The INDRA-FAZIA setup: an overview of the most recent results on isospin transport phenomena

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GANIL

for the INDRA-FAZIA collaboration

Colloque GANIL 2023
25-29 September 2023

Isospin transport phenomena

Nuclear symmetry energy at work in heavy ion reactions

Heavy ion collisions at intermediate energies → collect information on the **Isospin transport phenomena**: projectile-target nucleon exchange processes

- governed by the *symmetry energy* term of the **Nuclear Equation of State**: energy per nucleon as a function of *density* $\rho = \rho_n + \rho_p$ and *isospin asymmetry* $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$. By defining $x = \left(\frac{\rho - \rho_0}{3\rho_0}\right)$:

$$\frac{E}{A}(\rho, \delta) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho)\delta^2 \quad \text{where} \quad \frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \dots$$

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- The **isospin transport phenomena** can be expressed as:
  $$\mathbf{j}_n - \mathbf{j}_p \propto \frac{E_{sym}}{A}(\rho)\nabla\delta + \delta\frac{\partial\frac{E_{sym}}{A}(\rho)}{\partial\rho}\nabla\rho$$

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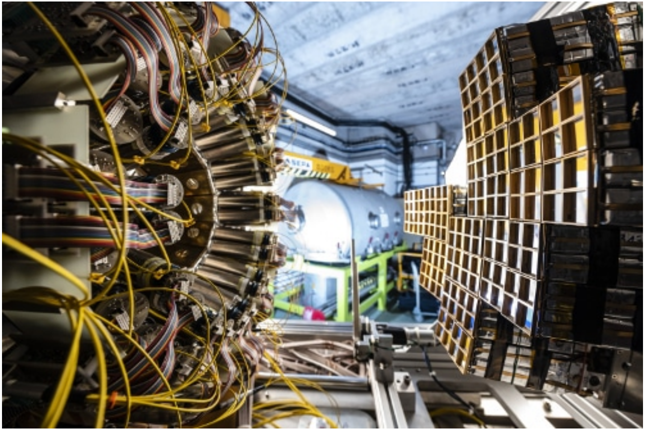
INDRA-FAZIA

The coupling of the two setups

INDRA and FAZIA: multi-detector apparatuses, designed for the detection of nuclear fragments produced heavy ion collisions at Fermi energies.
Their characteristics are in some respects complementary.



During the first months of 2019 the coupling between INDRA and FAZIA was completed in GANIL.

INDRA-FAZIA

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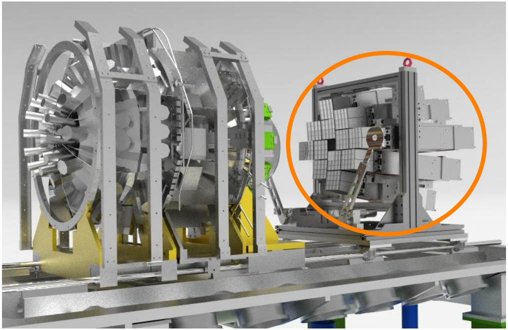

- The most forward polar angles (1.4°<θ< 12.6°) have been covered with 12 FAZIA blocks in a wall configuration at 1 m from the target. The first five rings of INDRA have been removed.
  → *isotopic identification of QP-like fragments*

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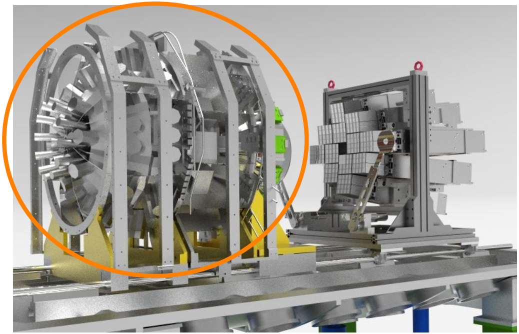

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  $\longrightarrow$ *isotopic identification of QP-like fragments*
- The remaining part of INDRA (rings 6-17) covers the polar angles between 14° and 176° (~ 80% of the 4π solid angle).
  $\longrightarrow$ *global variables for the estimation of the reaction centrality*

INDRA-FAZIA

The first experiments at GANIL

After the INDRA-FAZIA coupling, two experiments have been carried out at GANIL:

- E789 (2019): $^{58,64}Ni+^{58,64}Ni$ at 32, 52 MeV/nucl.
  C. Ciampi et al., Phys. Rev. C 106, 024603 (2022),
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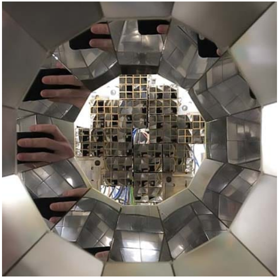
- E818 (2022): $^{58}Ni,^{36}Ar+^{58}Ni$ at 74 MeV/nucl.
  data reduction is now finished, analysis in progress
  → *see talk by Lucia Baldesi*



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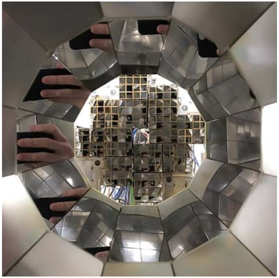


The isospin diffusion mechanism was the main topic of the E789 experiment:

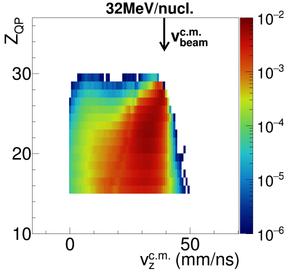
- All of the four possible combinations of the two reaction partners ^{58}Ni and ^{64}Ni have been studied
  ⇒ compare the products of the two asymmetric reactions with those of both the neutron rich and neutron deficient symmetric systems
- Two different incident beam energies 32 MeV/nucl and 52 MeV/nucl.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

Binary output channel

Study of the QP evaporation channel

Main goal: focus on the binary exit channel for semiperipheral and peripheral collisions

- selected as $\mathbf{M_{big} = 1}$, with $Z_{big} \geq 15$ and $\theta_{big}^{CM} < 90°$ ($v_z^{CM} > 0$) $\longrightarrow$ QP remnant



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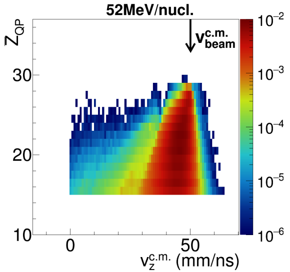

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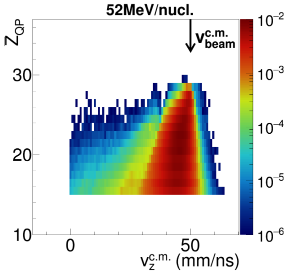
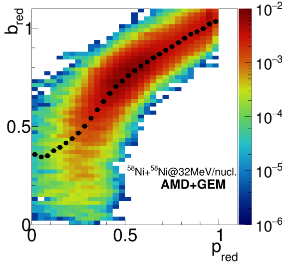


As reaction centrality estimator we select the **reduced momentum along the *z*-axis:** $p_{red} = \frac{p_z^{QP}}{p_{beam}}$

Its correlation with $b_{red} = b/b_{gr}$ is:

- reliable for $p_{red} \gtrsim 0.3$



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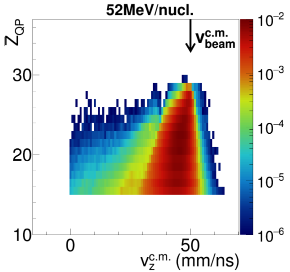

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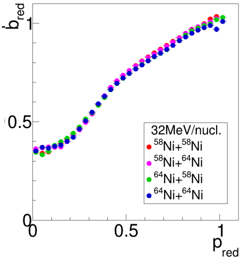

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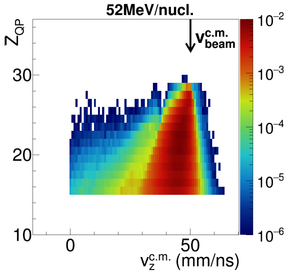

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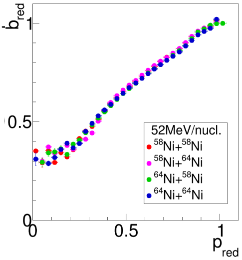

QP evaporation channel in Ni+Ni collisions

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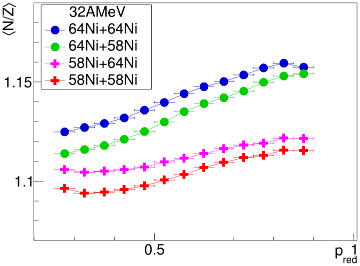
Evolution of $\langle N/Z \rangle$ of the QP remnant with centrality $\rightarrow$ **evidence of isospin diffusion**



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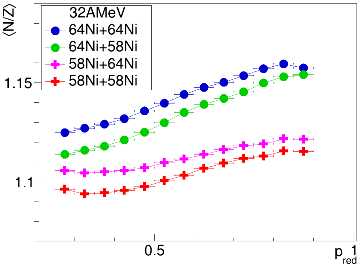

Isospin transport ratio: can highlight the effect, bypassing the effects acting similarly on the four systems (F. Rami et al., Phys. Rev. Lett. 84, 1120 (2000))
Given $A = {}^{64}$Ni, $B = {}^{58}$Ni:

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

where $i = AA, AB, BA, BB$ and X is an isospin sensitive observable (e.g. $\langle N/Z \rangle_{QPr}$).

