First experiment at GANIL with the INDRA-FAZIA setup

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for the INDRA-FAZIA collaboration

Colloque en hommage au Professeur Marc Lefort
Auditorium Irène Joliot-Curie, IJCLab, Orsay
6-7 October 2022

Contents

- Introduction:
  - Nuclear Equation of State (NEoS) and isospin transport phenomena
  - Breakup of the QP (or QT)
  - The INDRA-FAZIA apparatus and its first experiment

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- Conclusions and future perspectives

Nuclear Equation of State (NEoS)

Thermodynamic description of nuclear matter

Nuclear matter: infinite number of nucleons interacting only via nuclear forces (residual interaction of strong interactions between quarks)

- Bethe-Weizsäcker formula: first thermodynamic description of nuclei, only ground state.

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  Expand around $\rho \sim \rho_0$, *saturation density*:

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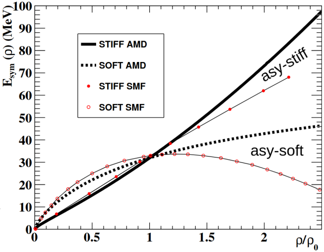


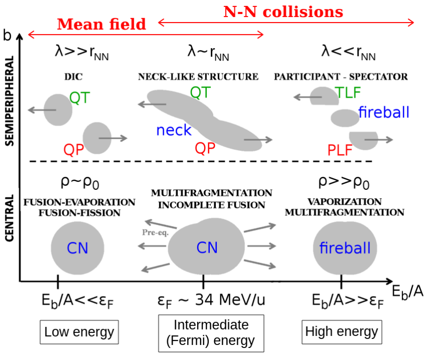
- Theoretical models $\longrightarrow$ two possible NEoS parametrisations: **asy-stiff** and **asy-soft**.

Heavy ion collisions

The Fermi energy regime

Heavy ion collisions allow to study the properties of nuclei far from equilibrium conditions

→ different outcomes depending on **energy regime** and **reaction centrality**



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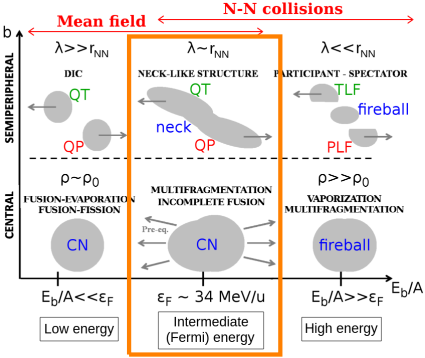
20 AMeV< E_b < 100 AMeV



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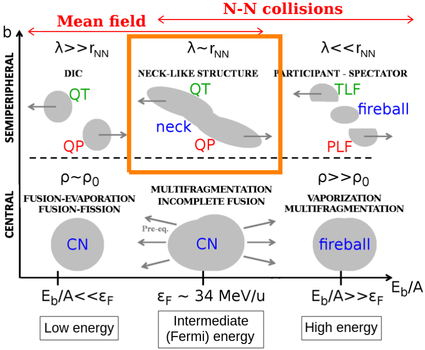

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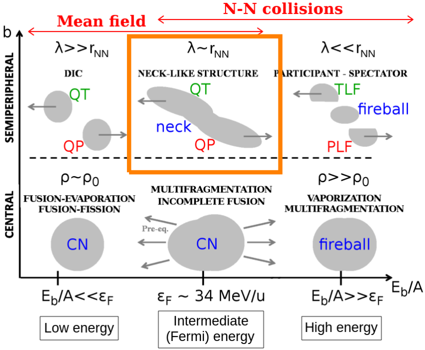

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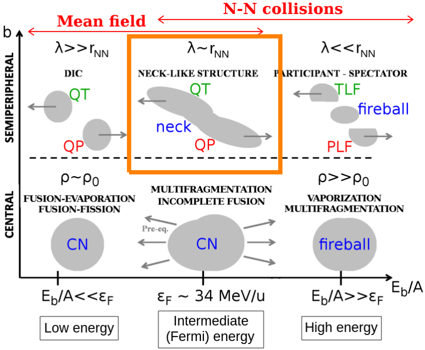

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  - Separation phase (late stage of contact phase): elongated low density *neck region* connects QP and QT ⇒ *midvelocity emission*

Isospin transport phenomena

Nuclear symmetry energy at work in heavy ion reactions

- During peripheral and semiperipheral collisions, the symmetry energy term governs the **isospin transport phenomena**, i.e. 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 collision:

$$\mathbf{j}_n - \mathbf{j}_p \propto \frac{E_{sym}}{A}(\rho)\boldsymbol{\nabla}\delta + \delta\frac{\partial\frac{E_{sym}}{A}(\rho)}{\partial\rho}\boldsymbol{\nabla}\rho$$

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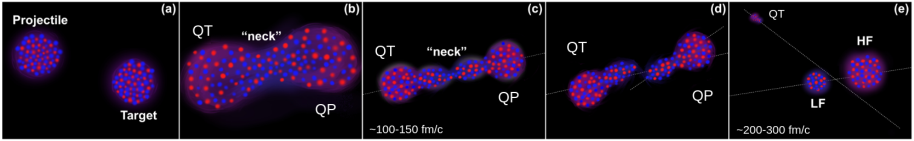
Breakup of the QP

Characteristics of the breakup channel



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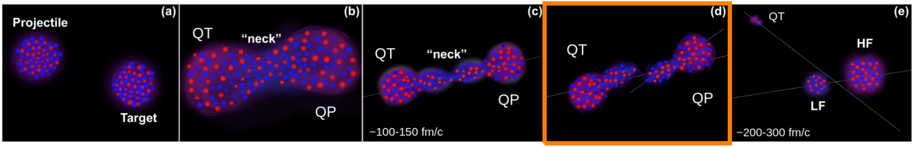

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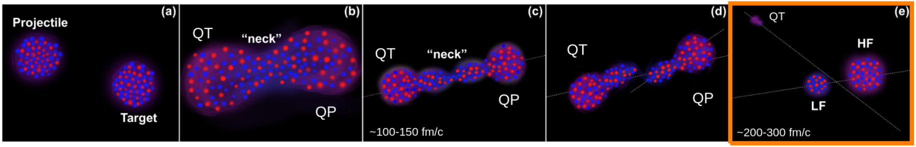

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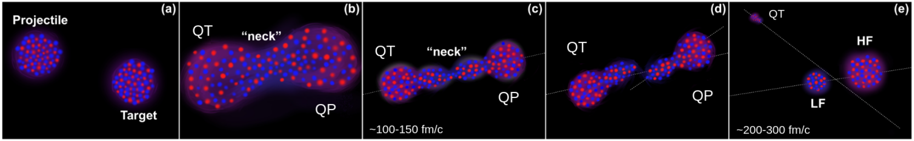

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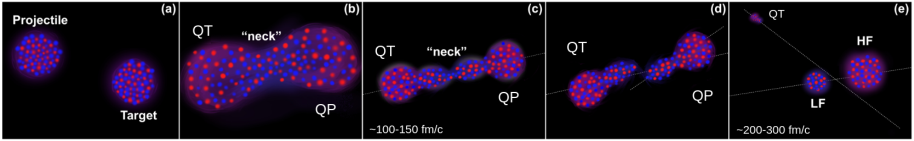

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- Isospin equilibration also between the two breakup fragments

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The INDRA-FAZIA apparatus aims to overcome the most common limitations and to collect the most comprehensive information on the event.

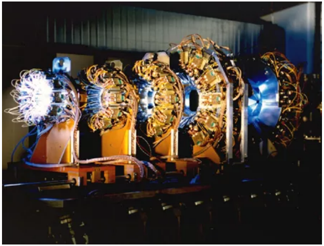
INDRA and FAZIA are both multi-detector apparatuses, designed for the detection of charged fragments produced in heavy ion collisions at Fermi energies.

Experimental setup

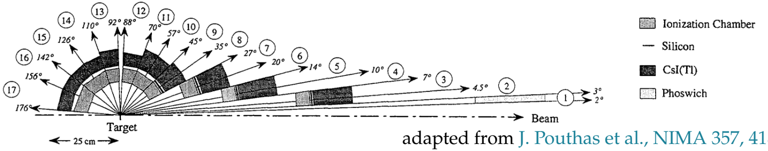
INDRA

INDRA *(Identification de Noyaux et Détection avec Résolutions Accrues)*: highly segmented array for detection and identification of charged products of heavy ion collisions at intermediate energies ($10 < E < 100\,A$MeV).

