Seminaria Oddziału II
IFJ-PAN, Kraków, Poland

Systematic analysis of nuclear reactions with a neutron rich projectile on multiple targets at intermediate energies

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Overview

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Nuclear Equation of State

Isospin transport

FAZIA detector

Particle identification

FAZIA-PRE experiment

FAZIA-PRE data analysis

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HIPSE simulations

Data comparison

Intermediate Energy Heavy-Ion Collisions

Intermediate Energy Heavy-Ion Collisions

→The energy dissipation w.r.t. relative velocity (v_{rel}) b/w the initial partners in any nuclear reaction can be linked to a wavelength,

$$\lambdabar = \frac{\lambda}{2\pi} = \frac{\hbar}{m_u v_{rel}}$$

→If order of $\lambdabar$ exceeds the mean nucleon-nucleon distance (~ 2 fm), the reaction corresponds to low energy regime (Beam energy, E_B< 20 MeV/A).

→If order $\lambdabar$ is shorter than the mean n-n distance, the reaction falls into the high energy regime (E_B> 100 MeV/A).

→When order of $\lambdabar$ is comparable to the mean n-n distance, the reaction falls in the intermediate or Fermi energy range, (20 < E_B< 100 MeV/A).

→ Interaction time related to relative velocity

$$\tau_{\text{interaction}} \propto 1 / v_{\text{rel}}$$

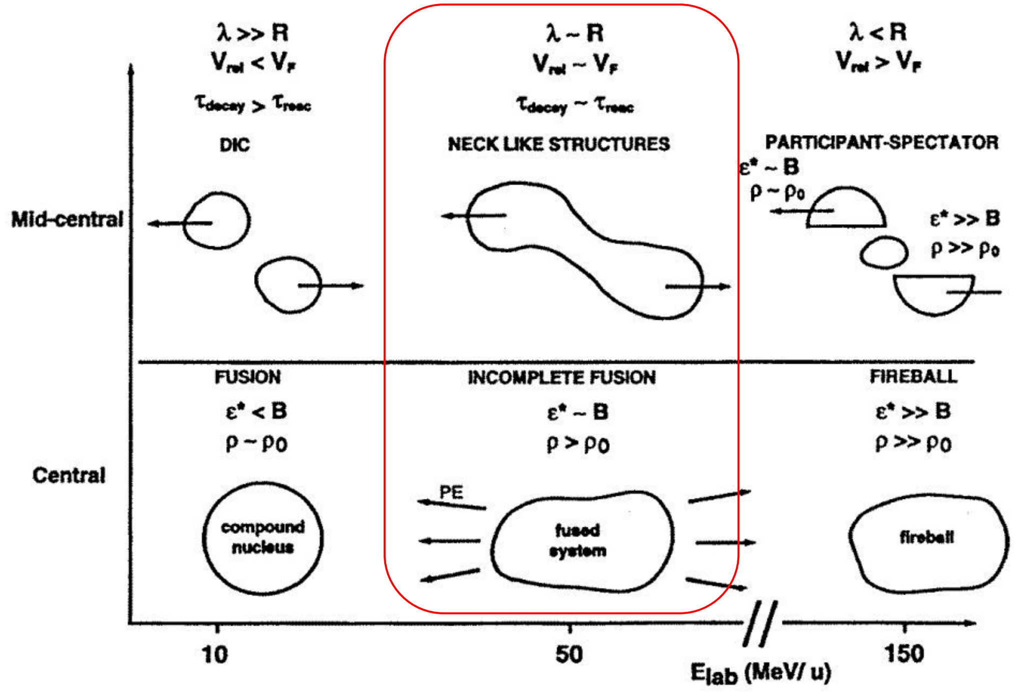
→ Interaction time comparable to thermalisation time

$$\tau_{\text{interaction}} \sim \tau_{\text{thermalisation}}$$

→ 2 situations:

Thermalised → Formation of primary fragments

Non-thermalised → Pre-equilibrium emissions

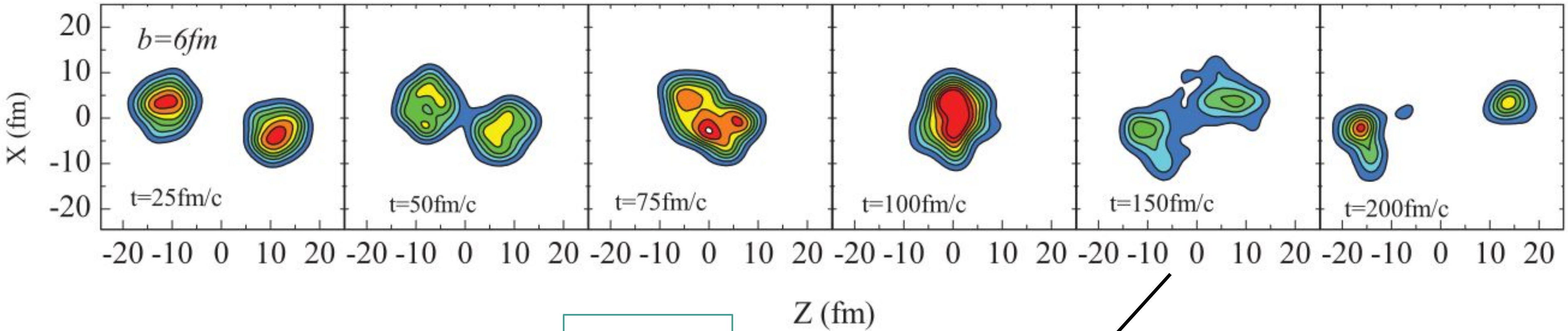


Intermediate Energy Heavy-Ion Collisions

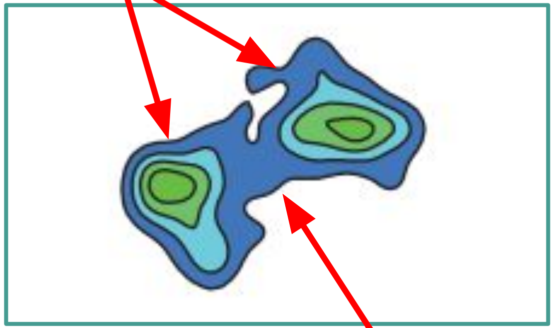
Peripheral collisions

^{124}Sn + ^{124}Sn collisions at 50 MeV/A

Yingxun Zhang *et. al.*, *Physical Review C* **85**, 024602 (2012)