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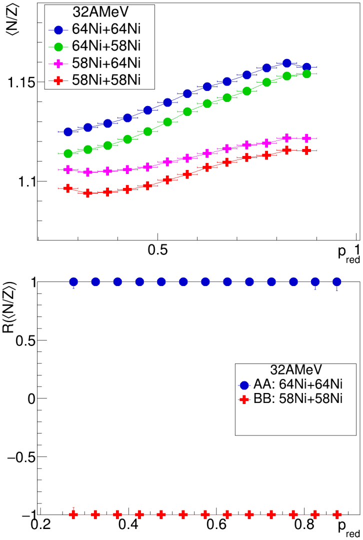

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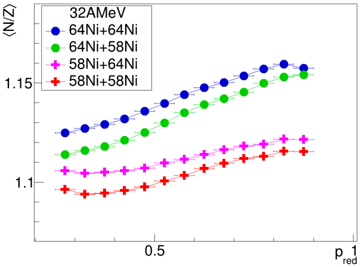

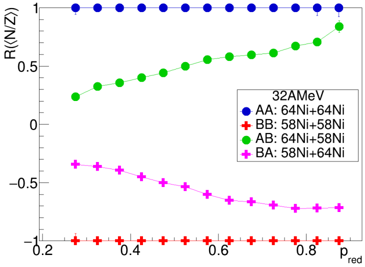

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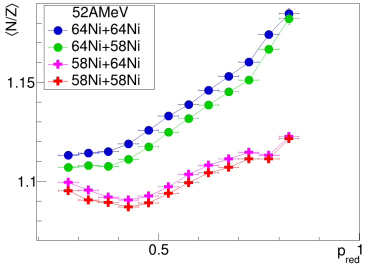

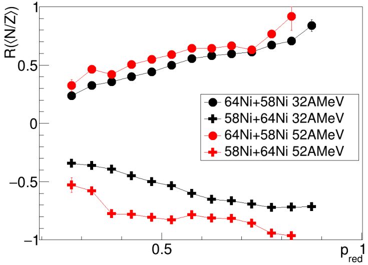

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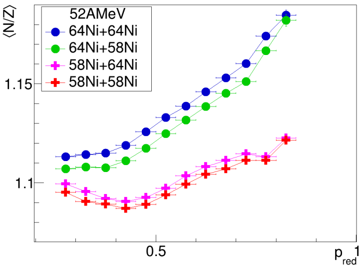

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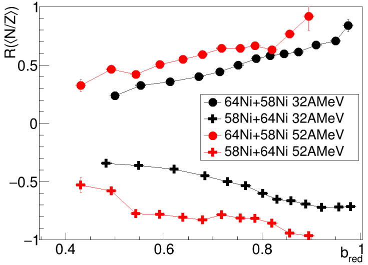

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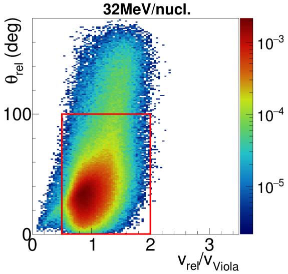
⇒ $\boldsymbol{\theta_{rel} < 90}$° and v_{rel} cond. depending on E_{beam}



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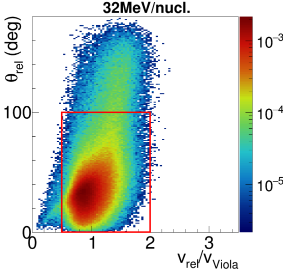

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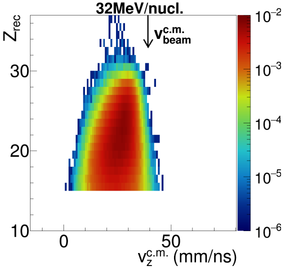

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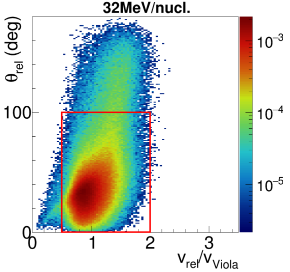

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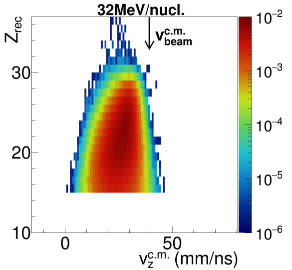
  → the "reconstructed" QP is compatible with a forward emitted heavy QP-like fragment



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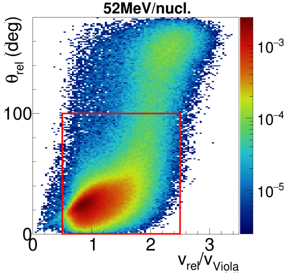
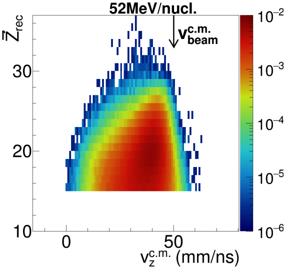


We also require:

- charge of the reconstructed QP $\boldsymbol{Z_{rec} = Z_H + Z_L \geq 15}$
  → the "reconstructed" QP is compatible with a forward emitted heavy QP-like fragment
- for the isospin analysis, both A identified
  ⇒ both $Z \geq 5$ fragments must be in FAZIA



QP breakup channel in Ni+Ni collisions

Channel selection: dynamical or statistical fission? (I)

Set of events compatible with a QP fission process → *of which kind?*

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Statistical fission

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- Fast process ($\sim 200 - 300\,\mathrm{fm/c}$), driven by reaction dynamics

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- More aligned configurations observed for larger mass asymmetries of the split

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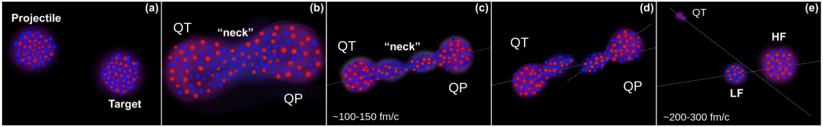
- Fast process (∼ 200 – 300 fm/c), driven by reaction dynamics
- More aligned configurations observed for larger mass asymmetries of the split

According to a possible interpretation of the dynamical fission:

- QP, QT separate featuring a strong deformation + angular momentum
- Prompt breakup → formation of a Light Fragment (LF, from the neck side) and a Heavy Fragment (HF) → **asymmetric**
- **Fast** process → LF emitted towards CM → **anisotropic**



adapted from A. Rodriguez Manso et al., PRC 95, 044604 (2017)

Experimental data: check the **asymmetry** and the **anisotropy** of the emission of the two fission fragments. We exploit:

QP breakup channel in Ni+Ni collisions

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- Mass asymmetry HF-LF:

$$\eta = \frac{A_H - A_L}{A_{rec}}$$

low η: symmetric split
high η: asymmetric split

QP breakup channel in Ni+Ni collisions

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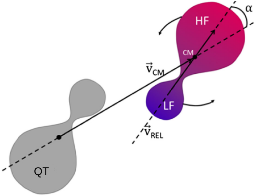

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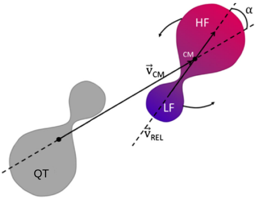

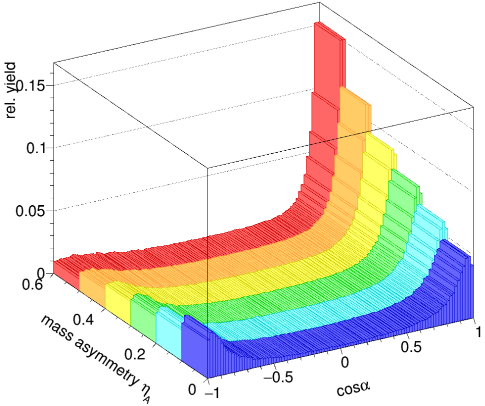

In the asymmetric configuration the backward emission of the LF is favoured, as expected for the dynamical fission