- Original configuration of 17 rings:
  - 1: Si + CsI(Tl)
  - 2-9: Ionisation ch. + Si + CsI(Tl)
  - 10-17: Ionisation ch. + CsI(Tl)
- Charge discrimination up to uranium, mass discrimination up to $Z = 4 - 5$, with low thresholds
- Large solid angle coverage (90%)



- High granularity (336 modules) → large particle multiplicity ($M_{tot}^{max} \sim 50$)



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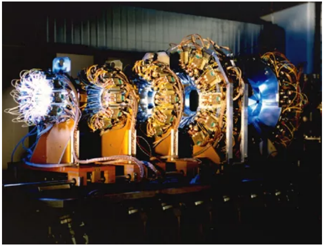

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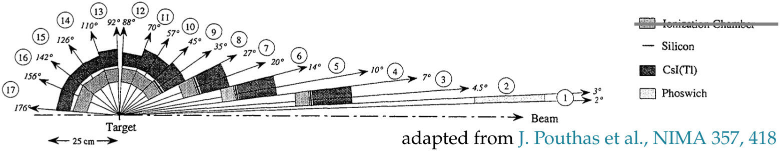

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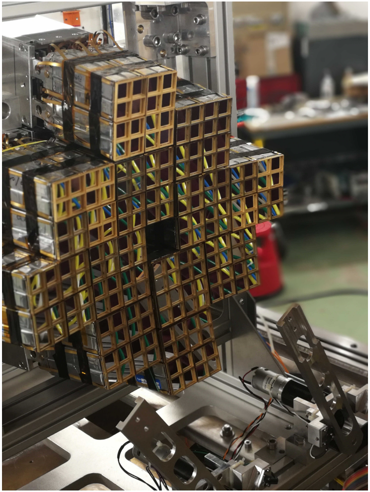

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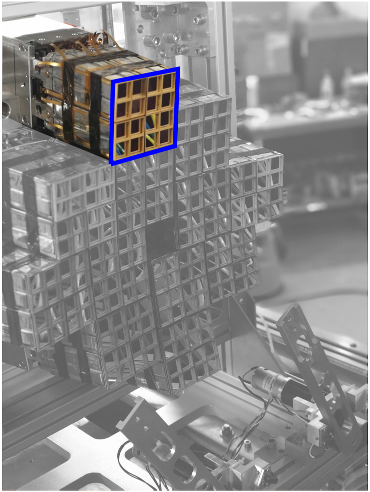
  - digital treatment of signals



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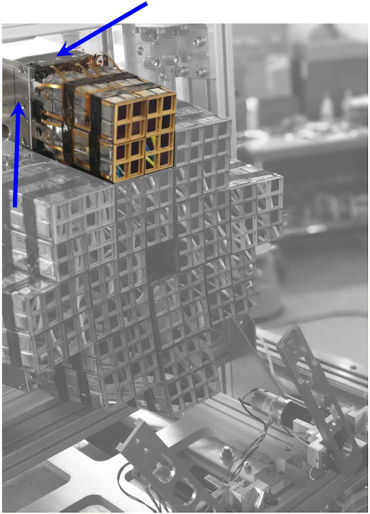

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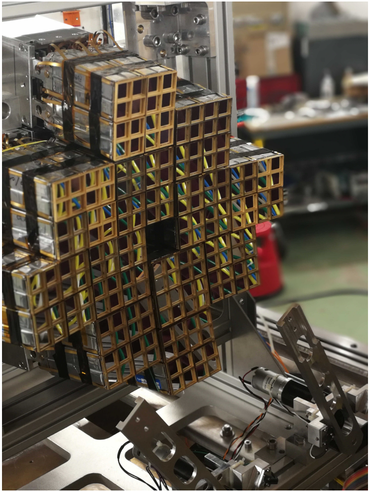

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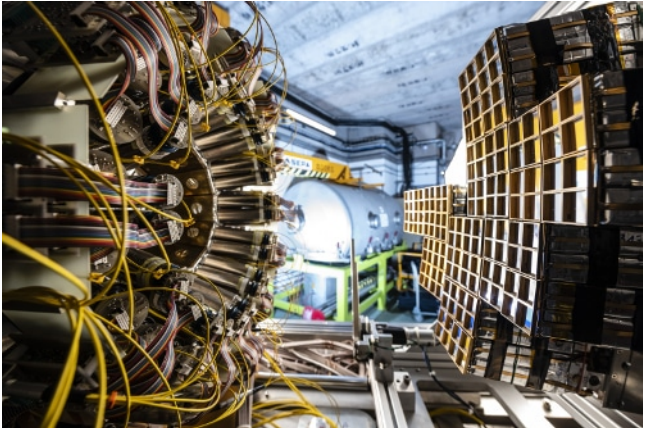
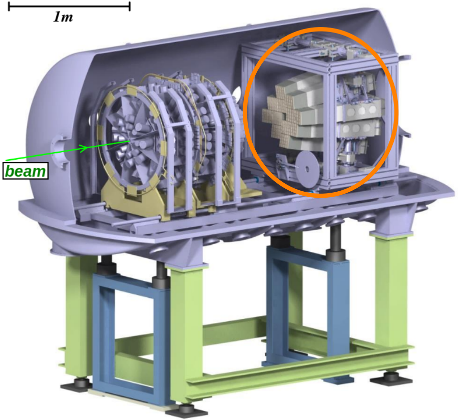
- Identification techniques: ΔE-E / PSA
  - Charge discrimination tested up to $Z \sim 55$
  - Mass discrimination up to $Z \sim 25$ / $Z \sim 22$

Experimental setup

The INDRA-FAZIA coupling



During the first months of 2019 the coupling between INDRA and FAZIA was completed in GANIL (Caen, FR).
The E789 experiment is the first experimental campaign exploiting this setup.



- The most forward polar angles (1.4°< θ < 12.6°) have been covered with 12 FAZIA blocks in a wall configuration at 1 m from the target. The first five rings of INDRA have been removed.
  → *isotopic identification of QP-like fragments*

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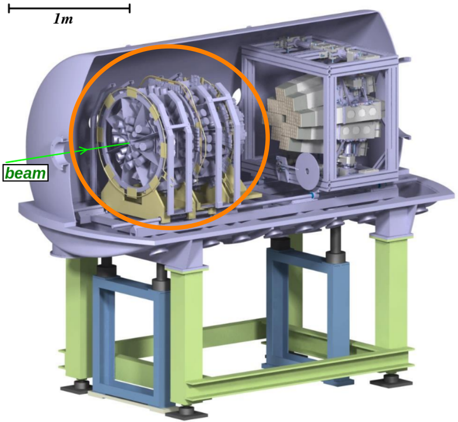
The INDRA-FAZIA coupling



- The most forward polar angles (1.4°<θ< 12.6°) have been covered with 12 FAZIA blocks in a wall configuration at 1 m from the target. The first five rings of INDRA have been removed.
  $\longrightarrow$ *isotopic identification of QP-like fragments*
- The remaining part of INDRA (rings 6-17) covers the polar angles between 14° and 176° (~ 80% of the 4π solid angle).
  $\longrightarrow$ *global variables for the estimation of the reaction centrality*

The E789 experiment

New insights on the symmetry energy term of the Nuclear Equation of State

The E789 experiment (april-may 2019) is the first campaign to exploit the coupled INDRA-FAZIA apparatus:

- All of the four possible combinations of the two reaction partners ^{58}Ni and ^{64}Ni have been studied
  ⇒ compare the products of the two asymmetric reactions with those of both the neutron rich and neutron deficient symmetric systems
- Two different incident beam energies 32 AMeV and 52 AMeV
  ⇒ different timescale of the interaction process and different inspected nuclear density range

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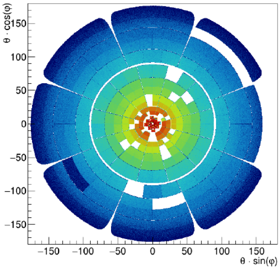
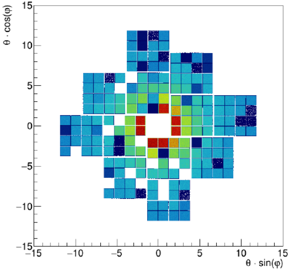




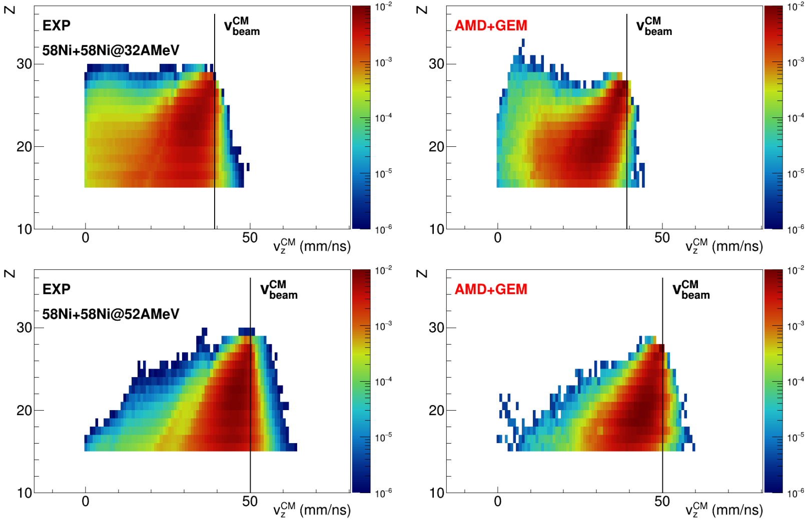
$\rightarrow$ Comparison of experimental results with AMD+GEMINI++ simulations, filtered according to the actual apparatus acceptance (mandatory to obtain information on physics processes)

QP evaporation channel (QPr)

QP evaporation channel

QPr channel selection

QP remnant: $\mathbf{M_{big} = 1}$, with $Z_{big} \geq 15$ and $\theta^{CM}_{big} < 90°$ ($v^{CM}_z > 0$)



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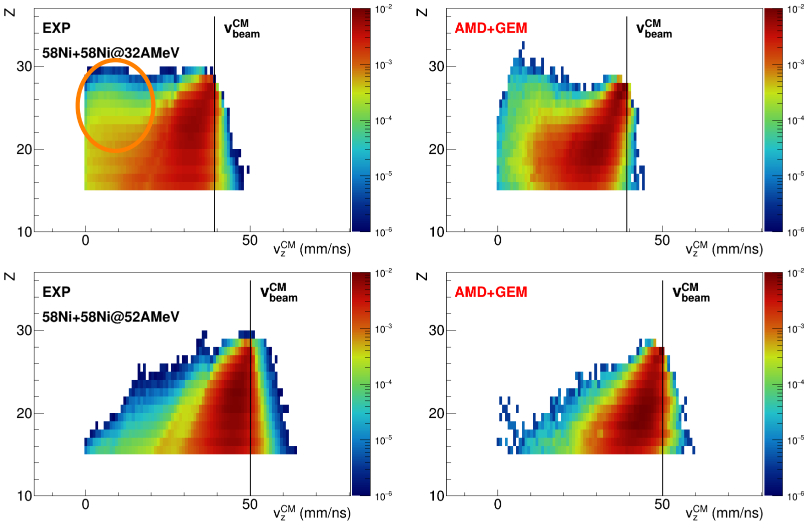