QT and QP



Neck Region

Intermediate Energy Heavy-Ion Collisions

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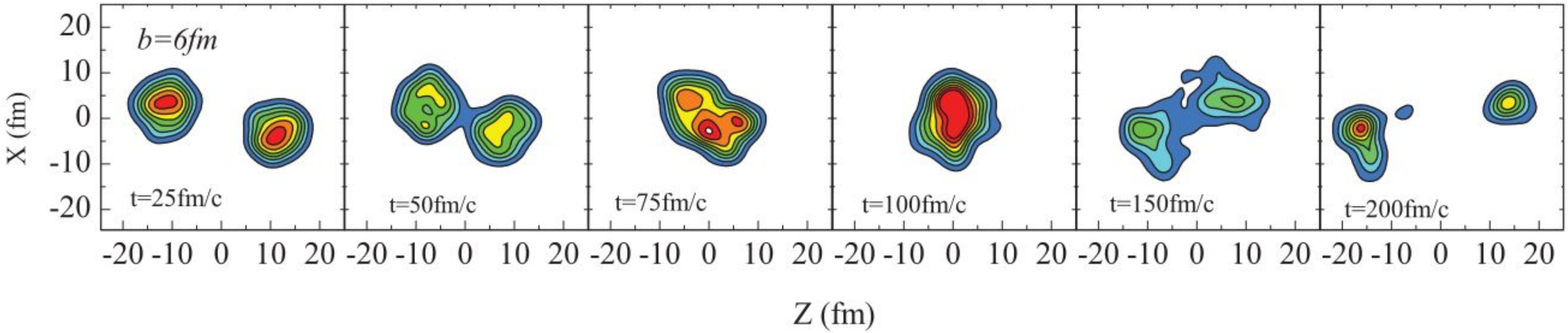
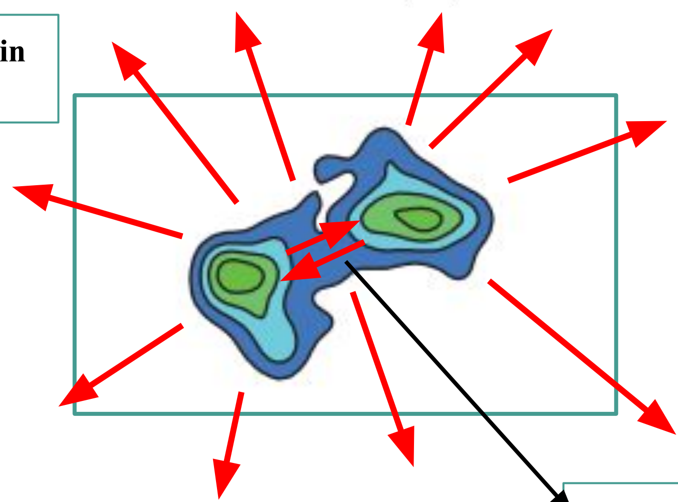


Fragment emission in all directions



Nucleon exchange in neck region

Nuclear Equation of State

Nuclear Equation of State

→ The nuclear Equation of State (EoS) describes relation between energy, temperature, nuclear density and neutron-proton (N/Z) ratios (isospin).

→ Staring with the Liquid Drop Model, the Bethe-Weizsacker formula for binding energy,

$$B.E. = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} \pm \delta(A, Z)$$

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Volume Energy Term

Surface Energy Term

Asymmetry Energy Term

Coulomb Energy Term

Pairing Term

Nuclear Equation of State

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where, A=N+Z is the mass number and a_V , a_S , a_C and a_A are coefficients.

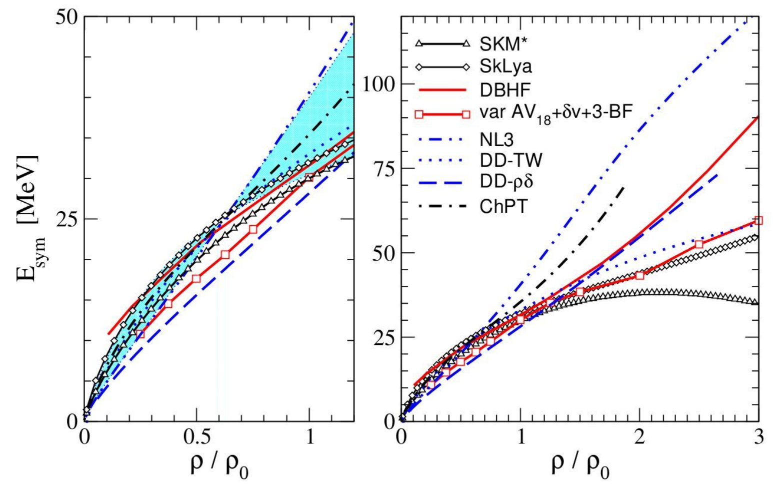
→ **Valid for a system at zero temperature and nuclear saturation density (~0.16 fm^{-3}).**

→ **For asymmetric nuclear matter, the binding energy can be written as a function of neutron and proton densities (ρ_n, ρ_p),**

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

$$E_{sym}(\rho) = \frac{1}{2} \frac{\partial^2 E(\rho, I)}{\partial I^2}\bigg|_{I=0}$$

where, $\rho = \rho_n + \rho_p$ is the nucleonic density, I = $(\rho_n - \rho_p)/\rho$ is the isospin asymmetry and E_{sym} is the symmetry energy.



Symmetry energy as a function of density as predicted by different models. The left panel shows the low density region while the right panel displays the high density range. ρ_0 → saturation density (~0.16 fm^{-3})

Nuclear Equation of State

Importance of studying E_{sym} :

→ Taylor series expansion of E_{sym} around ρ_0 ,

$$E_{sym}(\rho) = E_{sym}(\rho_0) - L\epsilon + 1/2K_{sym}\epsilon^2 + O[\epsilon^3]$$

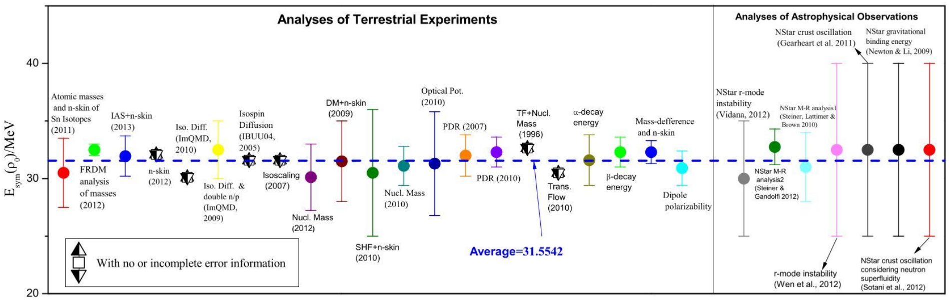
where $\epsilon \equiv (\rho_0 - \rho)/3\rho_0$, L and K_{sym} are the slope and curvature at ρ_0.