QP breakup channel in Ni+Ni collisions

Channel selection: dynamical or statistical fission? (III)

AMD+GEMINI calculations: check directly “how **fast**” the fission process is.
Dynamical fission → the fragments are present at 500 fm/c (end of AMD calc.)
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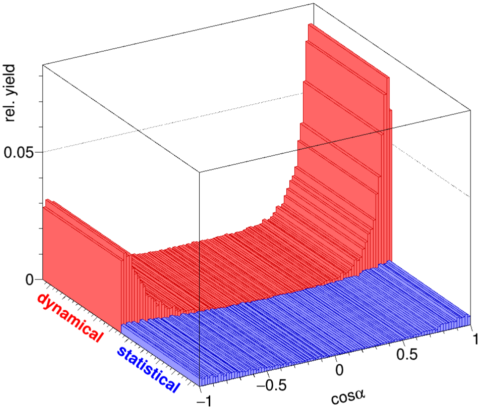

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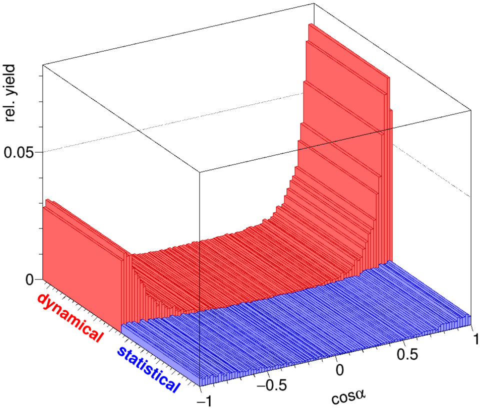
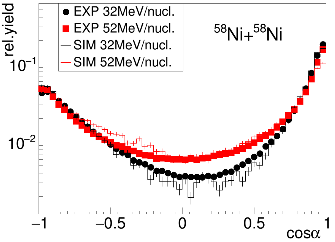


According to AMD+GEMINI++ about 90% (85%) of the fission events are dynamical for the reactions at 32 (52) MeV/nucl.



The α and η distributions are quite nicely reproduced.

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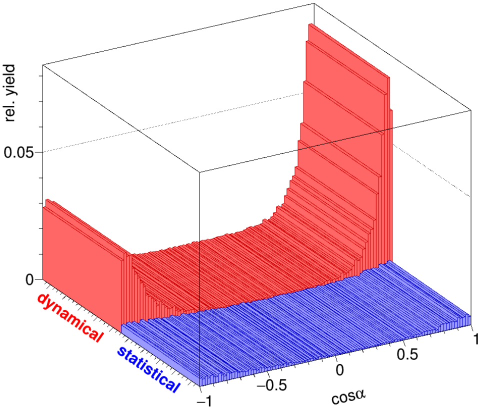

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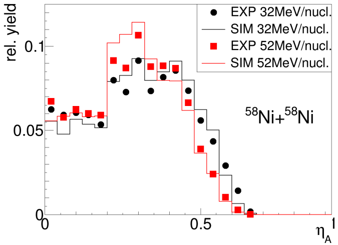

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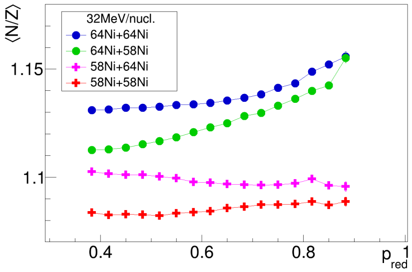
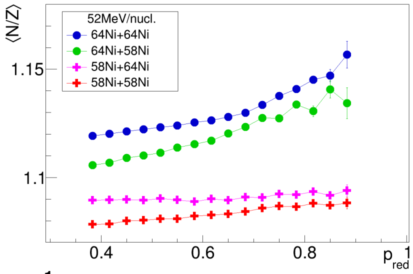
QP breakup channel in Ni+Ni collisions

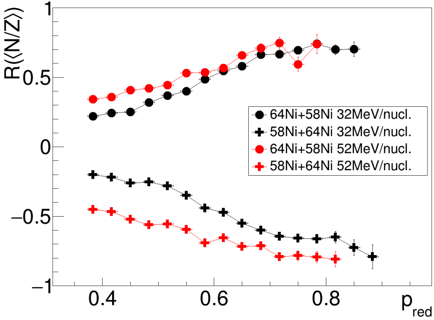
Isospin characteristics





Similarly to what found in the QPr channel, the **isospin diffusion** effect is visible also on the characteristics of the QP reconstructed from the two breakup fragments in the QPb channel.

The comparison between the two E_{beam} leads to the same observation: stronger equilibration for lower E_{beam}.



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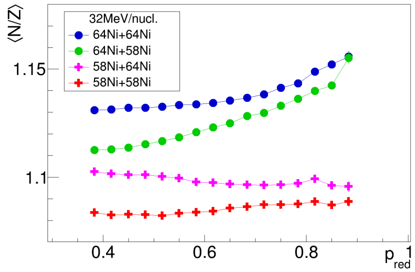

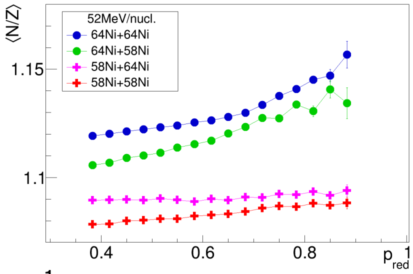

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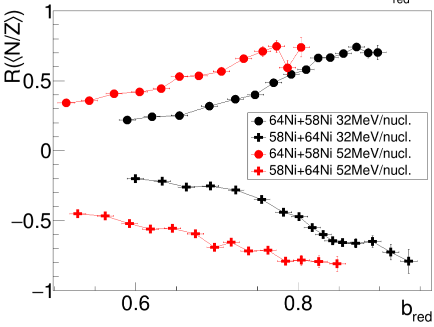
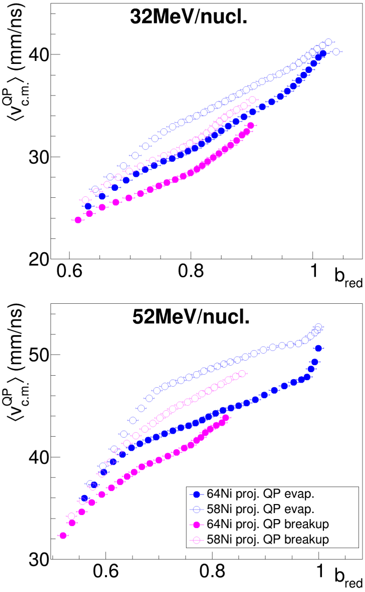


QP breakup channel in Ni+Ni collisions

Comparison with the evaporative channel: first overview



Some basic differences are already evident in the measured general properties of the QP (residue or reconstructed) in the two channels.

Comparison of $\langle \mathbf{v}_{\mathbf{cm}}^{\mathbf{QP}} \rangle$:

- fissioning QP slower than non-fissioning one

QP breakup channel in Ni+Ni collisions

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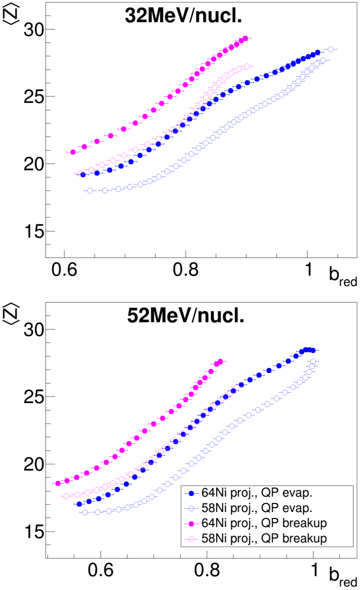

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QP breakup channel in Ni+Ni collisions

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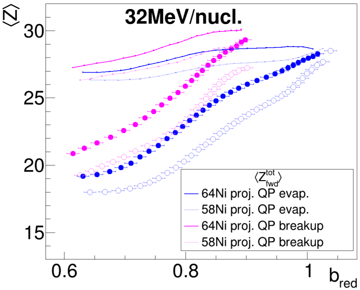