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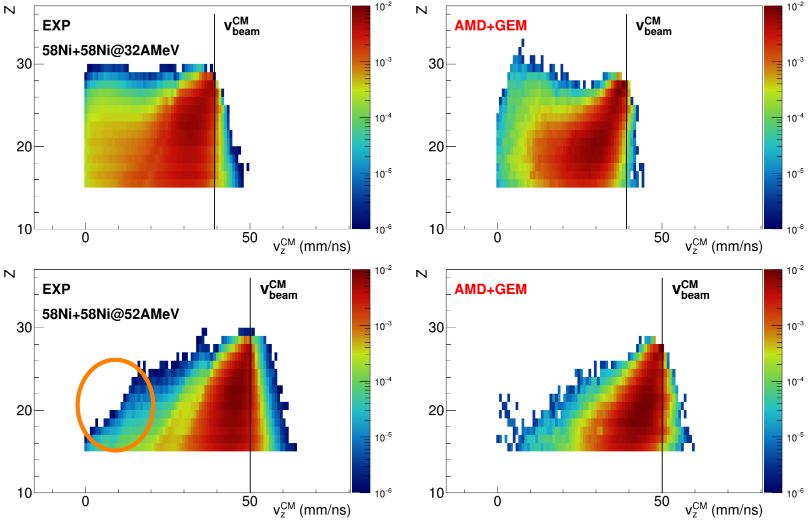
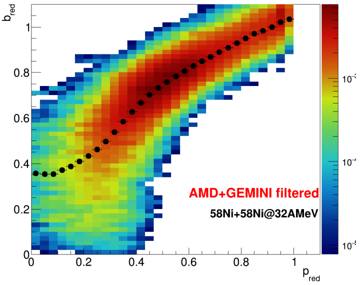


Reaction centrality estimation

Reduced QP momentum along the beam axis p_{red}

As reaction centrality estimator we select the **reduced momentum along the z-axis:**

$$p_{red} = \frac{p_z^{QP}}{p_{beam}}$$



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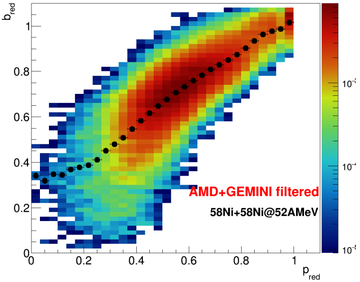

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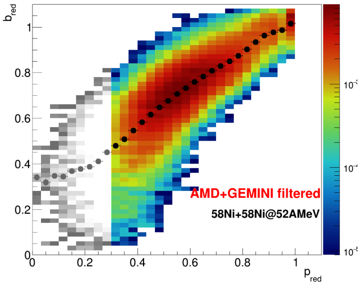

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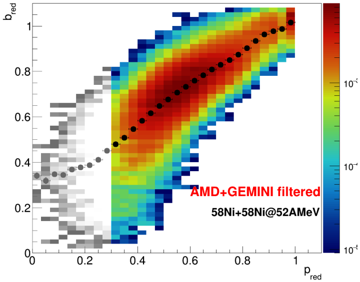

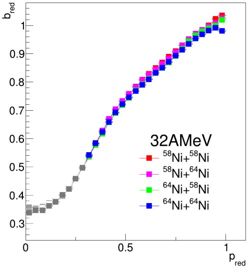

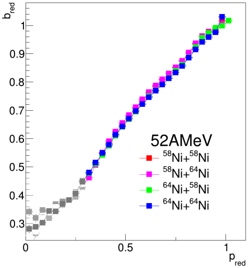

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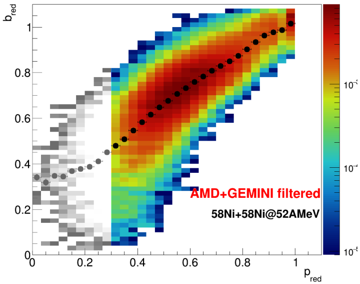
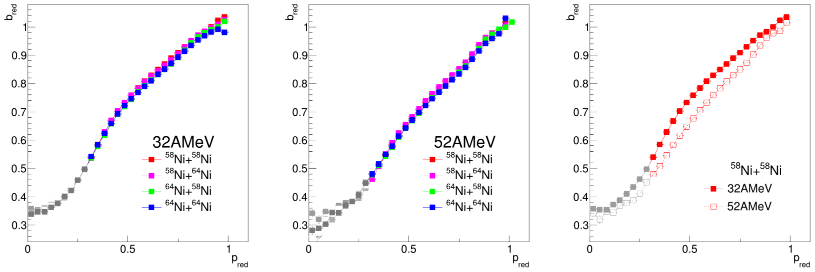
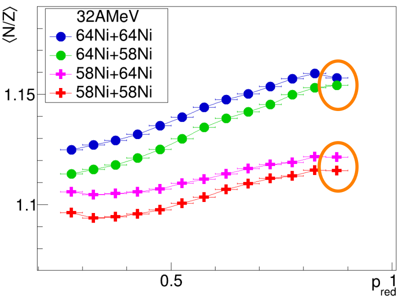
- the same for reactions at same energy
- similar for same system at two energies

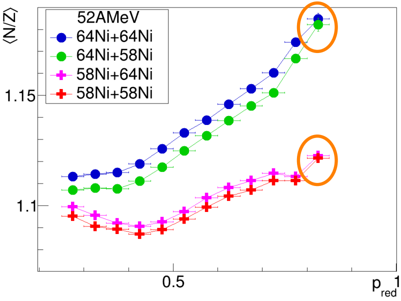




QP evaporation channel

Isospin diffusion: $\langle N/Z \rangle$ of the QP remnant





QP-QT equilibration in mixed systems:

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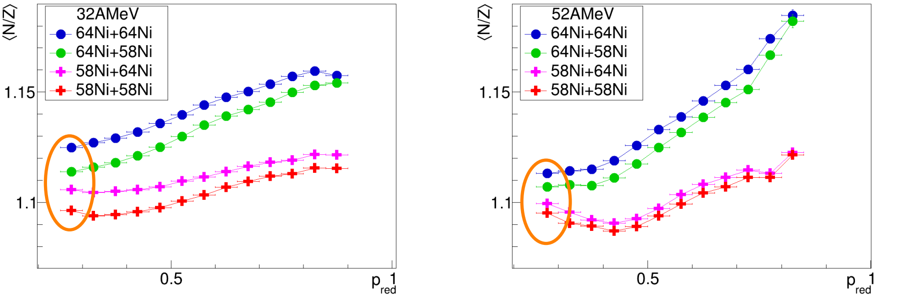

QP-QT equilibration in mixed systems:

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- more central: $\langle N/Z \rangle$ depends on target

$\rightarrow$ **evidence of isospin diffusion**, more clear at 32 AMeV

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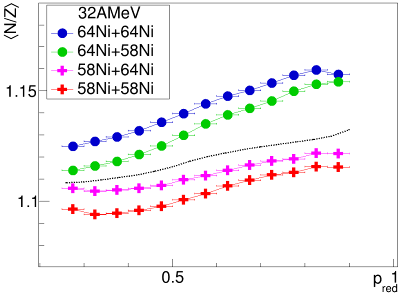

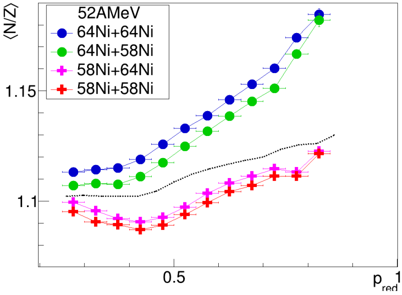

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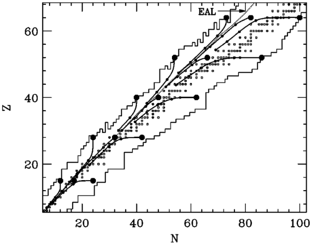
Decreasing behaviour with centrality

$\rightarrow$ **Evaporation Attractor Line (EAL)**

$$A = 2.072\,Z + 2.32 \times 10^{-3} Z^2$$



R. J. Charity, PRC58, 1073 (1998)

QP evaporation channel

Isospin diffusion: Isospin transport ratio

Isospin transport ratio technique → highlight isospin diffusion effect.
Given $A = ^{64}$Ni, $B = ^{58}$Ni:

$$R(X) = \frac{2X_i - X_{AA} - X_{BB}}{X_{AA} - X_{BB}}$$

where $i = AA, AB, BA, BB$ and X is an isospin sensitive observable (e.g. $\langle N/Z \rangle_{QPr}$).
→ bypass effects acting similarly on the four systems (apparatus acceptance or physical processes e.g. statistical decay)

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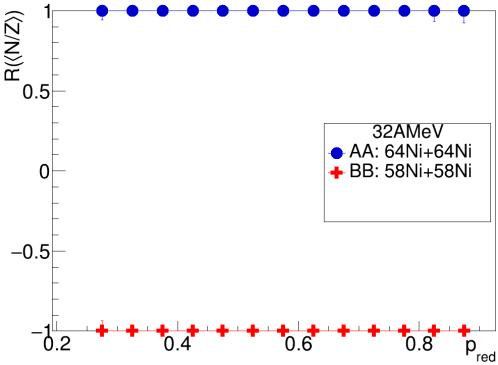