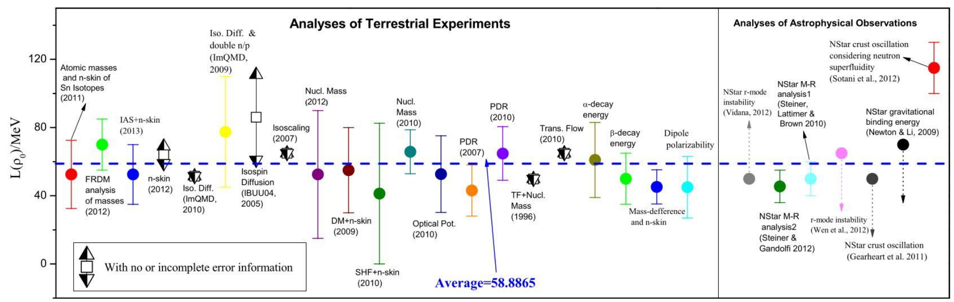
→ The slope L provides a link to the astrophysical regime as,

$$L = 3\rho_0 \frac{dE_{sym}(\rho)}{d\rho}\bigg|_{\rho_0} = \frac{3P_0}{\rho_0}$$

where P_0 is the pressure from E_{sym} in pure neutron matter and also contributes to the pressure in a neutron star.

→ There have been multiple terrestrial and astrophysical experiments to estimate L (59 ± 17 MeV) and E_{sym} (31.6 ± 0.9 MeV).





Nuclear Equation of State

→ The density dependence of the E_{sym} can be visualised by using, for example, the stochastic mean-field (SMF) transport approach. The E_{sym} can be written as a sum of its kinetic and potential parts as,

$$E_{sym} = E_{sym}(kinetic) + E_{sym}(potential)$$

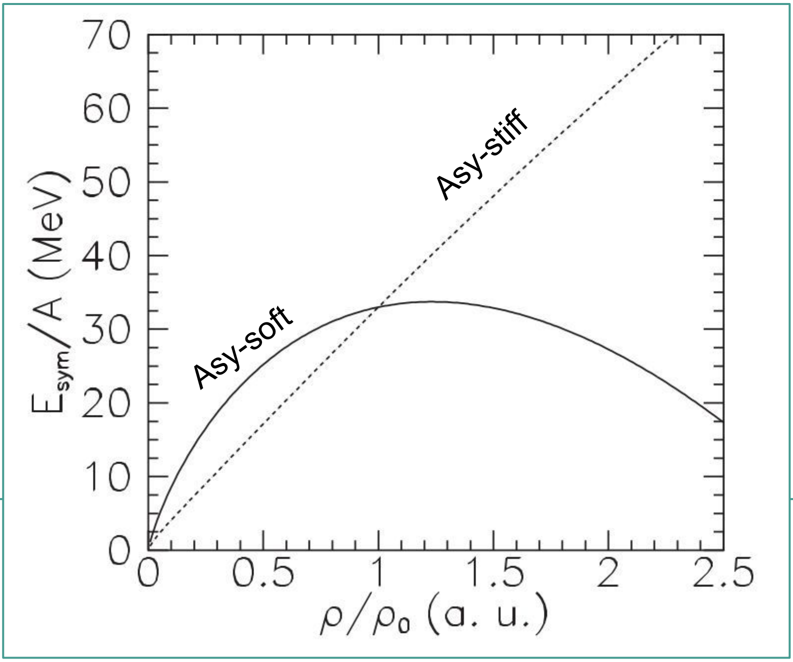
→ There are three different density parametrizations of the symmetry potentials:

- strong density dependence ($\propto \rho^2$) − Asy-superstiff
- linear dependence on density − Asy-stiff
- weaker density dependence with saturation around ρ_0 and further decreasing − Asy-soft

→ E_{sym} is larger for Asy-soft case below ρ_0.

→ Thus, isospin effects will be greater in Asy-soft case at sub-normal densities.

! This is also the region of concern for our research work !



Isospin Transport

Isospin Transport

Nucleon current relation:

$$\boldsymbol{j}_\mathrm{n} - \boldsymbol{j}_\mathrm{p} = (D_\mathrm{n}^{\rho} - D_\mathrm{p}^{\rho})\,\nabla\rho - (D_\mathrm{n}^{I} - D_\mathrm{p}^{I})\,\nabla I$$

$D^{\rho,\,I}$ → **transport coefficients**

$\rho = \rho_\mathrm{n} + \rho_\mathrm{p}$ → **nucleon density**

$I = (\rho_\mathrm{n} - \rho_\mathrm{p}) / \rho$ → **isospin asymmetry**

First term → Isospin drift: Nucleon movement in density gradient ($\nabla\rho$)

Second term → Isospin diffusion: Nucleon movement in isospin gradient (∇I)

D^{ρ} **and** D^{I} **are related to the symmetry energy term (E_{sym}) of the nuclear equation of state (EoS)**

$$D_n^{\rho} - D_p^{\rho} = 4I\frac{\partial E_{sym}}{\partial\rho} \qquad\qquad D_n^{I} - D_p^{I} = 4\rho E_{sym}$$

Isospin drift and diffusion phenomena are collectively called "isospin transport"

The isospin (N/Z) equilibration of the system is governed by the isospin transport with the help of E_{sym}

The degree of isospin equilibration can be calculated from the isospin transport ratio:

$$R_i = \frac{2X_i^M - X_i^H - X_i^L}{X_i^H - X_i^L} \qquad\qquad (\,X \rightarrow \langle N\rangle/Z\,)$$

Asymmetric nuclear matter (N/Z≠1) with large N/Z can be used to study the isospin transport phenomena

Isospin transport and E_{sym} can be studied to put constraints on the nuclear EoS which is not well understood far from ground state

FAZIA Detector

FAZIA Detector

→ FAZIA (Forward-angle A & Z Identification Array) is a charged particle multi-detector with an excellent mass resolution