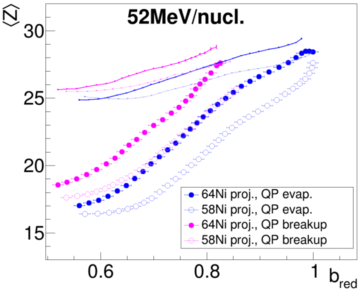

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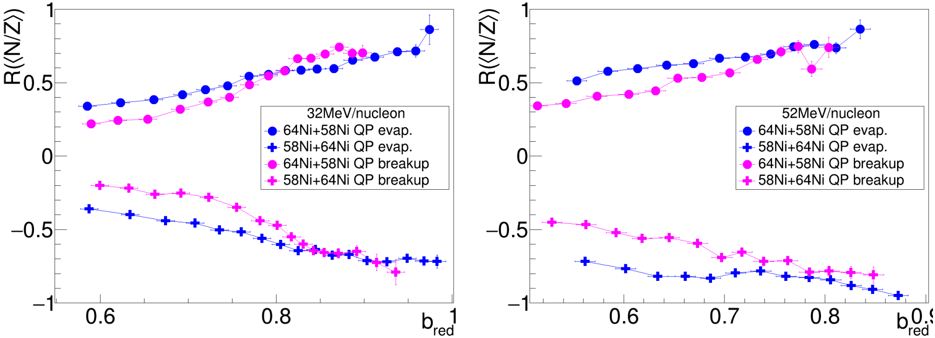
- average total charge detected in the forward hemisphere $\langle \mathbf{Z^{tot}_{fwd}} \rangle$ for the breakup channel is still ~1 charge unit larger

QP breakup channel in Ni+Ni collisions

Comparison with the evaporative channel: isospin characteristics



At both energies, for the same reaction centrality a higher degree of isospin equilibration is obtained in the breakup channel than in the evaporative one.

The QP breakup channel seems to select a set of events where a stronger role has been played by the isospin diffusion between projectile and target.

QP breakup channel in Ni+Ni collisions

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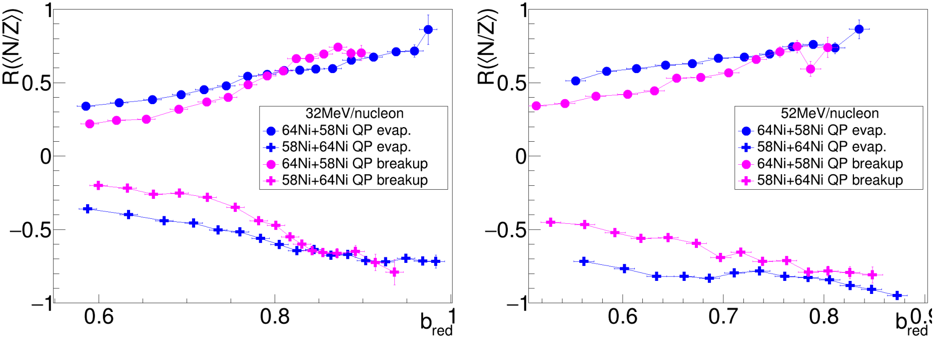

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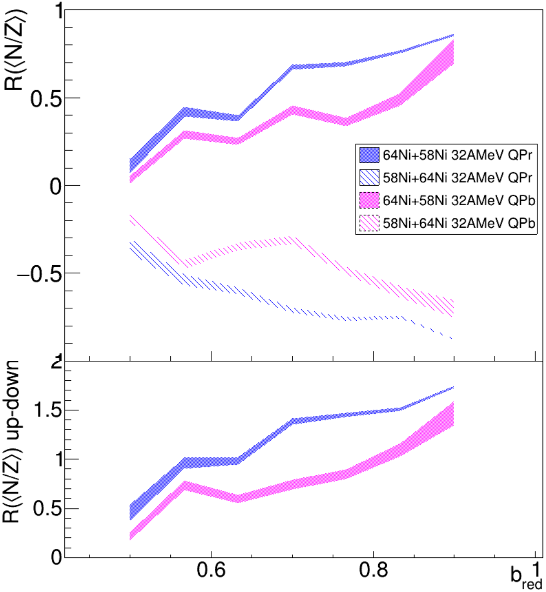
Are we indirectly selecting some events in the tail of the distribution of some parameter related to the reaction dynamics?

QP breakup channel in Ni+Ni collisions

What does the model predict?



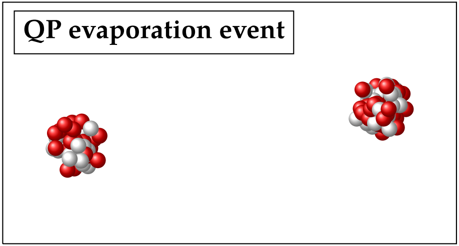
AMD+GEM++ simulations

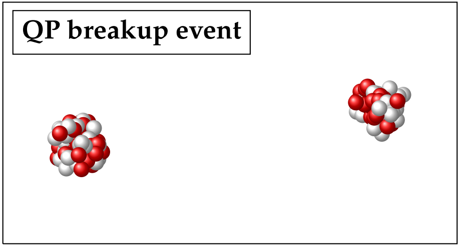
Analysis of the unfiltered simulated datasets (adapting the selection criteria)
→ exclude any possible role of the apparatus acceptance

The stronger isospin equilibration in the breakup channel is visible also in AMD+GEMINI++.
→ track down the differences in the two dynamical scenarios

QP breakup channel in Ni+Ni collisions

A possible interpretation





A possible semiclassical interpretation:

QP breakup channel in Ni+Ni collisions

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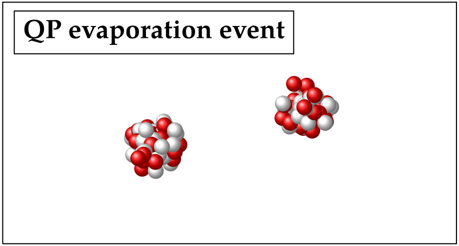

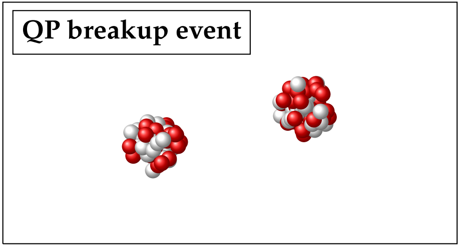

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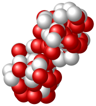
- for the same entrance channel conditions

QP breakup channel in Ni+Ni collisions

A possible interpretation

QP evaporation event



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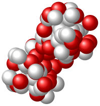

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QP breakup channel in Ni+Ni collisions

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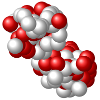

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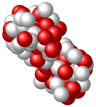

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QP breakup channel in Ni+Ni collisions

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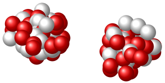

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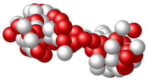

A possible semiclassical interpretation:

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- leading to more pronounced deformations of the interacting QP+QT

QP breakup channel in Ni+Ni collisions

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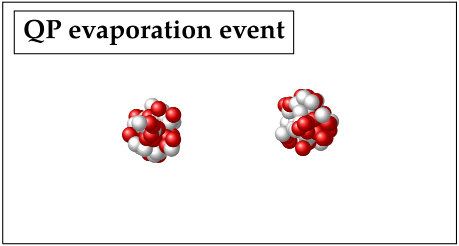

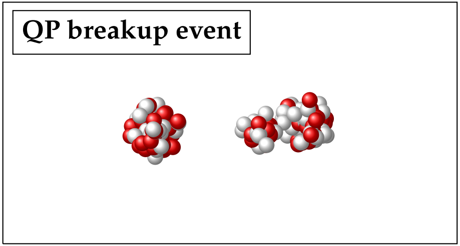

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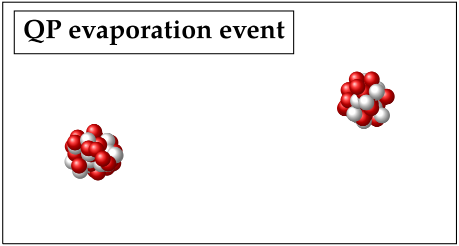

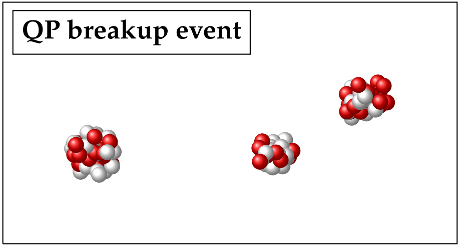

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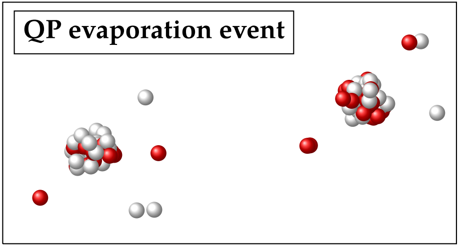

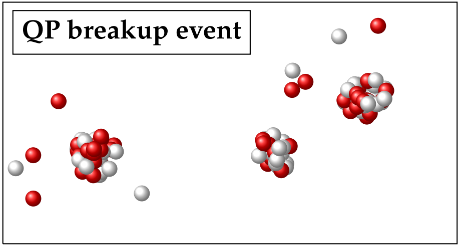

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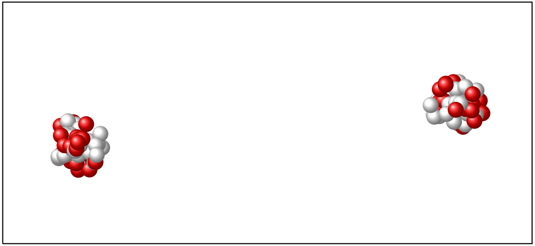
- due to a longer contact time, more isospin equilibration could be achieved

QP-QT interaction time

Extracting the information from AMD

Quite a naive picture (e.g. we do not take into account the density range explored in the contact area), but we could exploit the AMD simulations to extract the contact time information.