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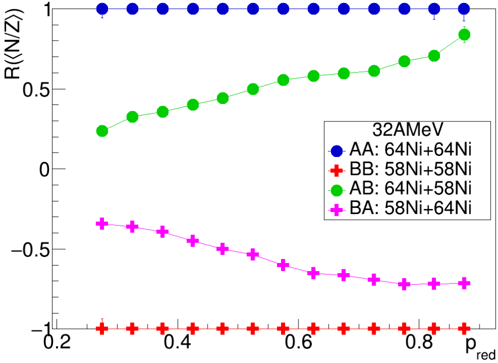

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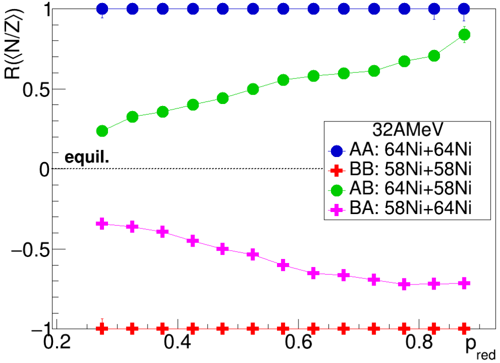
- Complete equilibration is not reached → central collisions not considered



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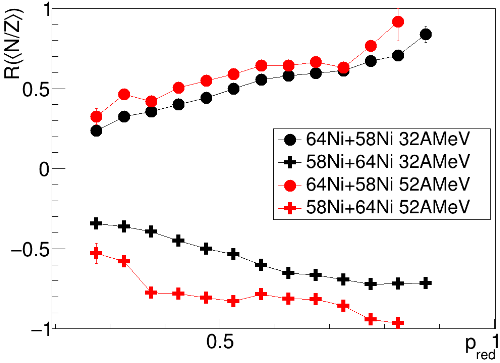
C.Ciampi et al., PRC 106, 024603 (2022)



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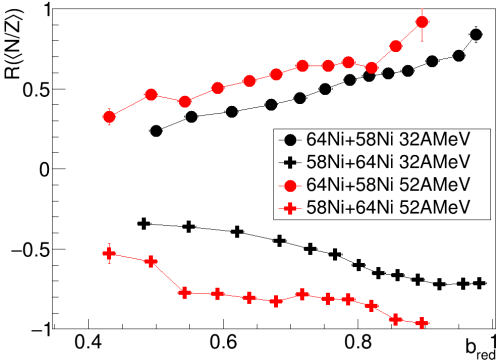

QP breakup channel (QPb)

QP breakup channel

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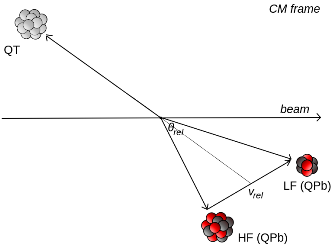
QP breakup: events with $\mathbf{M_{big} = 2}$.
Both fragments must come from QP.



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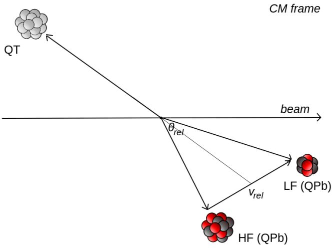
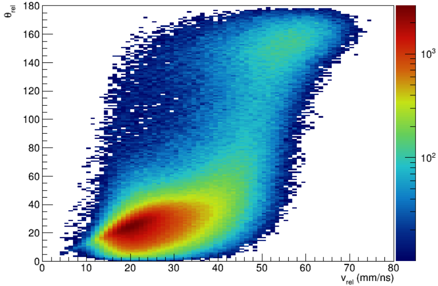
Correlation θ_{rel} vs v_{rel} of the two fragments $Z \geq 5$:





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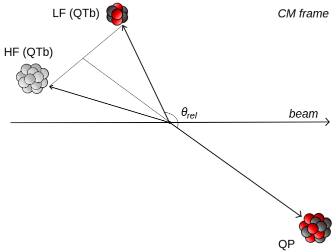

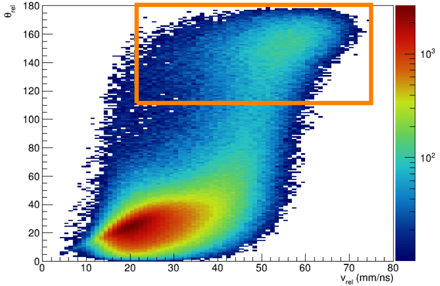

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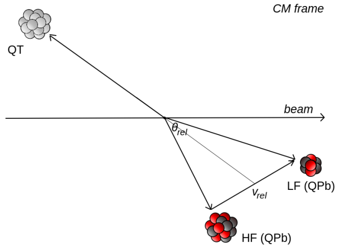

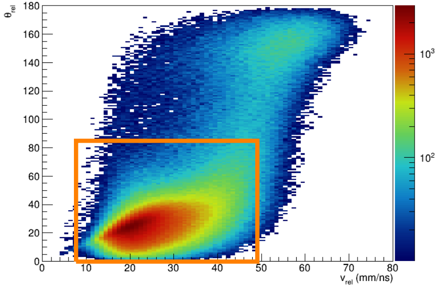

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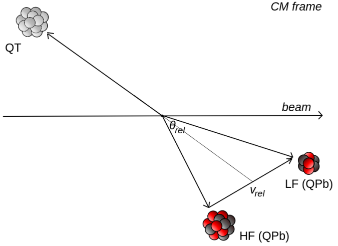
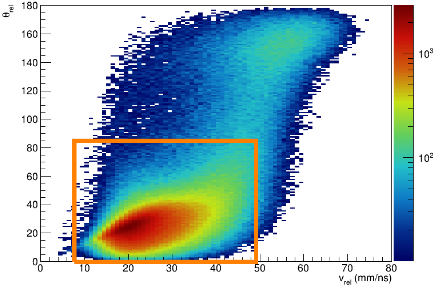
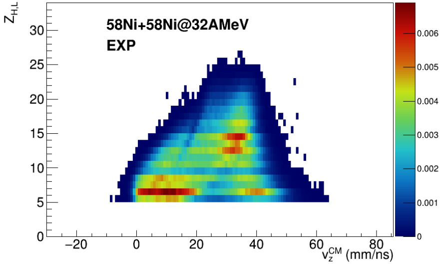
Conditions also on the v_{rel} depending on the reaction energy, and on $Z_H + Z_L \geq 15$.

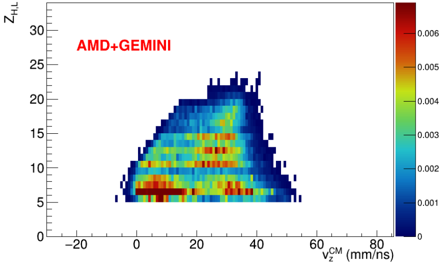




QP breakup channel

Selected events





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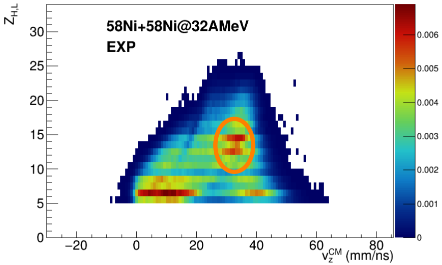

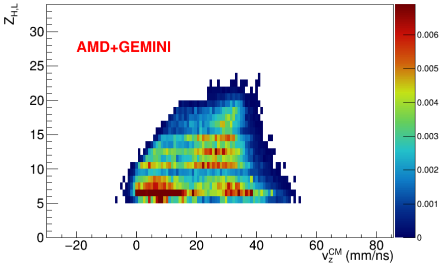

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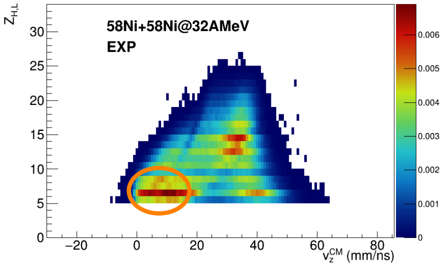

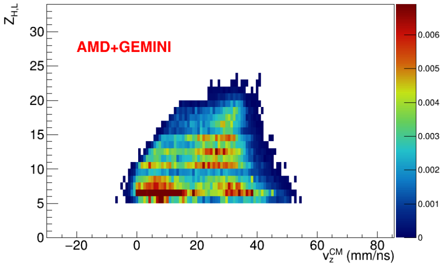

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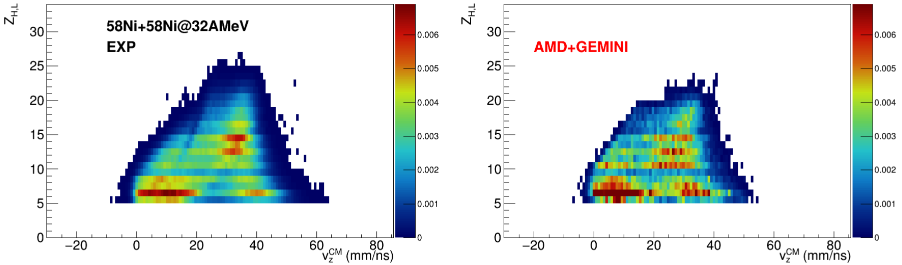
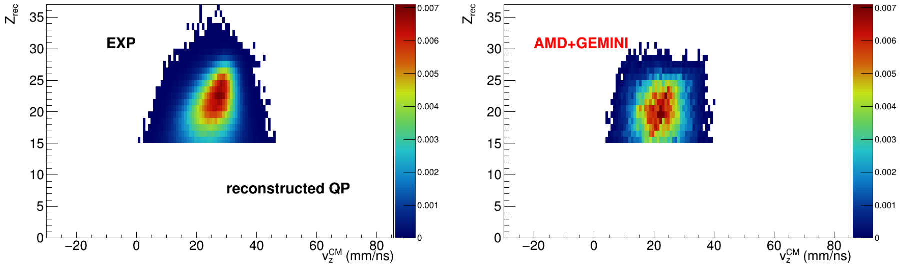


We reconstruct the QP from HF and LF: $Z_{rec} = Z_H + Z_L$ and v_{rec} of their CM.



