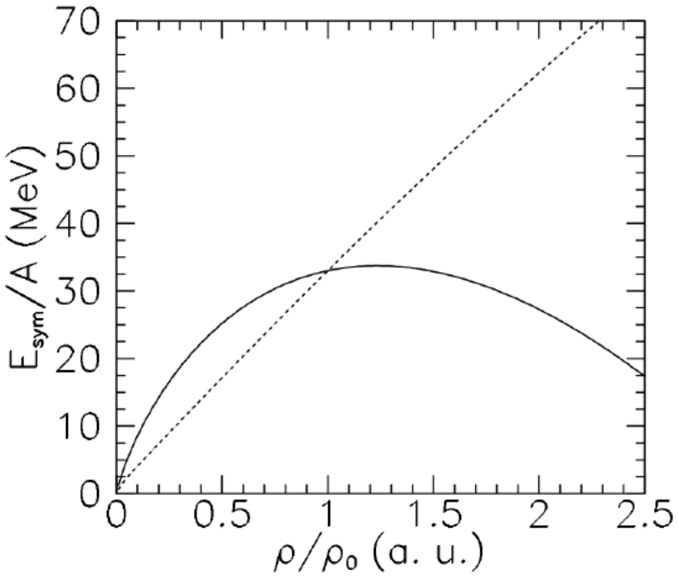
$$\frac{E}{A}(\rho, \delta) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho)\delta^2$$

  - 1° term: binding energy for symmetric nuclear matter
  - 2° term: dependence from isospin asymmetry.

Expand around $\rho \sim \rho_0$ (ρ_0 saturation density)

$$\frac{E_{sym}}{A}(\rho) = S_{sym} + L_{sym}\left(\frac{\rho - \rho_0}{3\rho}\right) + \frac{1}{2}K_{sym}\left(\frac{\rho - \rho_0}{3\rho}\right)^2 + \cdots$$

- Theoretical models → two possible parametrisations: asy-stiff and asy-soft



Isospin transport phenomena

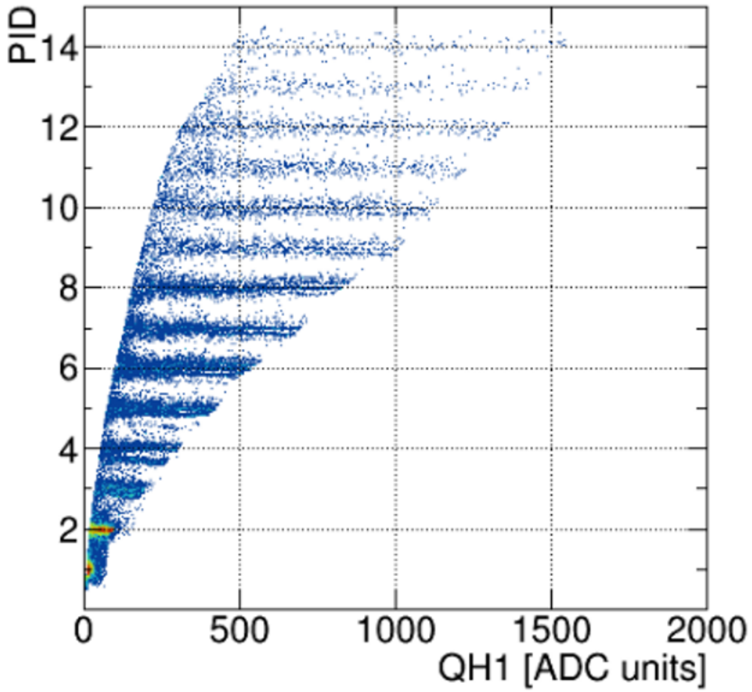
- During peripheral collisions, the symmetry energy term governs the isospin transport phenomena, i.e. the nucleon exchange between projectile and target
- It can be expressed as the difference between the neutron and proton currents between the two nuclei during the collsion:

$$j_n - j_p \propto \frac{E_{sym}}{A}(\rho)\nabla\delta + \delta \frac{\partial \frac{E_{sym}}{A}(\rho)}{\partial \rho} \nabla\rho$$