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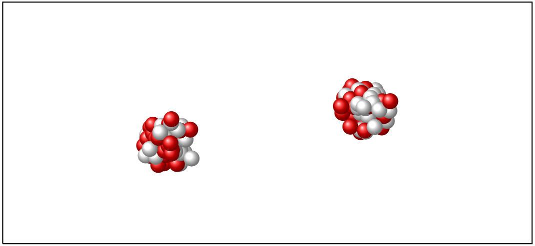

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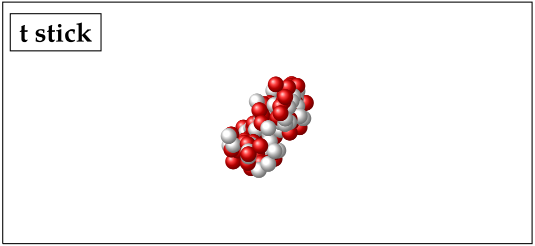

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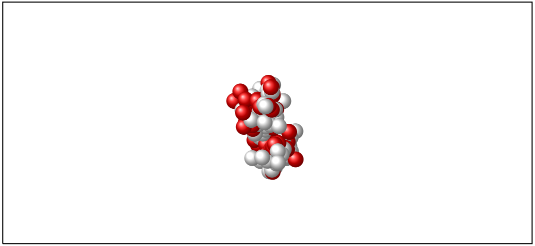

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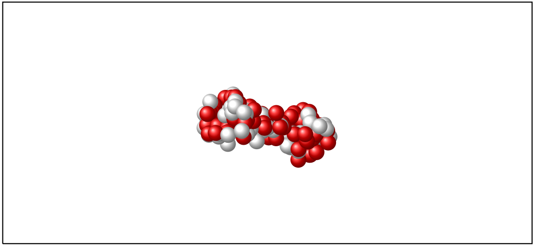

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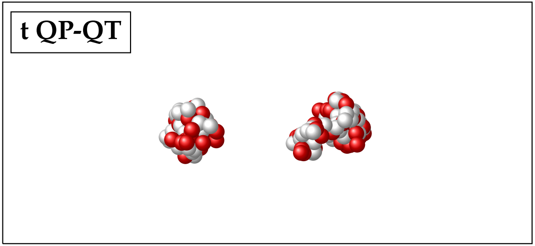

We apply the fragment reconstruction algorithm with a 20fm/c timestep.

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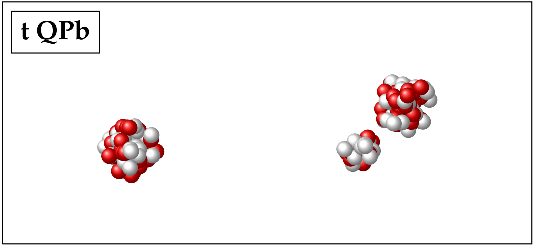

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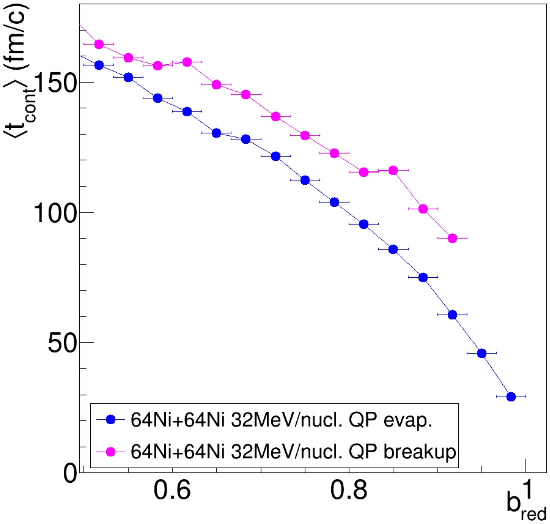

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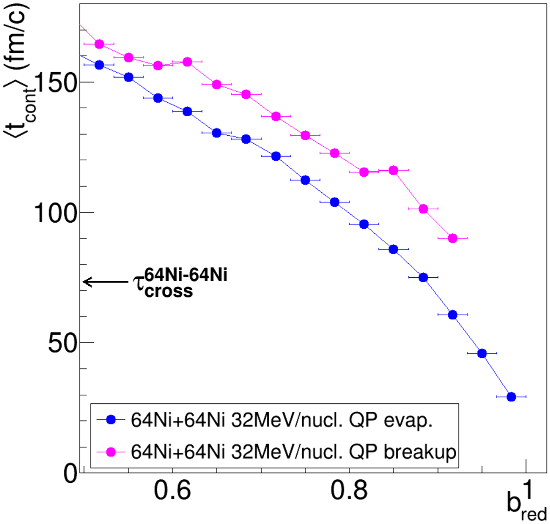

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- *Slightly longer contact times are on average indirectly selected in the breakup channel with respect to the evaporative one*
- Reliability of $\langle t_{cont} \rangle$:
  $\tau_{cross} = 2R_0(A_p^{1/3} + A_t^{1/3})/v_{beam}^{lab}$
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QP-QT interaction time

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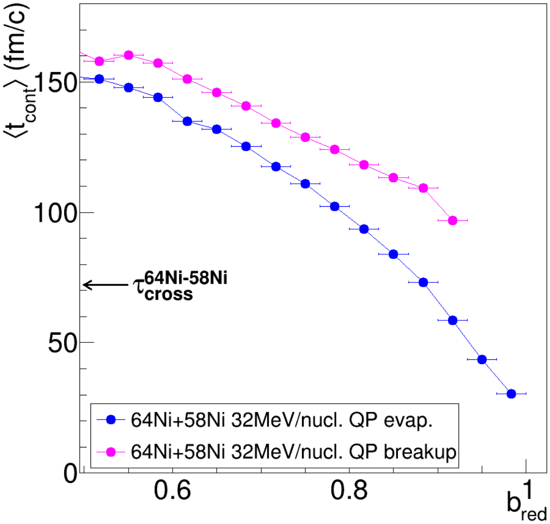

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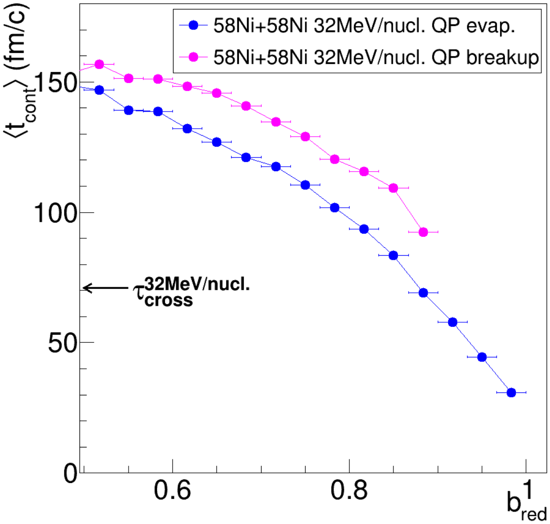

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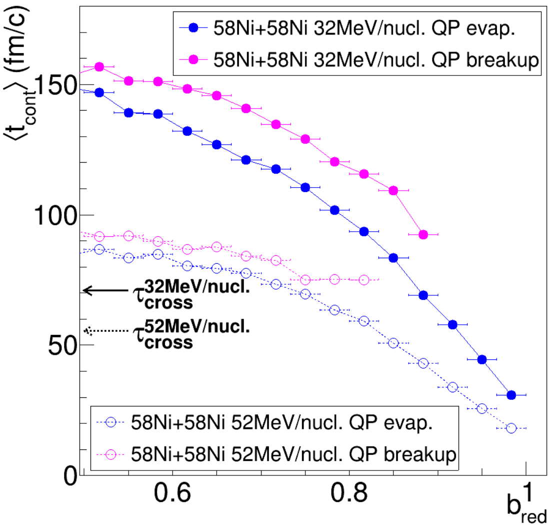