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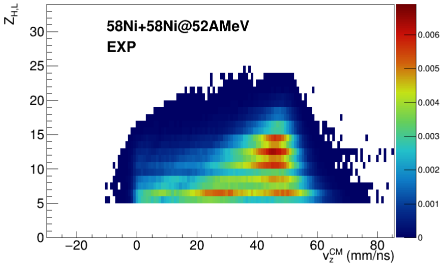
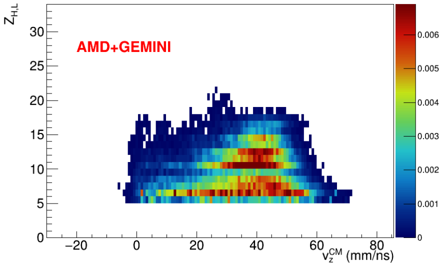
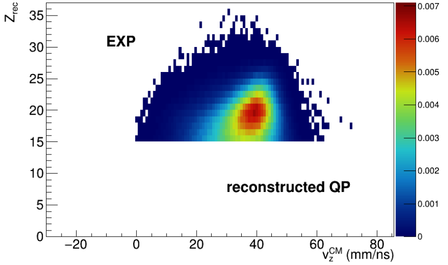
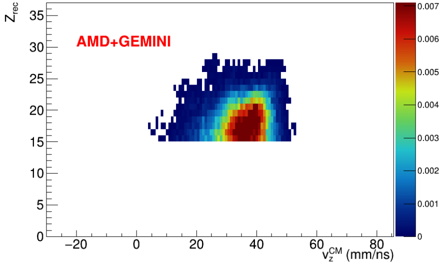


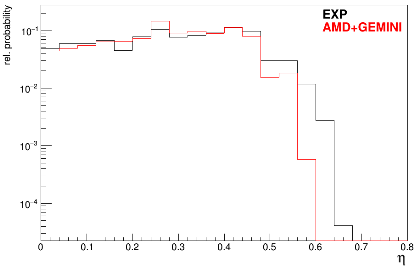






Charge asymmetry between H and L:

$$\eta = \frac{Z_H - Z_L}{Z_{rec}}$$



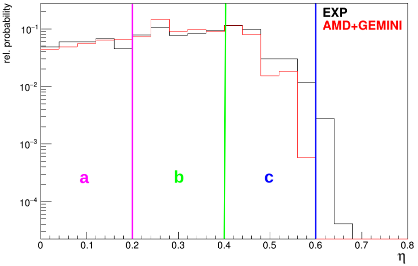
QP breakup channel

Characteristics of the breakup fragments

Charge asymmetry between H and L:

$$\eta = \frac{Z_H - Z_L}{Z_{rec}}$$

- three η intervals:
  - (a) $\eta \leq 0.2 \rightarrow$ symmetric
  - (b) $0.2 < \eta \leq 0.4$
  - (c) $0.4 < \eta \leq 0.6 \rightarrow$ asymmetric



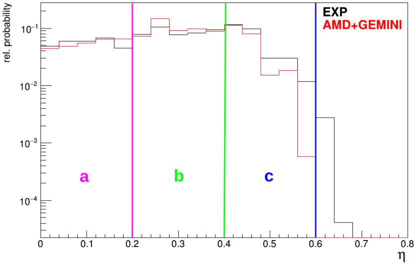
QP breakup channel

Characteristics of the breakup fragments

Charge asymmetry between H and L:

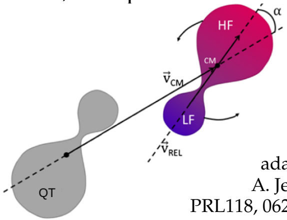
$$\eta = \frac{Z_H - Z_L}{Z_{rec}}$$

- three η intervals:
  - (a) $\eta \leq 0.2 \longrightarrow$ symmetric
  - (b) $0.2 < \eta \leq 0.4$
  - (c) $0.4 < \eta \leq 0.6 \longrightarrow$ asymmetric

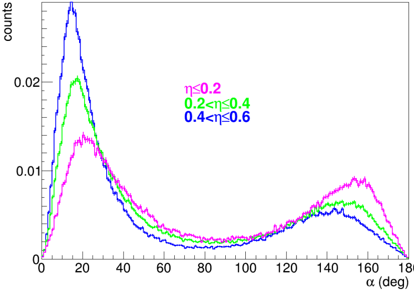


α angle between the QP-QT separation axis ($\vec{v}_{QP_{rec}}$) and the breakup axis ($\vec{v}_{rel}$):

- in the asymmetric configuration the backward emission of the LF is favoured, as expected

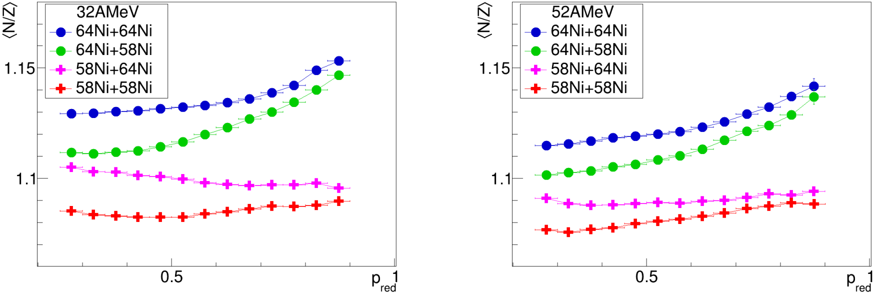


adapted from A. Jedele et al., PRL118, 062501 (2017)



QP breakup channel

Isospin diffusion: $\langle N/Z \rangle$ of the reconstructed QP



The isospin equilibration is clearly visible also from the characteristics of the QP reconstructed from the two breakup fragments in the QPb channel.
→ **evidence of isospin diffusion**

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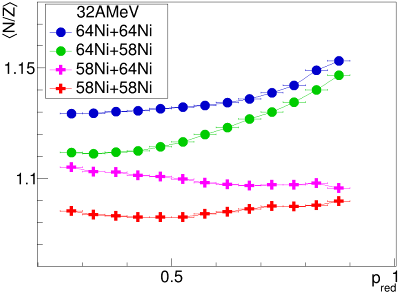

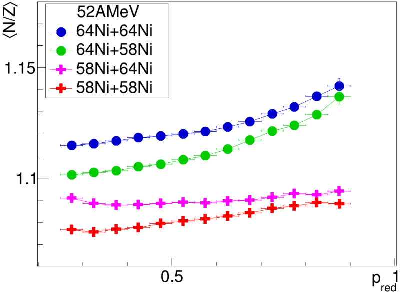

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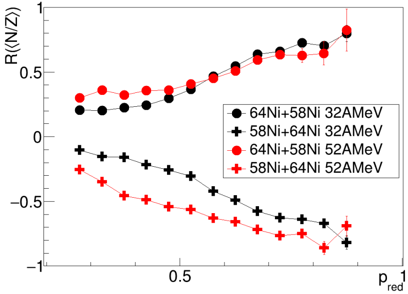
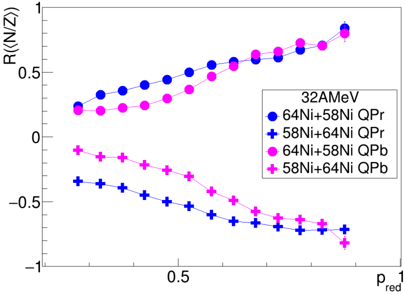
→ **evidence of isospin diffusion**

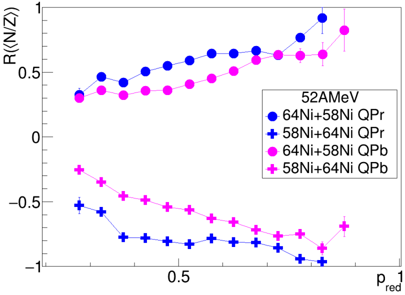
The **isospin transport ratio** can be built also in this case.



Isospin diffusion

Comparison between the QPr and QPb channels





Compare the isospin equilibration in the two reaction channels:

- At both energies, for the same p_{red} value ($\Rightarrow$ same reaction centrality) a higher degree of isospin equilibration is obtained in the QPb channel than in the QPr channel.