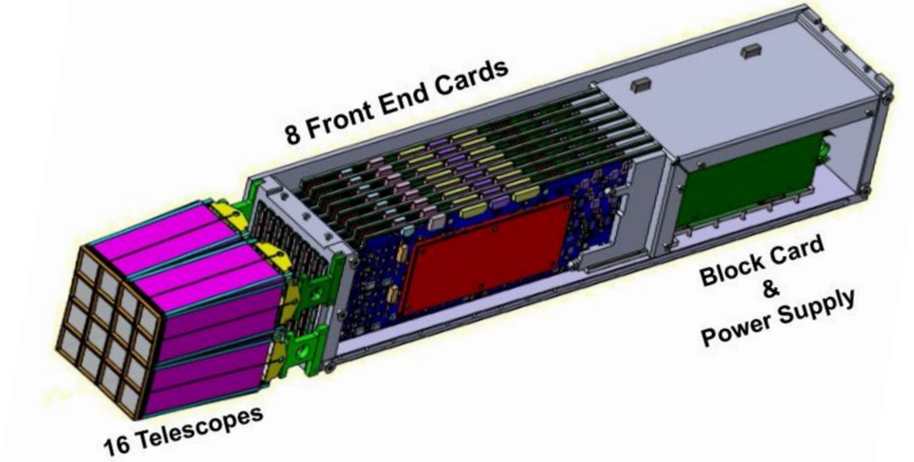
→ Basic detection module of FAZIA is called a FAZIA Block

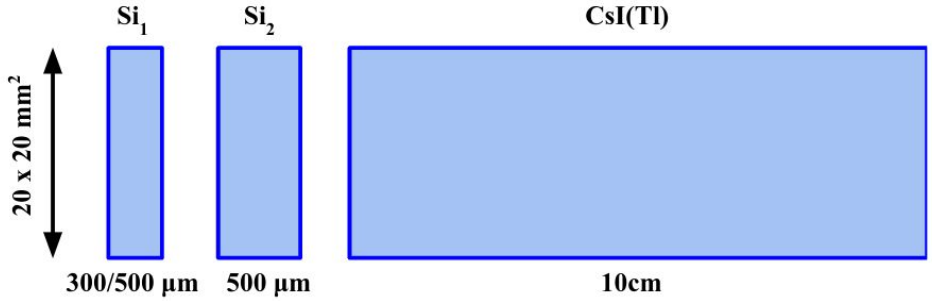
→ Block consists of 16 detection telescopes, each made of two Si layers (300/500 µm and 500 µm) and one CsI scintillator (10 cm)

→ Si-Si-CsI telescopes have 2x2 cm^2 active area and a block covers 0.01 sr at 1 m from target

→ Two telescopes connected to one front-end electronics (FEE) card each - total 8 FEE cards.

→ Block card for output to data acquisition system and input for power supply





→ FAZIA collaboration improved the charged particle identification techniques and the detector is now capable to identify charged particles with mass (A) resolution up to charge (Z) ~ 20.

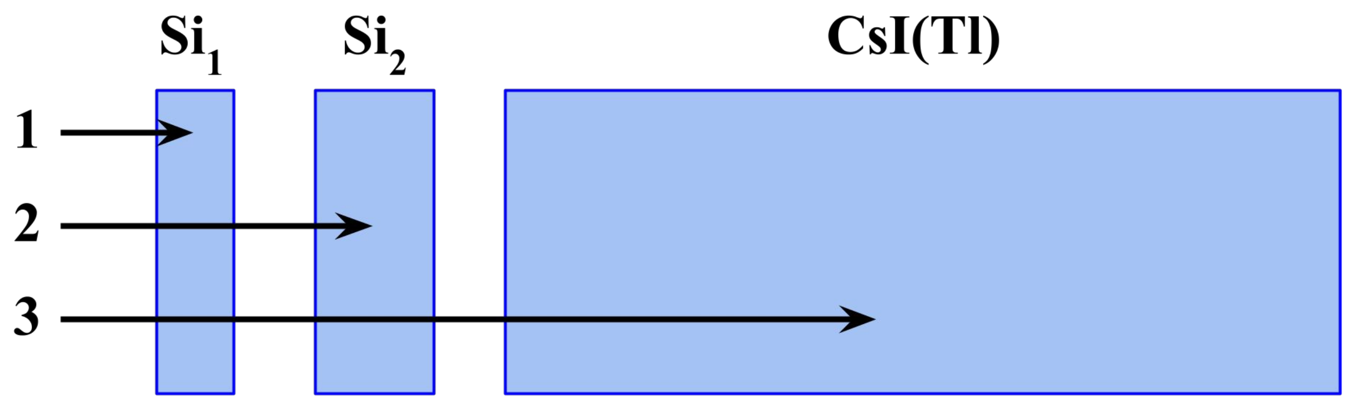
→ There is no neutron (N) identification with the detector.

→ N can be calculated using N = A-Z up to the A identification limit.

→ N/Z can then be further studied !

Particle Identification

Particle Identification

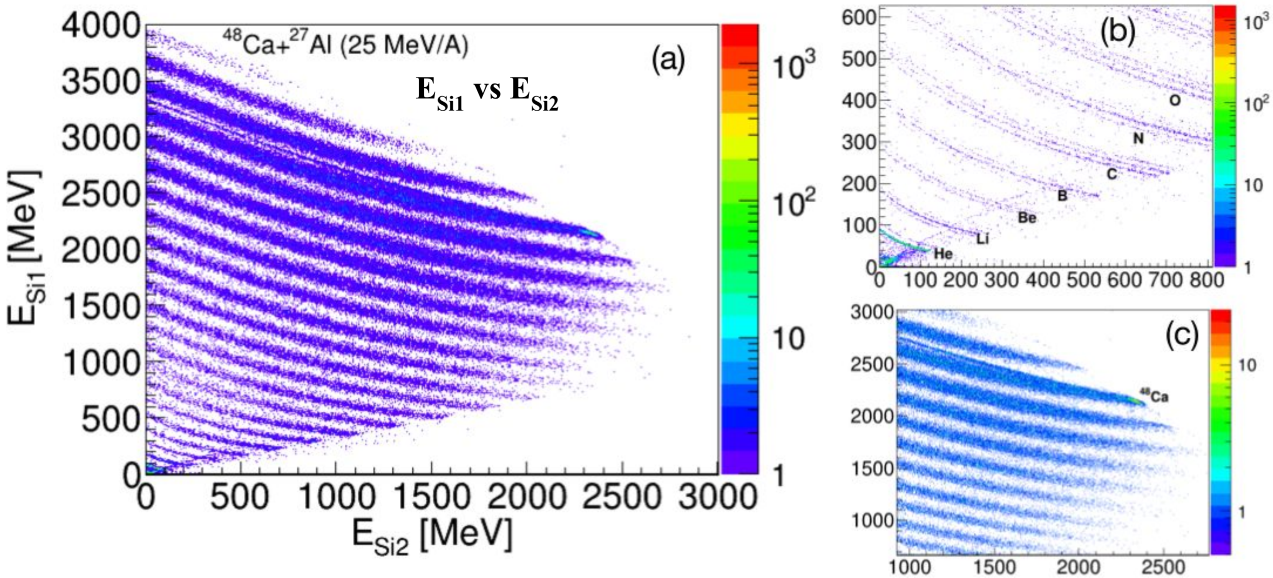


There can be 3 scenarios for a charged particle entering the detector telescope:

1. The particle stops in Si_1
2. The particle deposits a fraction of energy in Si_1 and stops in Si_2
3. The particle deposits fractions of energy in Si_1 and Si_2 and stops in CsI

Particle Identification

ΔE-E Method



From Bethe-Bloch formula,

$$-\frac{dE}{dx} \propto \frac{Z^2}{v^2} \propto \frac{Z^2 A}{E}$$

Energy loss in thickness *t*

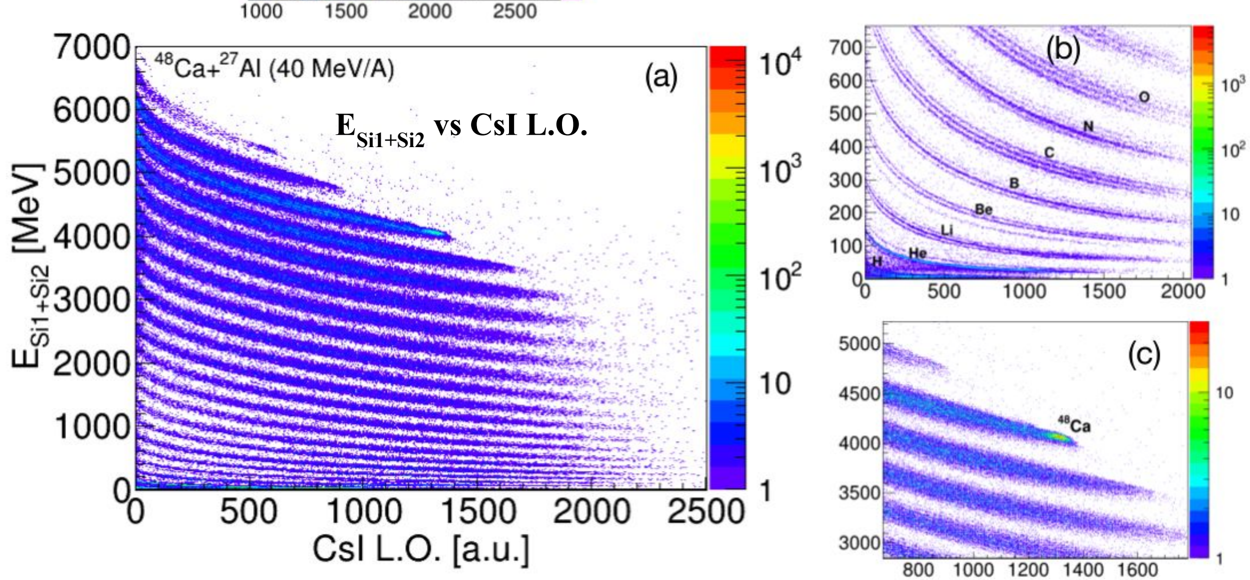
$$\Delta E = -\frac{dE}{dx}t \quad or, \quad \Delta E = C\frac{z^2 A}{E}t$$

Remaining energy, E_r

$$E_r = E - \Delta E$$

or,

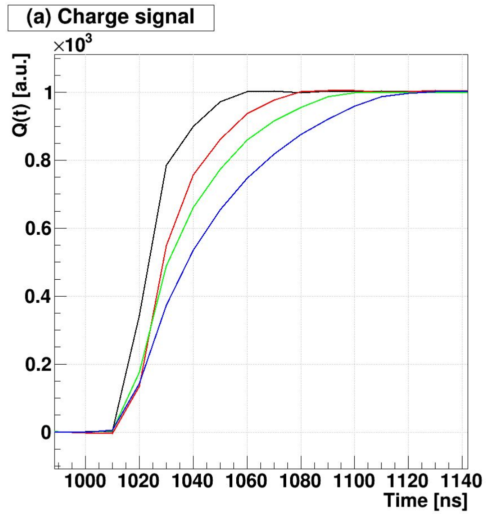
$$E_r = C\frac{z^2 A}{\Delta E}t - \Delta E$$