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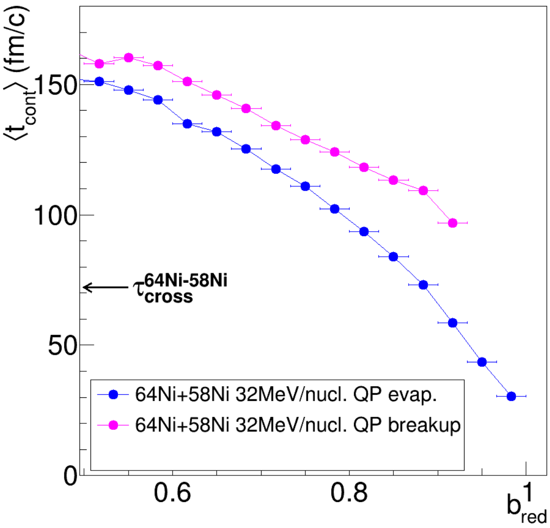

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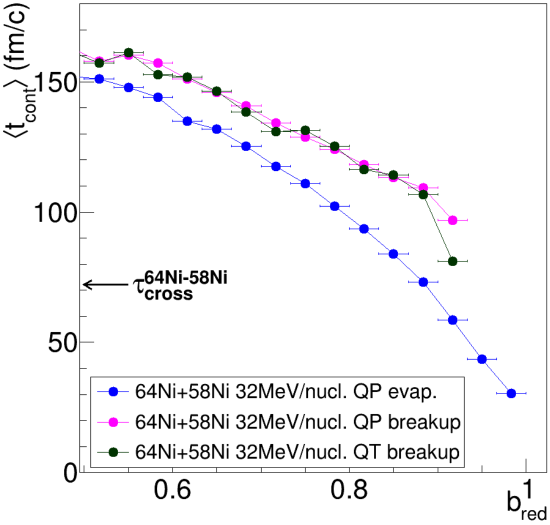

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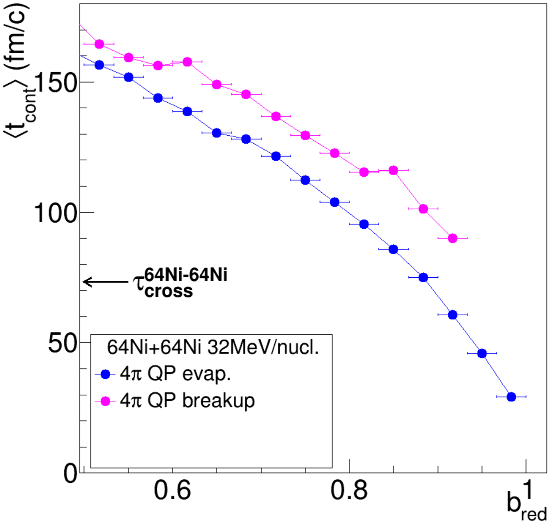

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Analysis after filter:

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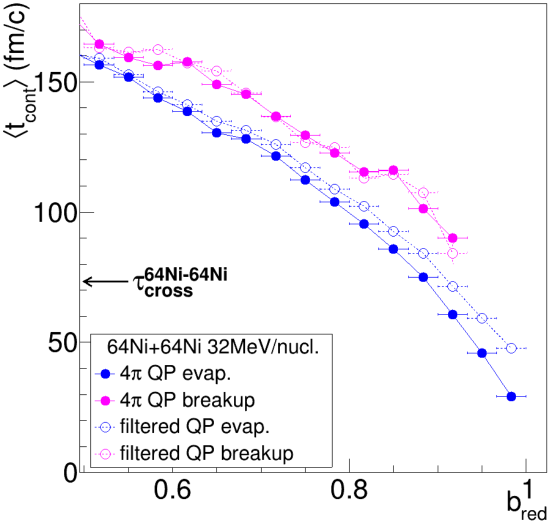

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Analysis after filter:

- Small t_{cont} variation only for the evaporative channel, but still longer for QP breakup

Summary and future perspectives

Summary

- INDRA-FAZIA E789: ^{64,58}Ni+^{64,58}Ni at 32 and 52 MeV/nucl.
- QP-QT isospin equilibration in the two reaction channels:
  - clear relaxation of the isospin imbalance in asymmetric systems
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Future perspectives

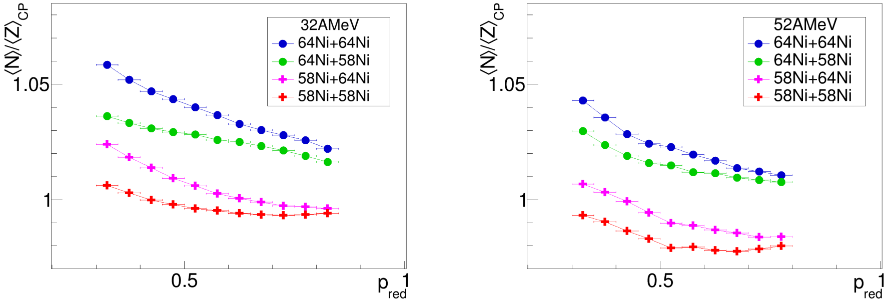
- Study the other dynamical features related to a longer interaction (e.g., density evolution) selected by the breakup channel, as well as the consequences on the sensitivity to the NEoS parametrization
- Isospin equilibration between QP breakup fragments HF and LF
- Detailed comparison with models: AMD and BUU model (S.Mallik et al., J. Phys. G: Nucl. Part. Phys. 49 (2022) 015102)

Thank you!

Backup slides

Isospin diffusion

QPr channel: characteristics of the evaporated particles (I)

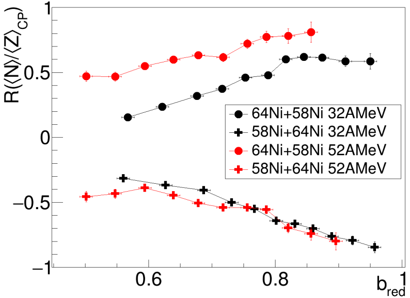


The QP-QT isospin equilibration can be evidenced also on the characteristics of the QP deexcitation emissions.

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

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

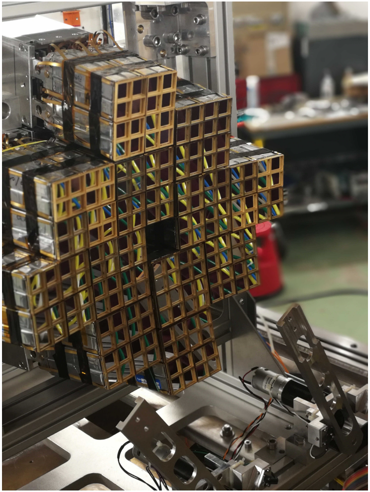
considering LCPs and IMFs with $A > 1$.



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

FAZIA

Main characteristics of the setup



FAZIA *(Forward-angle A and Z Identification Array)*: state of the art of ion identification in the Fermi energy domain.

- Result of R&D activities to refine:
  - detector performance
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FAZIA

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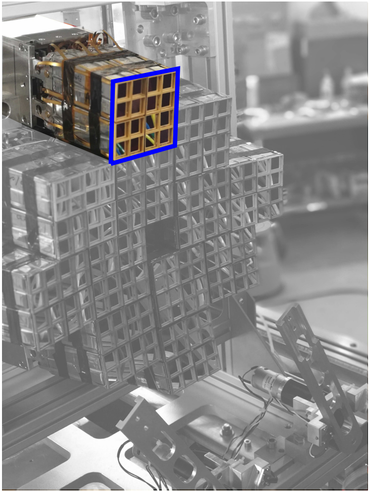

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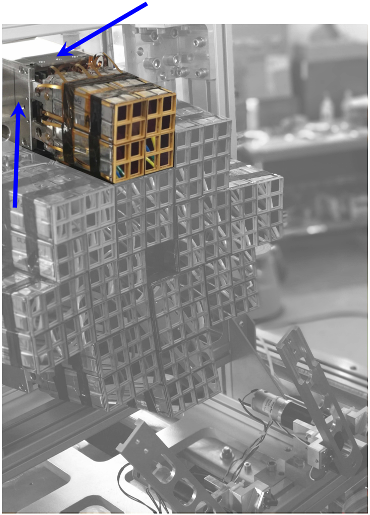