Isospin diffusion

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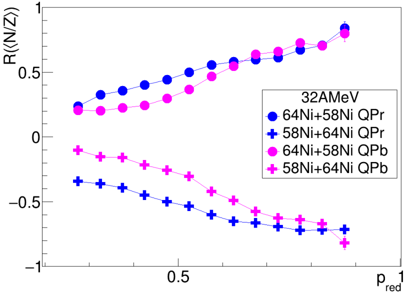

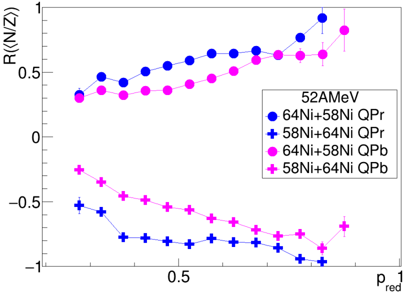

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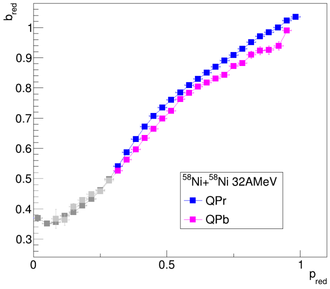

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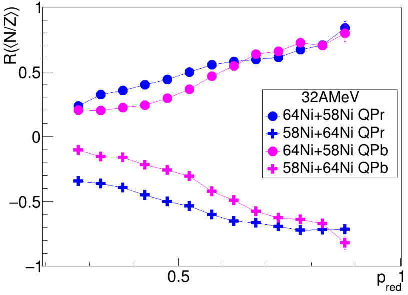

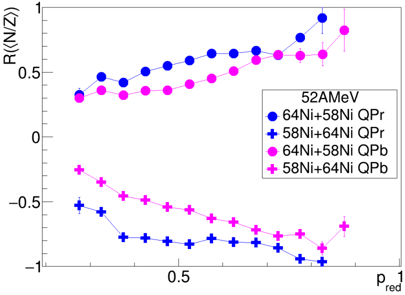

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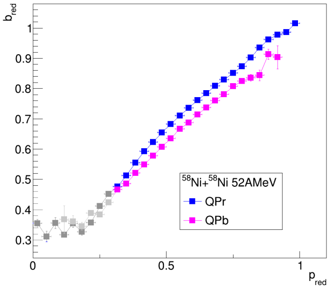

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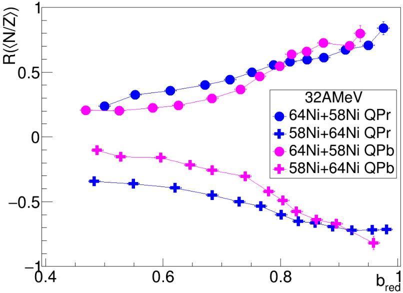

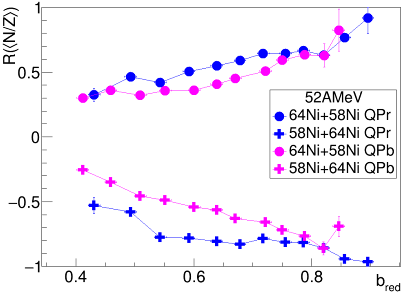

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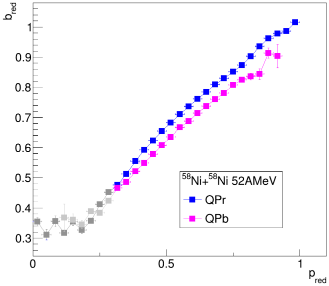

Summary and future perspectives

Summary:

- INDRA-FAZIA E789: ^{64,58}Ni+^{64,58}Ni at 32 AMeV and 52 AMeV
- Selection of QP evaporation (QPr) and QP breakup (QPb) channels
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  - Dynamical code: AMD
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- Further investigations on the isospin transport ratio:
  - studied as a function of other centrality related observables
  - calculated exploiting other isospin related observables

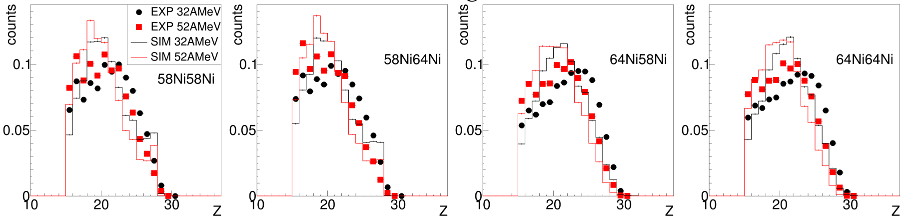
Thank you

Backup slides

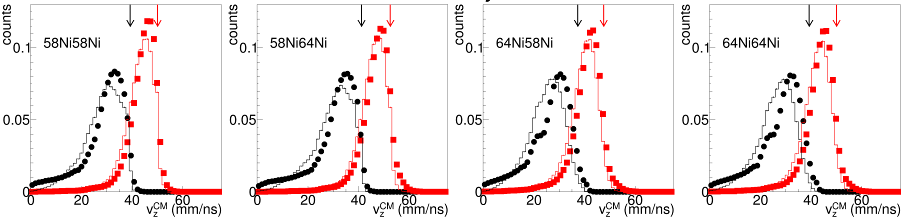
QP evaporation channel

Characteristics of the QP remnant

QP remnant charge distribution



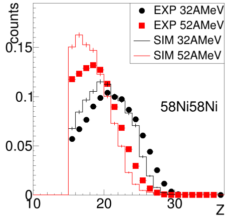
QP remnant velocity distribution



QP breakup channel

Characteristics of the reconstructed QP

Reconstructed QP charge distribution



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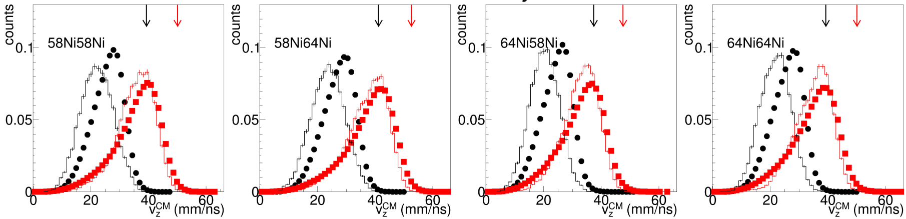
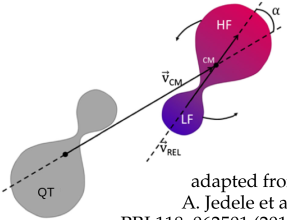


Breakup of the QP

What are we looking for?



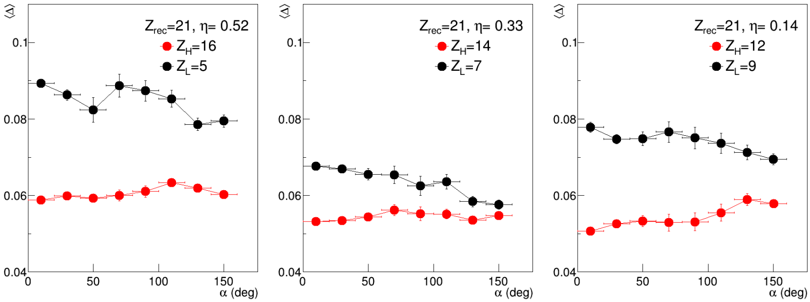
adapted from
A. Jedele et al.,
PRL118, 062501 (2017)

- For a longer time interval elapsed between the QP-QT split and the QP breakup:
  - the α angle between the separation axis $\hat{v}_{CM}$ and the breakup axis $\hat{v}_{rel}$ increases: if the breakup timescale is short compared to the QP rotation period, α can be adopted as a "clock"
  - the degree of isospin equilibration inside the original QP increases $\rightarrow$ neutron content of the breakup fragments HF and LF

- Within this interpretation of the phenomenon:
  - small α angle $\rightarrow$ limited isospin equilibration HF-LF (LF similar to neck)
  - large α angle $\rightarrow$ higher degree of isospin equilibration between HF e LF
- *Equilibration chronometry*: study of isospin observables for HF and LF as a function of α $\rightarrow$ timescale of isospin equilibration ($\sim$ zs)
- In a recent study, no correlation between the α angle and $(t_{breakup} - t_{DIC})$ has been found in the framework of the dynamical model AMD

Characteristics of the breakup fragments

Isospin equilibration between HF and LF



$\langle \Delta \rangle = \langle \frac{N-Z}{A} \rangle$ of the two breakup fragments as a function of the α angle:

- Data trends compatible with the picture proposed in literature:
  - LF more neutron rich than the HF.
  - larger HF-LF asymmetry for low α angles, more equilibrated for increasing α

Characteristics of the breakup fragments

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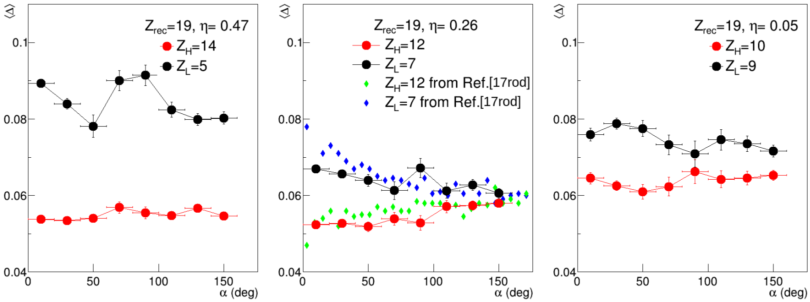

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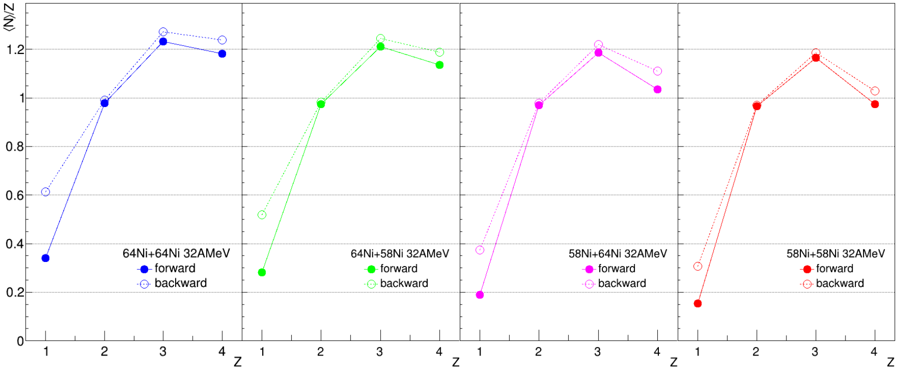
  - larger HF-LF asymmetry for low α angles, more equilibrated for increasing α
- Within the small charge asymmetries explored, $\langle\Delta\rangle_L$ depends mostly on the identity of the LF, and less on the partner HF
- Results for $Z_H = 12, Z_L = 7$ are quite comparable to A. Rodriguez Manso et al., PRC95, 044604 (2017)

Isospin drift

QPr channel: LCPs and IMFs



- We analyse the isospin content of LCPs and IMFs according to their emission pattern, i.e. their orientation with respect to the QP remnant:
  - forward: forward QPr emission of LCPs and IMFs
  - backward: backward QPr emission of LCPs and IMFs, with $v_z^{CM} > 0$
- **Isospin drift** → $\langle N \rangle$ for the backward emissions is higher than the forward one. Clean interpretation for symmetric systems.