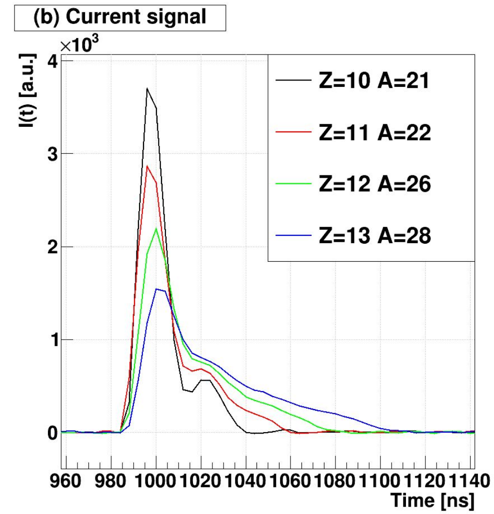


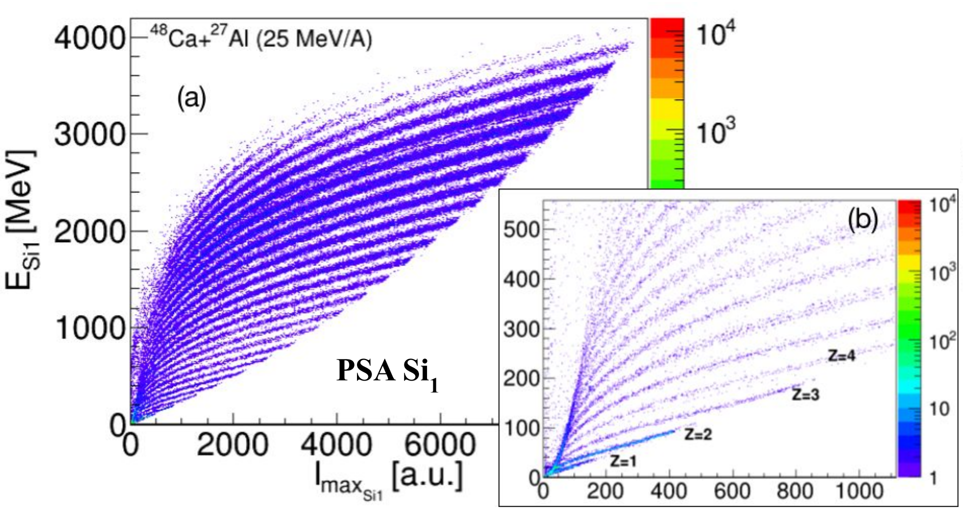
Particle Identification

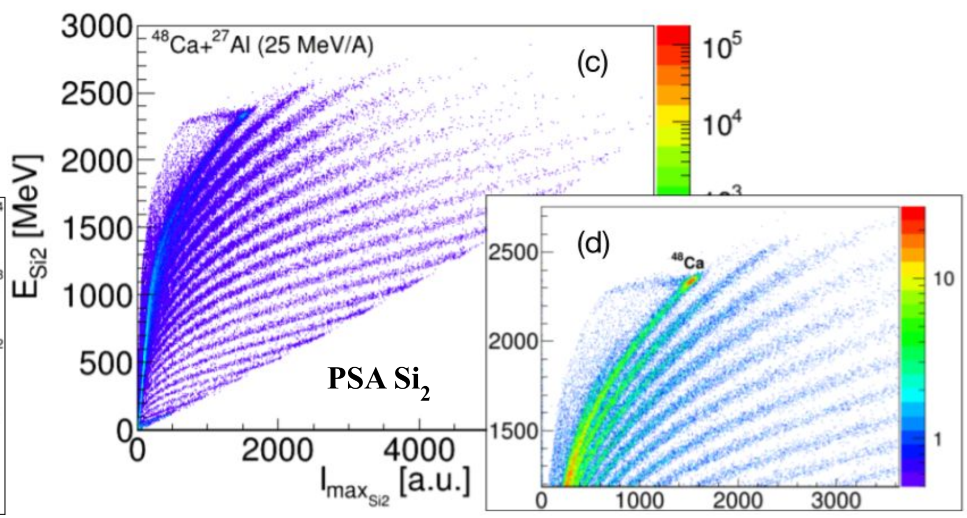
Pulse-Shape Analysis

Si PSA

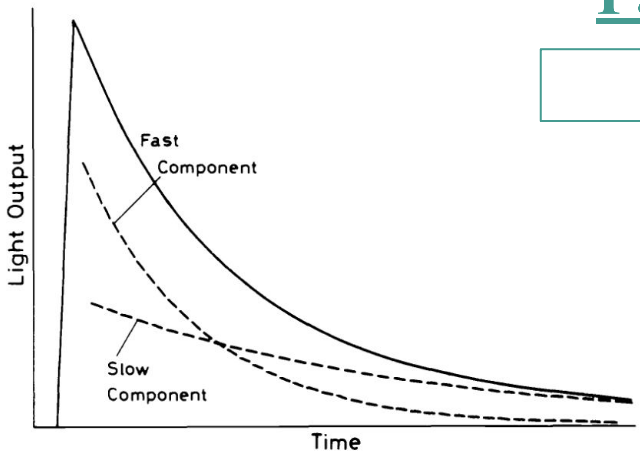








Particle Identification



Pulse-Shape Analysis

CsI PSA

Light pulse decay,

$$I(t) = ae^{t/\tau_f} + be^{t/\tau_s}$$

τ_f, τ_s → **fast/slow time constants**

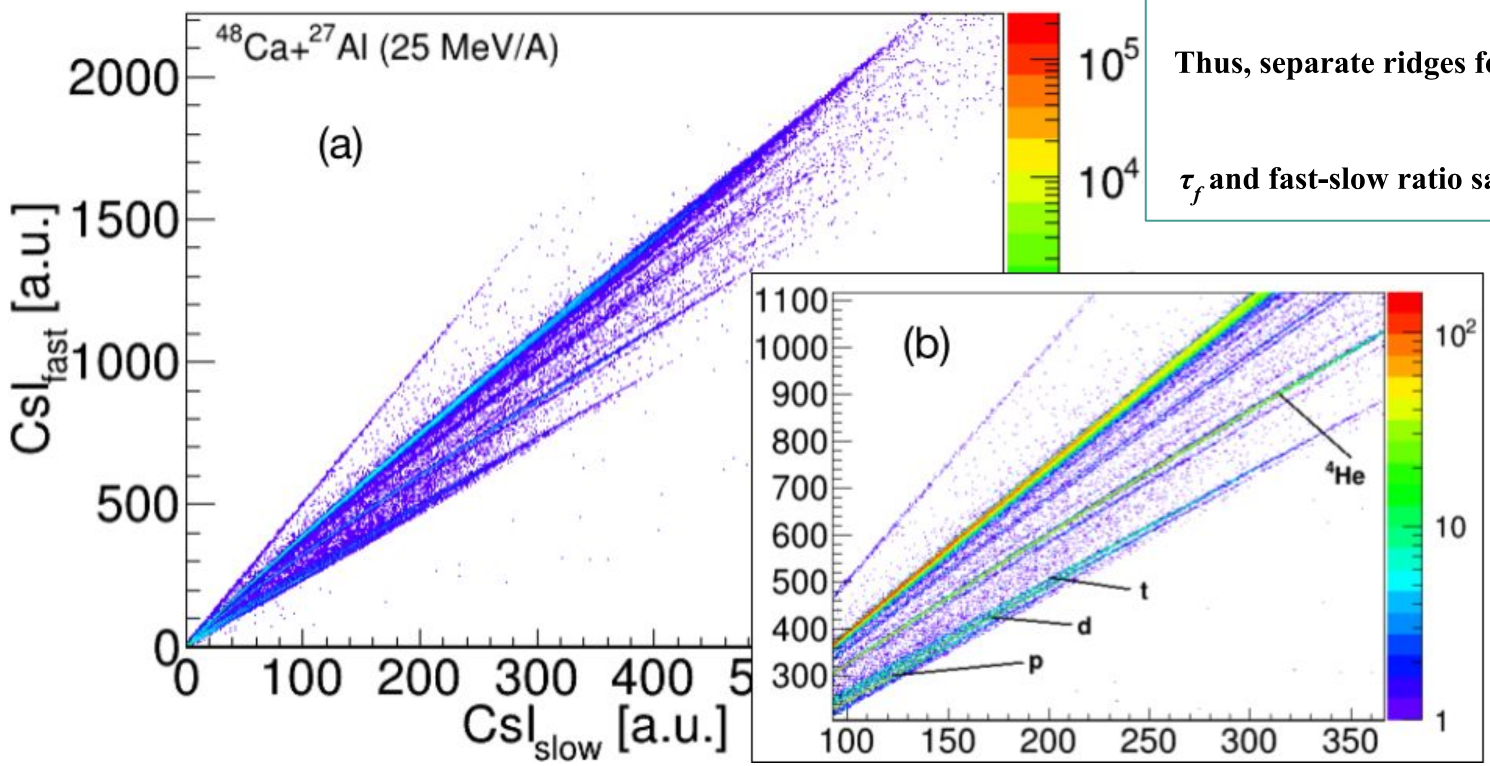
τ_s **~ 7 µs (constant)**

τ_f **~ 0.4 - 0.7 µs**

Dependent on Z, A and E of the particle

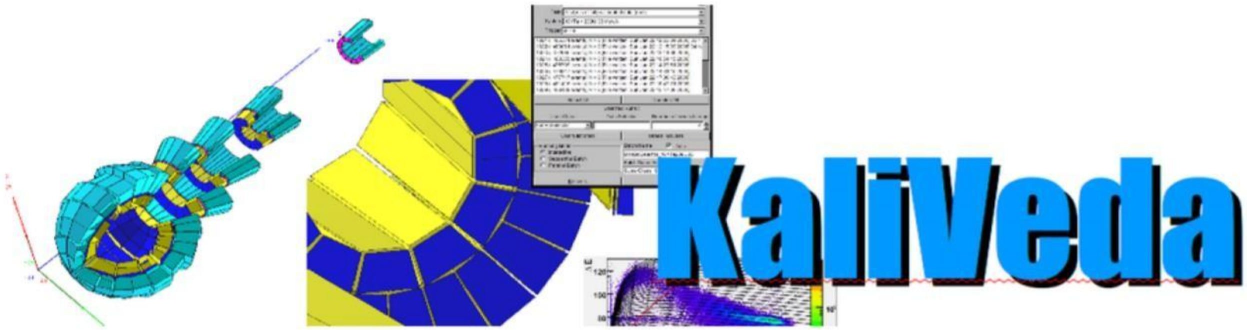
Thus, separate ridges for each isotope