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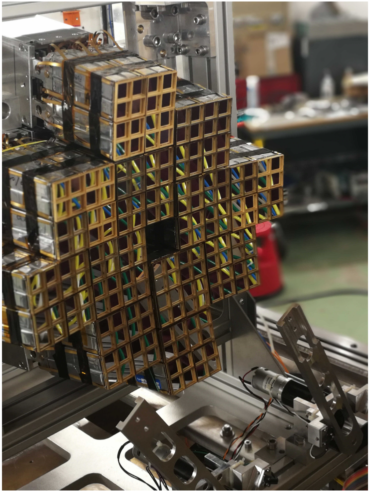

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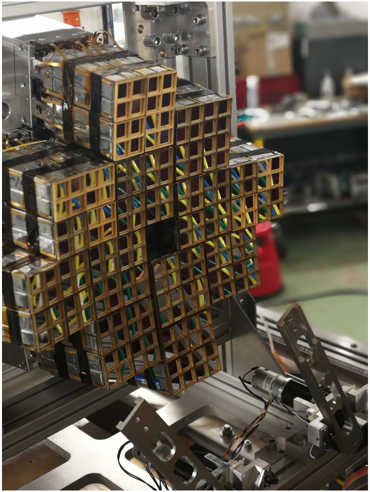

→ *see talks by G. Casini, A. Camaiani*

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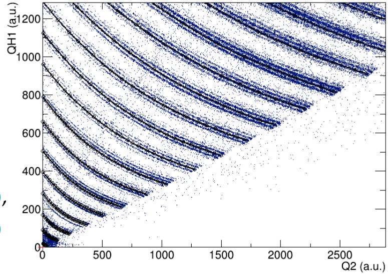
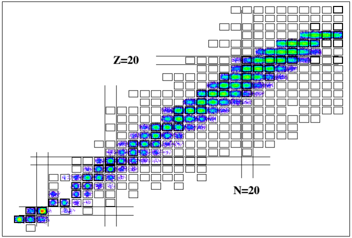
FAZIA

The experimental campaigns

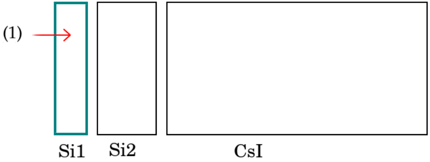
After the R&D phase, the first experimental campaign started at LNS, Catania:

- ISOFAZIA (2015):
  ^{80}Kr+^{40,48}Ca at 35 MeV/nucl.
  S. Piantelli et al., Phys. Rev. C 101, 034613 (2020),
  S. Piantelli et al., Phys. Rev. C 103, 014603 (2021)
- FAZIASYM (2015):
  ^{40,48}Ca+^{40,48}Ca at 35 MeV/nucl.
  A. Camaiani et al., Phys. Rev. C 102, 044607 (2020),
  A. Camaiani et al., Phys. Rev. C 103, 014605 (2021)
- FAZIACOR (2017):
  ^{20}Ne,^{32}S+^{12}C at 25, 50 MeV/nucl.
  C. Frosin et al., Phys. Rev. C 107, 044614 (2023)
  → *see talk by A. Camaiani*
- FAZIAPRE (2018):
  ^{40,48}Ca+^{12}C at 25, 40 MeV/nucl.
  S. Piantelli et al., Phys. Rev. C 107, 044607 (2023)
- FAZIAZERO (2018):
  ^{12}C+^{12}C at 62 MeV/nucl.





Experimental setup
Identification techniques

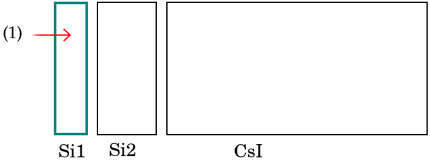


Different identification methods depending on the stopping layer:

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



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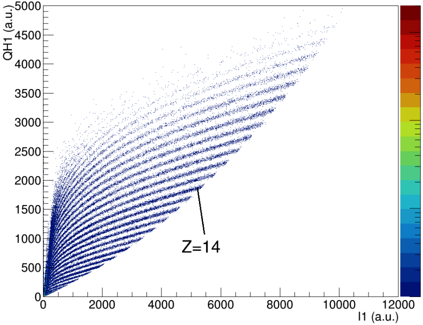
Signal shape → Shape-related parameter → PSAq: E vs t_{rise} / PSAi: E vs I_{max}

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



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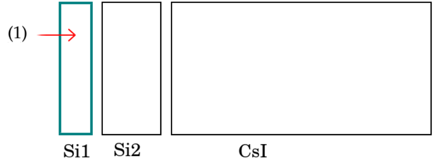

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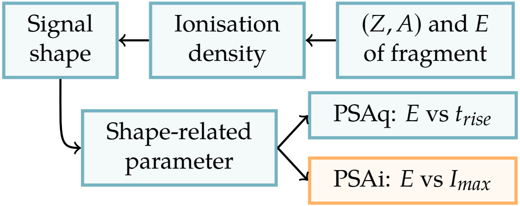

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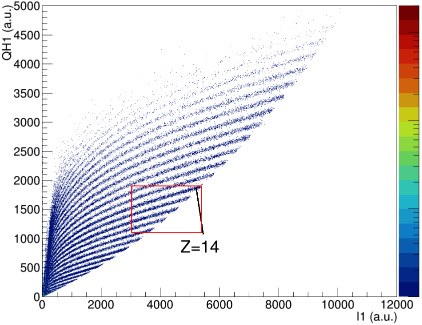

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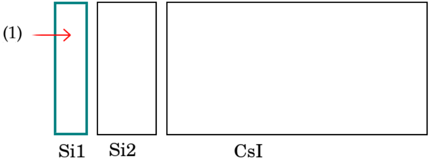

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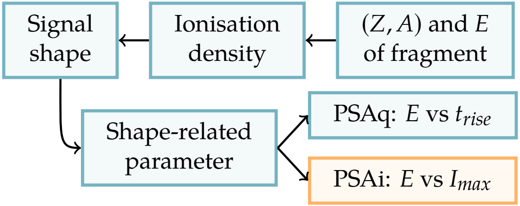

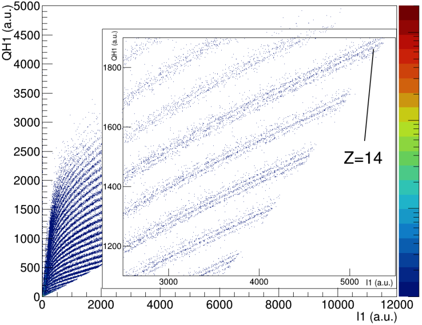

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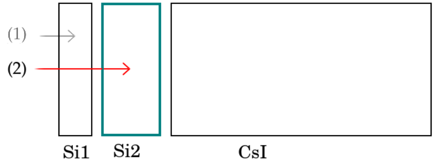

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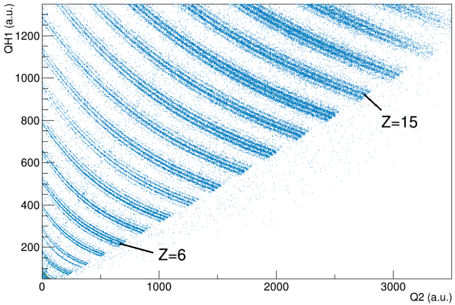
Δ***E-E technique***: based on the mechanism of kinetic energy dissipation of charged particles in matter → Bethe-Bloch

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

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

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

Identify the ejectiles stopped in the second stage detector



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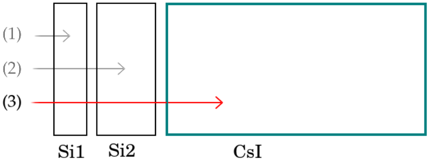

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3. CsI: ΔE-E Si2-CsI

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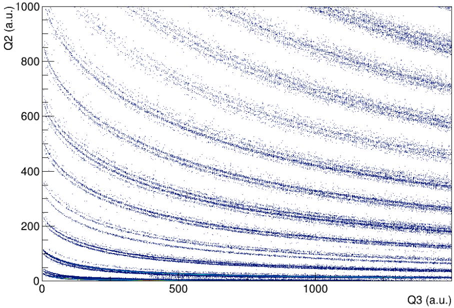
Identify the ejectiles stopped in the second stage detector, and also in the third stage



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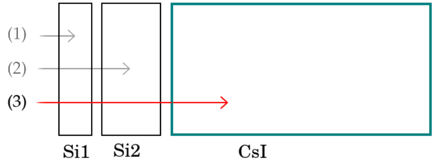