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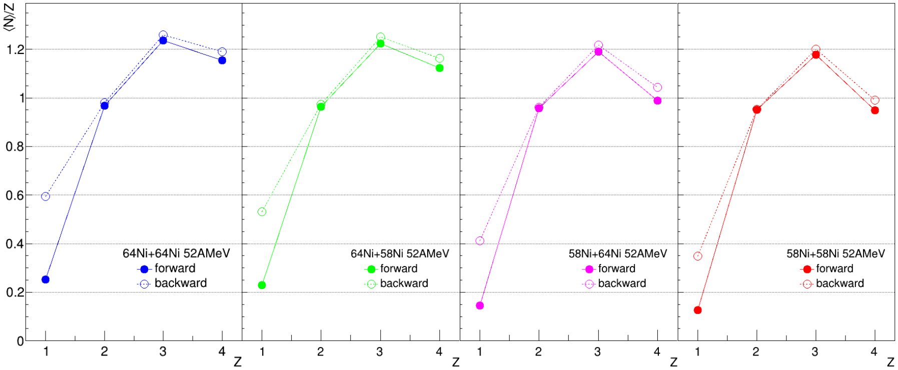

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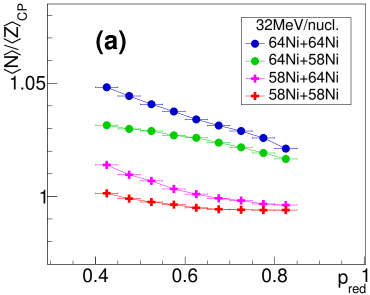
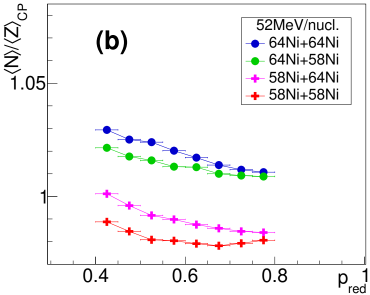
Isospin diffusion

QPr channel: characteristics of the evaporated particles (I)





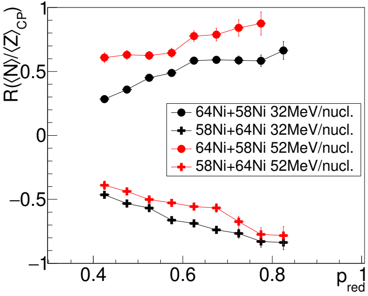
The QP-QT isospin equilibration can be evidenced also on the characteristics of the QP deexcitation emissions.

→ e.g., isospin ratio for complex particles forward emitted with respect to the QP remnant.

$$\langle N \rangle / \langle Z \rangle_{CP} = \sum_i \sum_\nu N_\nu^i / \sum_i \sum_\nu Z_\nu^i$$

considering LCPs and IMFs with $A > 1$.

see E. Galichet et al., PRC 79, 064614 (2009)



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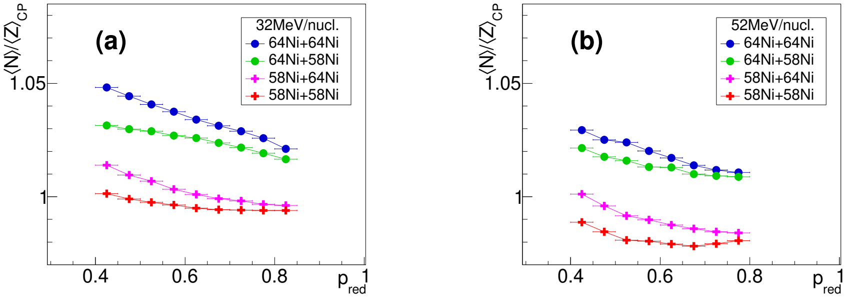

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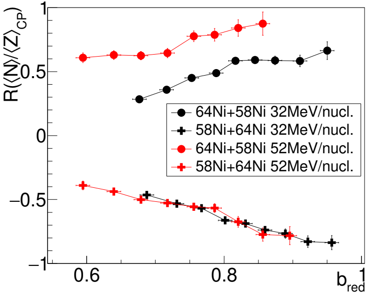

Isospin diffusion

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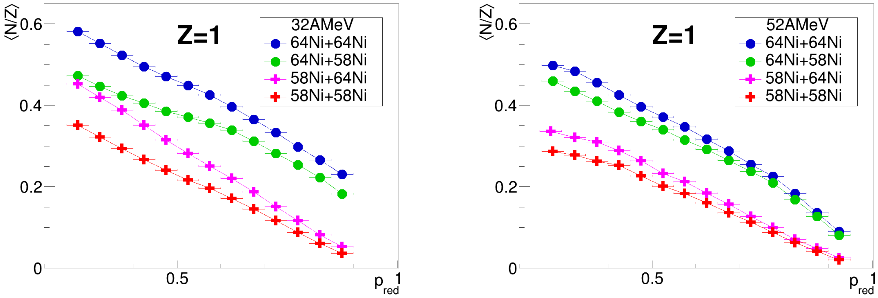

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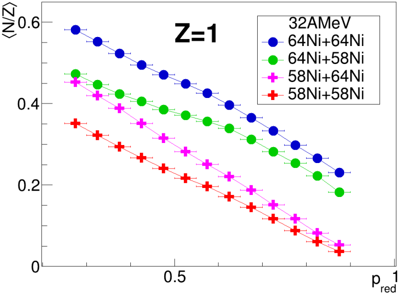

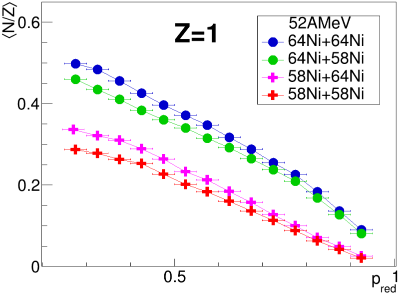

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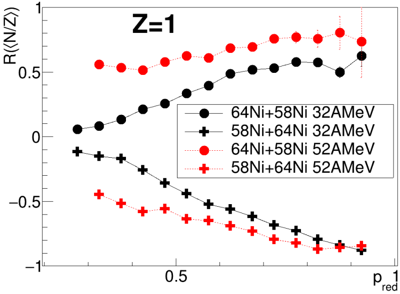
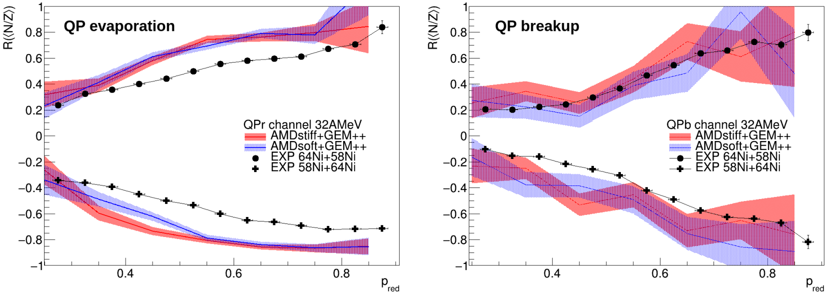
We build the **isospin transport ratio**. The higher degree of equilibration at 32 AMeV is confirmed.



Isospin diffusion

Comparison between the QPr and QPb channels: model predictions



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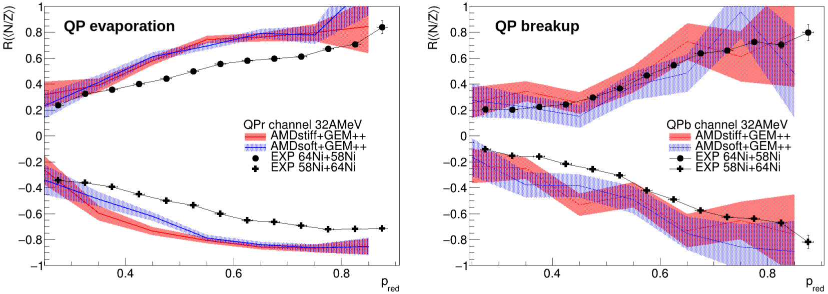

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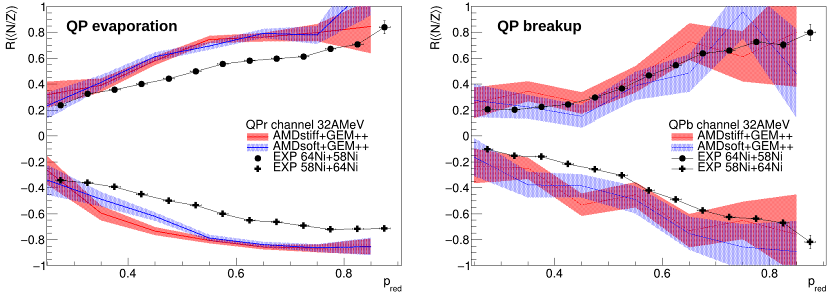

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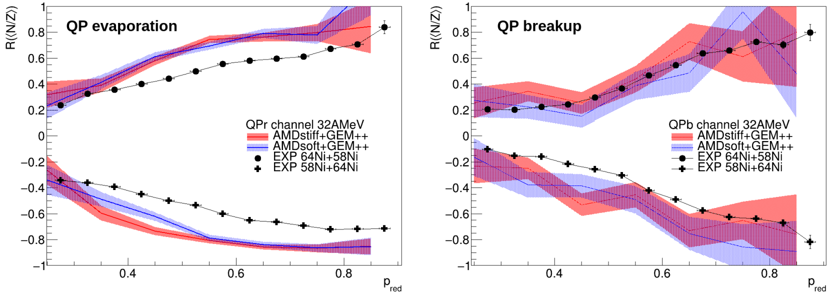