τ_f **and fast-slow ratio saturates ~ Z>5**



Particle Identification

Identification procedure



- **Simulation & analysis of heavy-ion collision data in 5-100 MeV/nucleon energy range.**
- **C++ framework based on ROOT.**

1. NUCLEI & EVENTS Nuclei & events (collections of nuclei)

- **nuclear properties, reaction kinematics, systematics**

2. DETECTOR SIMULATION Detector simulation

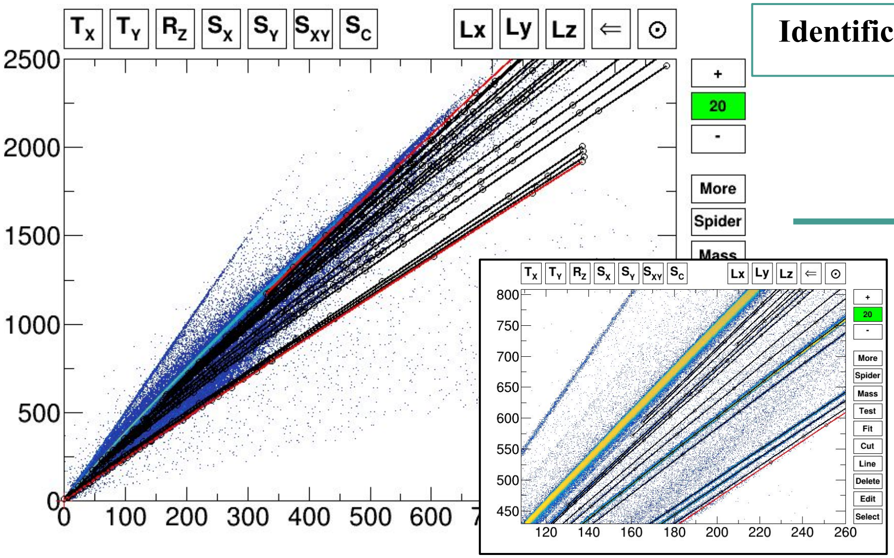
- **geometry, energy-loss calculations**

3. PARTICLE IDENTIFICATION Particle identification

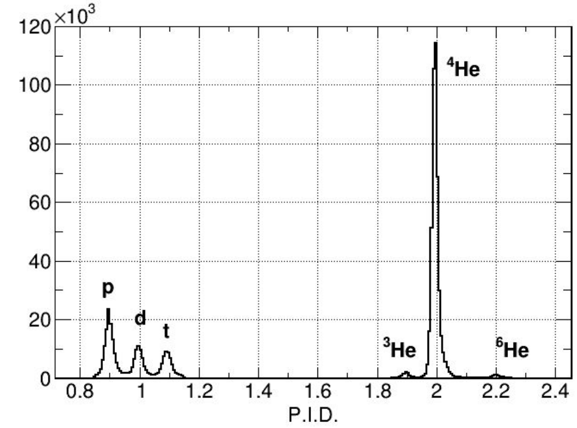
- **Z & A identification grids, semi-automatic identification**