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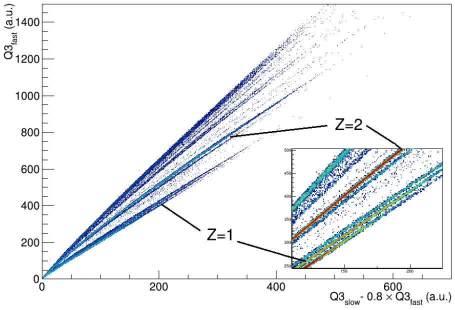
Pulse Shape Analysis in CsI: used for high-energy LCPs.
Intensity of scintillation light:

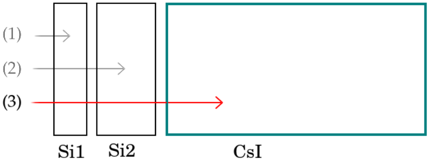
$$I(t) = I_{fast} \cdot \frac{e^{-t/\tau_{fast}}}{\tau_{fast}} + I_{slow} \cdot \frac{e^{-t/\tau_{slow}}}{\tau_{slow}}$$

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

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.
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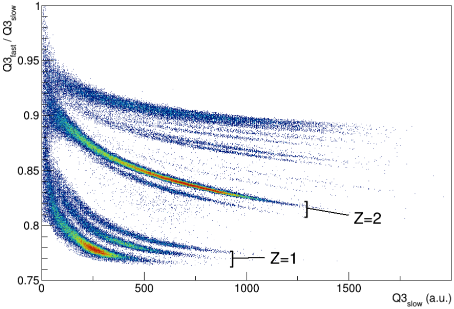
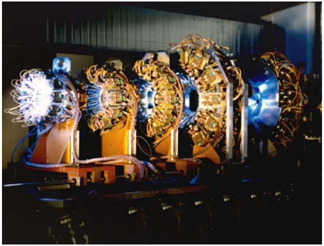


INDRA

Main characteristics of the setup

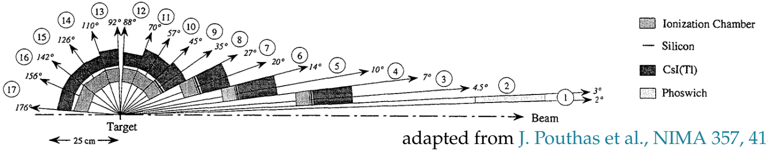
INDRA *(Identification de Noyaux et Détection avec Résolutions Accrues)*: highly segmented array for detection and identification of charged products of heavy ion collisions at intermediate energies (10 < E < 100 AMeV).

- 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 $Z \sim 4$
  → Electronics upgrade (2020): now up to $Z \sim 10$
  J. D. Frankland et al., Nuovo Cim. C 45, 43 (2022)



→ *see talks by Q. Fable, T. Génard*

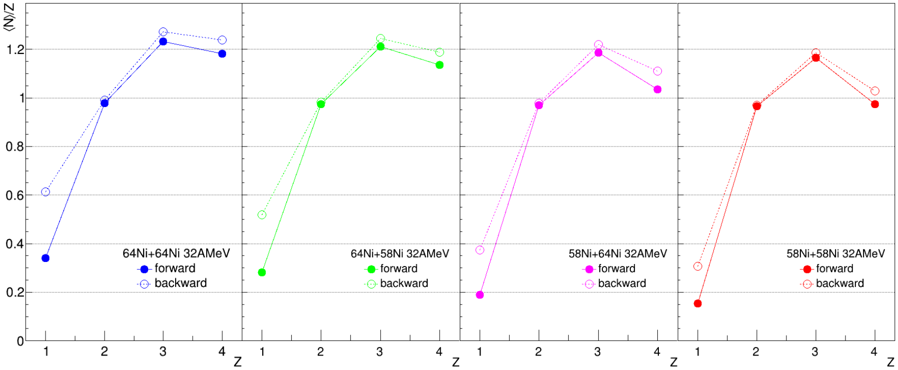
- Large solid angle coverage (90%) with high granularity (336 modules)



adapted from J. Pouthas et al., NIMA 357, 418 (1995)

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** $\rightarrow \langle N \rangle$ for the backward emissions is higher than the forward one. Clean interpretation for symmetric systems.

Isospin drift

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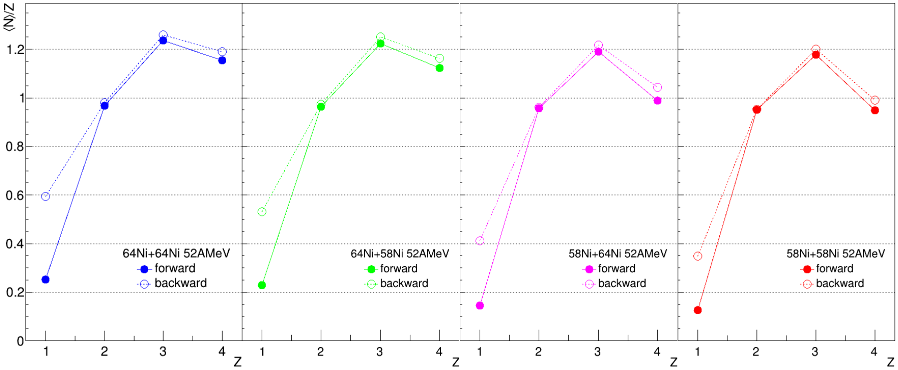

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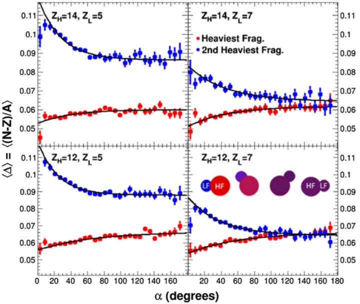
QP breakup channel in Ni+Ni collisions

Recent highlights on dynamical fission

- For a longer time interval elapsed between the QP-QT split and the QP breakup:
  - the degree of isospin equilibration inside the original QP increases
  - the α angle between the separation axis and the breakup axis increases: for a short breakup timescale α can be adopted as a "clock"

$\Rightarrow$ *Equilibration chronometry*: extraction of a timescale of isospin equilibration ($\sim$ zs)



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

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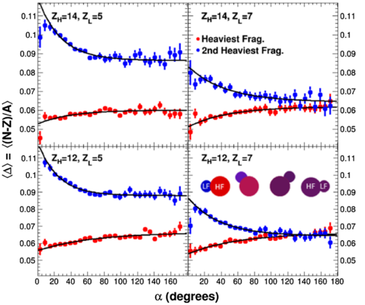

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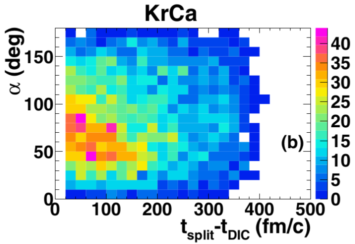
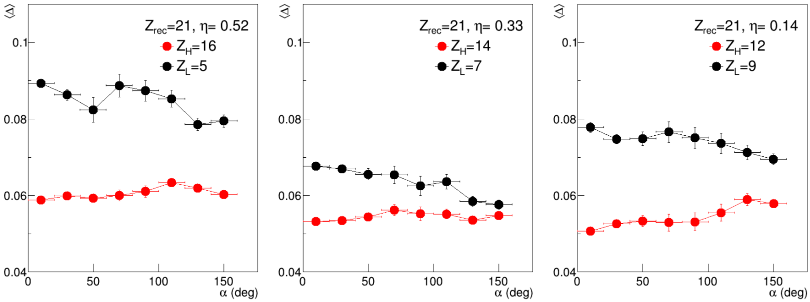


- However, no correlation between the α angle and $(t_{breakup} - t_{QP-QT})$ has been found in the framework of AMD

from S. Piantelli et al., PRC101, 034613 (2020)

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

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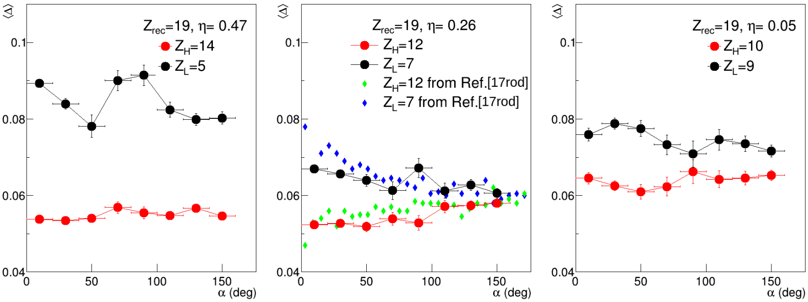

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- Within the small charge asymmetries explored, $\langle\Delta\rangle_L$ depends mostly on the identity of the LF, and less on the partner HF
- Results for $Z_H = 12, Z_L = 7$ are quite comparable to A. Rodriguez Manso et al., PRC95, 044604 (2017)