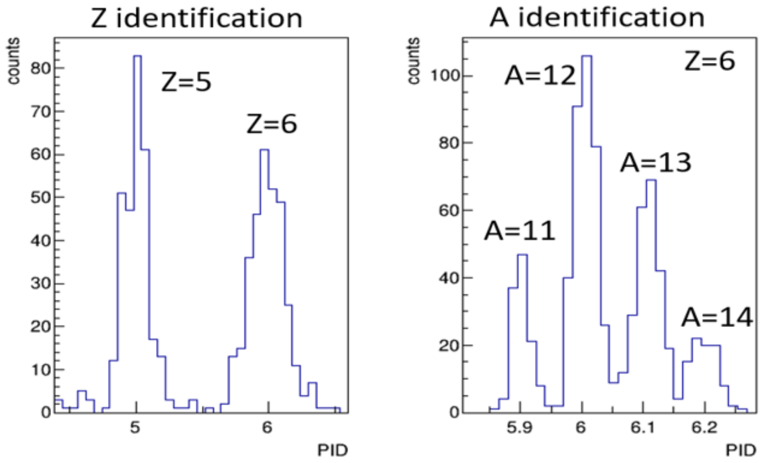
  - Isospin diffusion: driven by an isospin gradient in the system (asymmetric system), leading to isospin equilibration. Sensitive to $\frac{E_{sym}(\rho)}{A}$
    - QP-QT isospin equilibration
  - Isospin drift: driven by density gradient (neck $\rho < \rho_0$). Can be isolated choosing a symmetric system. Sensitive to $\frac{\partial E_{sym}/A(\rho)}{\partial \rho}$
    - Neutron enrichment of the neck region

Figure-of-Merit (FoM) method

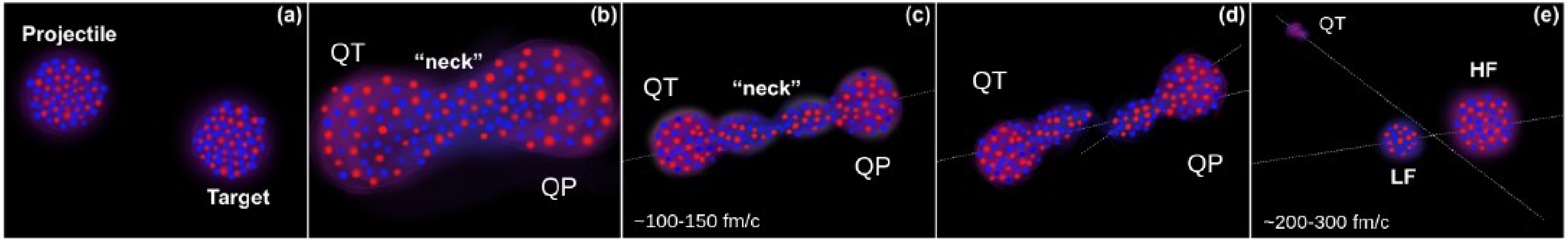
- the PID vs Energy correlation is divided into consecutive energy intervals.
- For each of them the data are projected on the PID axis by integrating the event density over the energy interval obtaining the PID distribution spectra relative to each interval.
- I evaluated the FoM for the adjacent element pairs (Z threshold) and for the adjacent most abundant isotopic pairs of a given Z (A threshold).
- The energy threshold is determined as the energy above which the two peaks have a FoM > 0,7.



$$FoM = \frac{PID_2 - PID_1}{FWHM_2 + FWHM_1}$$



Breakup of the QP



- Breakup or dynamical fission: fast, asymmetric and anisotropic fission process with a time scale of 200-300 fm/c
  - Different from statistical fission, a de-excitation process taking place in longer time scales and characterised by isotropic angular distribution
  - A possible interpretation of the phenomenon
    - QP, QT separate featuring a strong deformation and angular momentum
    - Prompt breakup
      - Formation of a Light Fragment (form the neck side) and a Heavy Fragment -> asymmetric
    - Fast process
      - LF emitted towards CM -> anisotropic
  - Isospin equilibration also between the two breakup fragments