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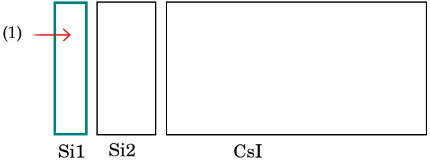
Experimental setup

Identification techniques



Different identification methods depending on the stopping layer:

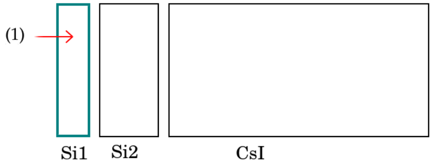
1. Si1: PSA-Si

Pulse Shape Analysis: identification of fragments stopped in a detector (e.g. Si1)

Signal shape ⟵ Ionisation density ⟵ (Z, A) and E of fragment

Experimental setup

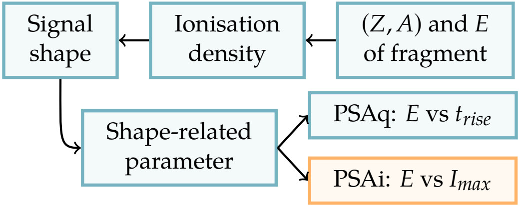
Identification techniques



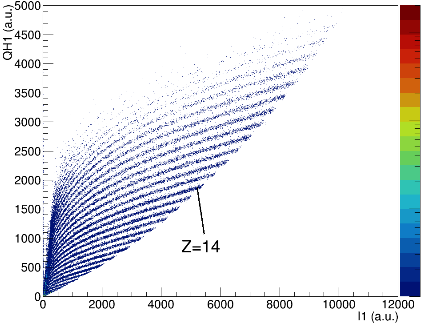
Different identification methods depending on the stopping layer:

1. Si1: PSA-Si

Pulse Shape Analysis: identification of fragments stopped in a detector (e.g. Si1)

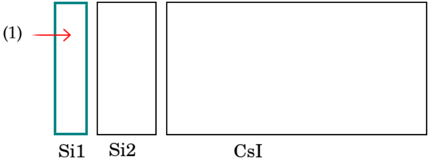


- A good doping uniformity is mandatory
- Si detectors are reverse mounted



Experimental setup

Identification techniques



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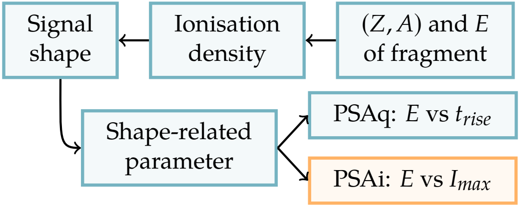

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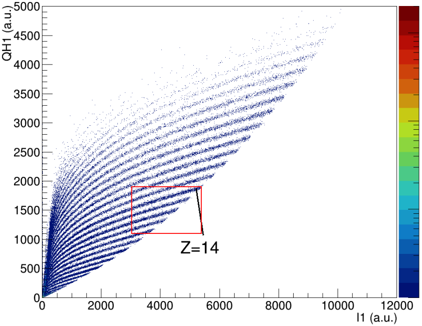
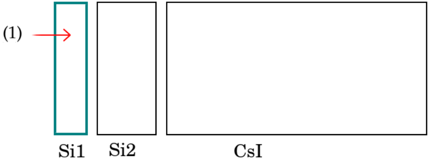


Experimental setup

Identification techniques



Different identification methods depending on the stopping layer:

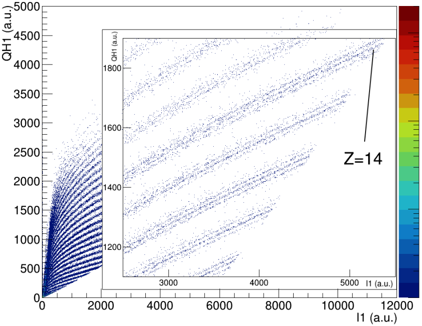
1. Si1: PSA-Si

Pulse Shape Analysis: identification of fragments stopped in a detector (e.g. Si1)

Signal shape ← Ionisation density ← (Z, A) and E of fragment

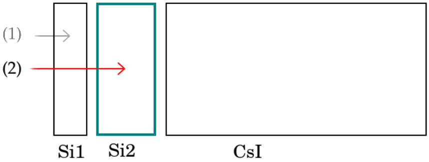
Signal shape → Shape-related parameter → PSAq: E vs t_{rise} ; PSAi: E vs I_{max}

- A good doping uniformity is mandatory
- Si detectors are reverse mounted



Experimental setup

Identification techniques



Different identification methods depending on the stopping layer:

1. Si1: PSA-Si
2. Si2: ΔE-E Si1-Si2

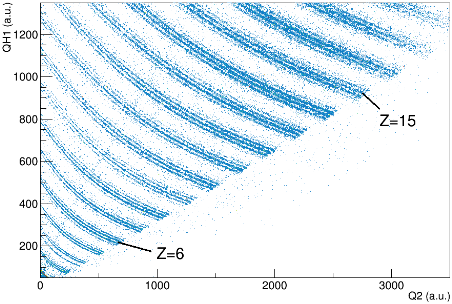
Δ*E-E technique*: based on the mechanism of kinetic energy dissipation of charged particles in matter → Bethe-Bloch

$$-\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} Nz \left[\ln \frac{2m_e v^2}{I} - \ln(1-\beta^2) - \beta^2 \right]$$

In a non-relativistic approx. ($E_0 = \Delta E + E_{res}$):

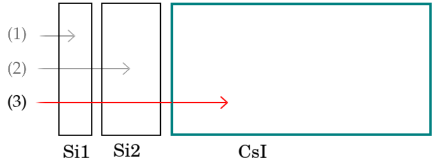
$$\Delta E \propto \frac{Z^2}{v^2} \cdot \Delta x \propto \frac{Z^2 A}{E_0} \cdot \Delta x \Rightarrow \Delta E \cdot E_0 = kZ^2 A$$

Identify the ejectiles stopped in the second stage detector



Experimental setup

Identification techniques



Different identification methods depending on the stopping layer:

1. Si1: PSA-Si
2. Si2: ΔE-E Si1-Si2
3. CsI: ΔE-E Si2-CsI

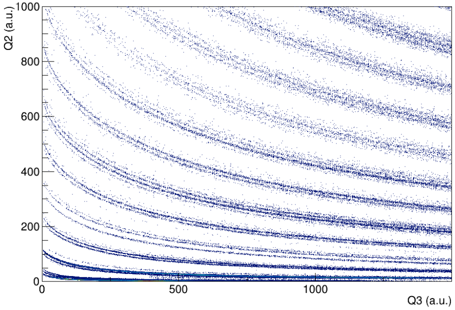
Δ***E*-*E* technique**: based on the mechanism of kinetic energy dissipation of charged particles in matter → Bethe-Bloch

$$-\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} Nz \left[\ln \frac{2m_e v^2}{I} - \ln(1-\beta^2) - \beta^2 \right]$$

In a non-relativistic approx. ($E_0 = \Delta E + E_{res}$):

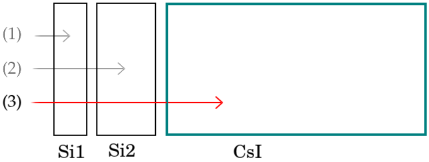
$$\Delta E \propto \frac{Z^2}{v^2} \cdot \Delta x \propto \frac{Z^2 A}{E_0} \cdot \Delta x \Rightarrow \Delta E \cdot E_0 = kZ^2 A$$

Identify the ejectiles stopped in the second stage detector, and also in the third stage



Experimental setup

Identification techniques



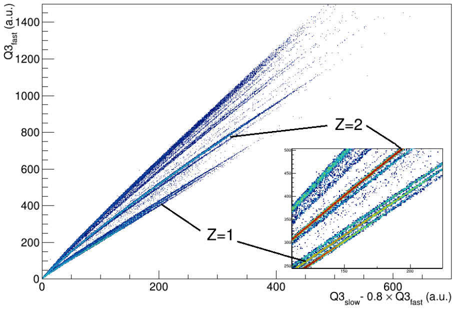
Different identification methods depending on the stopping layer:

1. Si1: PSA-Si
2. Si2: ΔE-E Si1-Si2
3. CsI: ΔE-E Si2-CsI or PSA-CsI

Pulse Shape Analysis in CsI: used for high-energy LCPs.
Intensity of scintillation light:

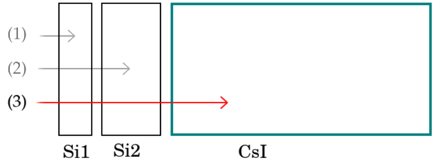
$$I(t) = I_{fast} \cdot \frac{e^{-t/\tau_{fast}}}{\tau_{fast}} + I_{slow} \cdot \frac{e^{-t/\tau_{slow}}}{\tau_{slow}}$$

where $\tau_{fast} \sim 700\,\text{ns}$ and $\tau_{slow} \sim 5\,\mu\text{s}$. The ratio I_{fast}/I_{slow} depends on (Z, A) and E of fragment.
Digital electronics: two trapezoidal shapers with different flat top applied to CsI signal.



Experimental setup

Identification techniques



Different identification methods depending on the stopping layer:

1. Si1: PSA-Si
2. Si2: ΔE-E Si1-Si2
3. CsI: ΔE-E Si2-CsI or PSA-CsI

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Digital electronics: two trapezoidal shapers with different flat top applied to CsI signal.