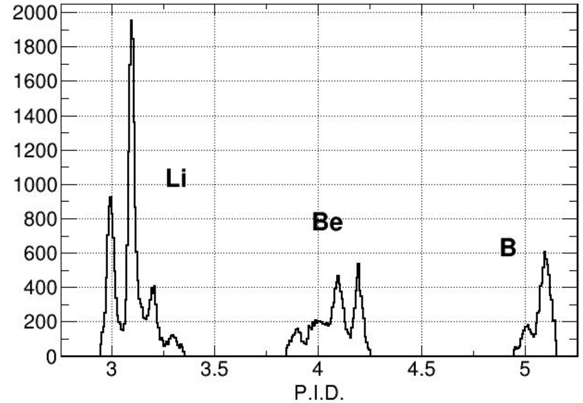
Particle Identification

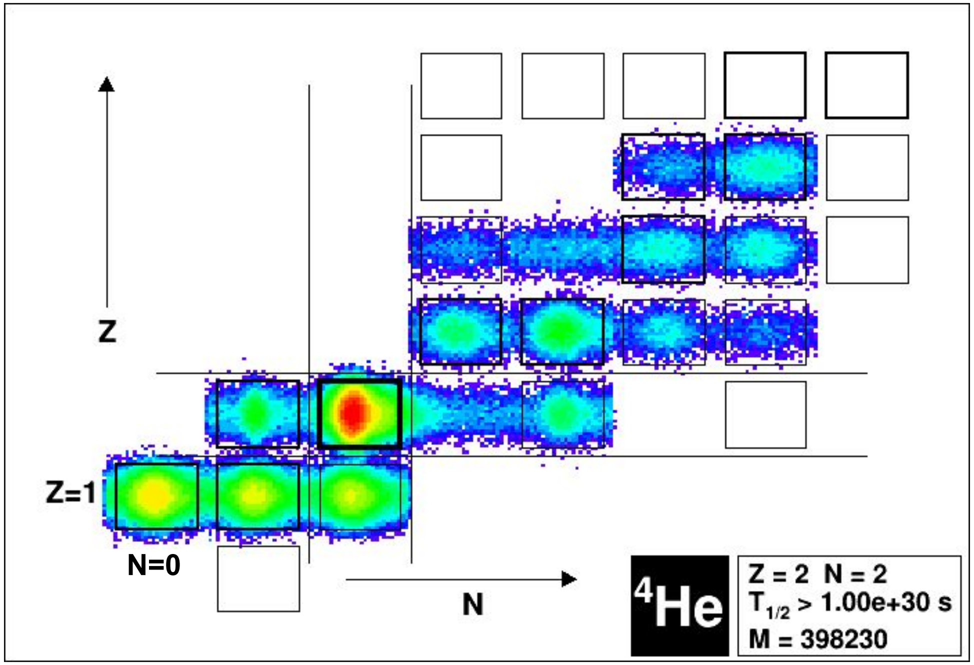
Identification procedure



Linearisation





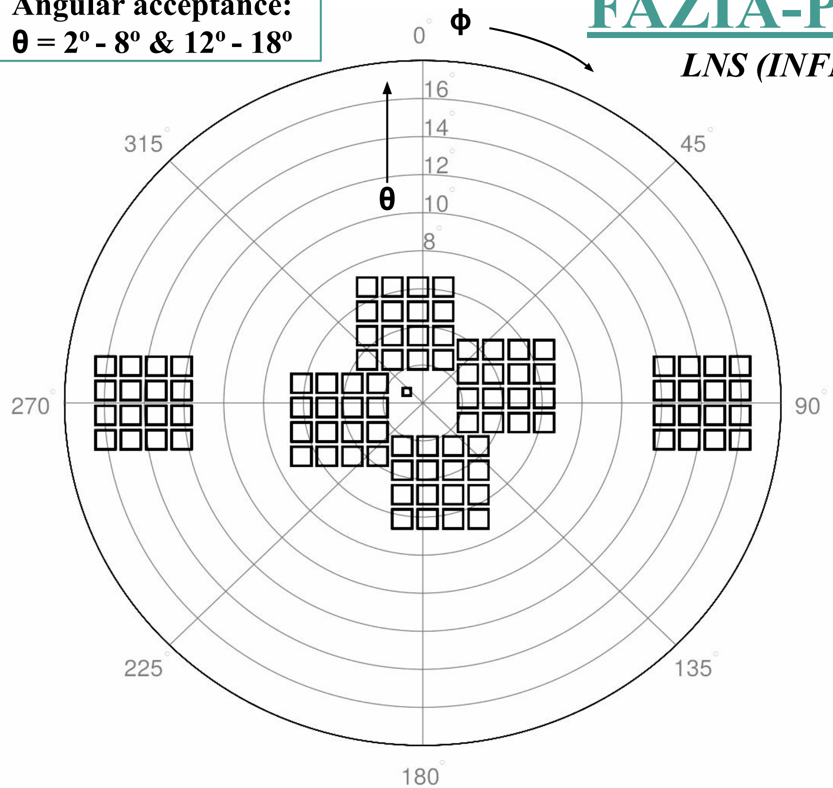


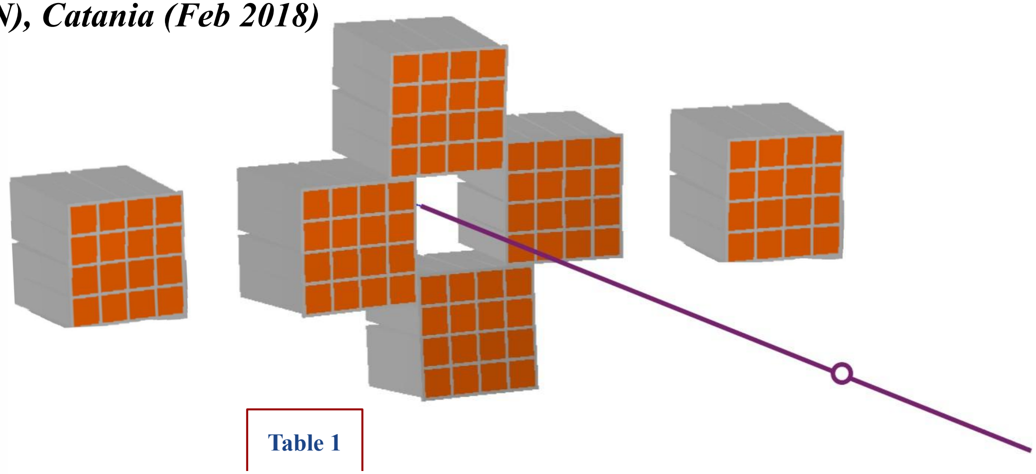
FAZIA-PRE experiment

FAZIA-PRE experiment

LNS (INFN), Catania (Feb 2018)

Angular acceptance:
θ = 2° - 8° & 12° - 18°





Goal:

Effects on fragment N/Z due to initial neutron abundance and pre-equilibrium neutron emission

Table 1

Projectile	$^{48}_{20}$Ca				
E_B [MeV/A]	25			40	
v_B [cm/ns]	6.81			8.51	
Target	$^{12}_{6}$C	$^{27}_{13}$Al	$^{40}_{20}$Ca	$^{12}_{6}$C	$^{27}_{13}$Al
t [μg/cm^2]	239	216	500	239	216
v_{CM} [cm/ns]	5.48	4.4	3.76	6.87	5.53
E^{av}_{CM} [MeV/A]	3.99	5.74	6.18	6.38	9.17
θ_{gr}	0.89°	1.81°	2.69°	0.55°	1.12°

→ **Table 1: Experimental details of FAZIA-PRE experiment: beam energy (E_B), beam velocity (v_B), target thickness (t), centre-of-mass velocity (v_{CM}), available energy in CM (E_{CM}^{av}) & grazing angle (θ_{gr})**

→ **Table 2: N/Z of individual nuclei present in the experiment.**

→ **Table 3: Total N/Z of each reaction system in the experiment.**

Table 2

Nucleus	N/Z
^{48}Ca	1.4
^{12}C	1.0
^{27}Al	1.07
^{40}Ca	1.0

Table 3

System	N/Z total
^{48}Ca+^{12}C	1.31
^{48}Ca+^{27}Al	1.27
^{48}Ca+^{40}Ca	1.2

Aim of research

→ Analyse the FAZIA-PRE data w.r.t. target mass and beam energy for basic reaction observables such as charge (Z), mass (A), multiplicity of charged particles (M_{tot}) and parallel velocity ($v_{||}$) and the isospin observable, $\langle N \rangle/Z$.

→ Compare the observations of experimental data with HIPSE event generator to determine whether HIPSE can be used to study isospin physics.

FAZIA-PRE Data Analysis

FAZIA-PRE Data Analysis

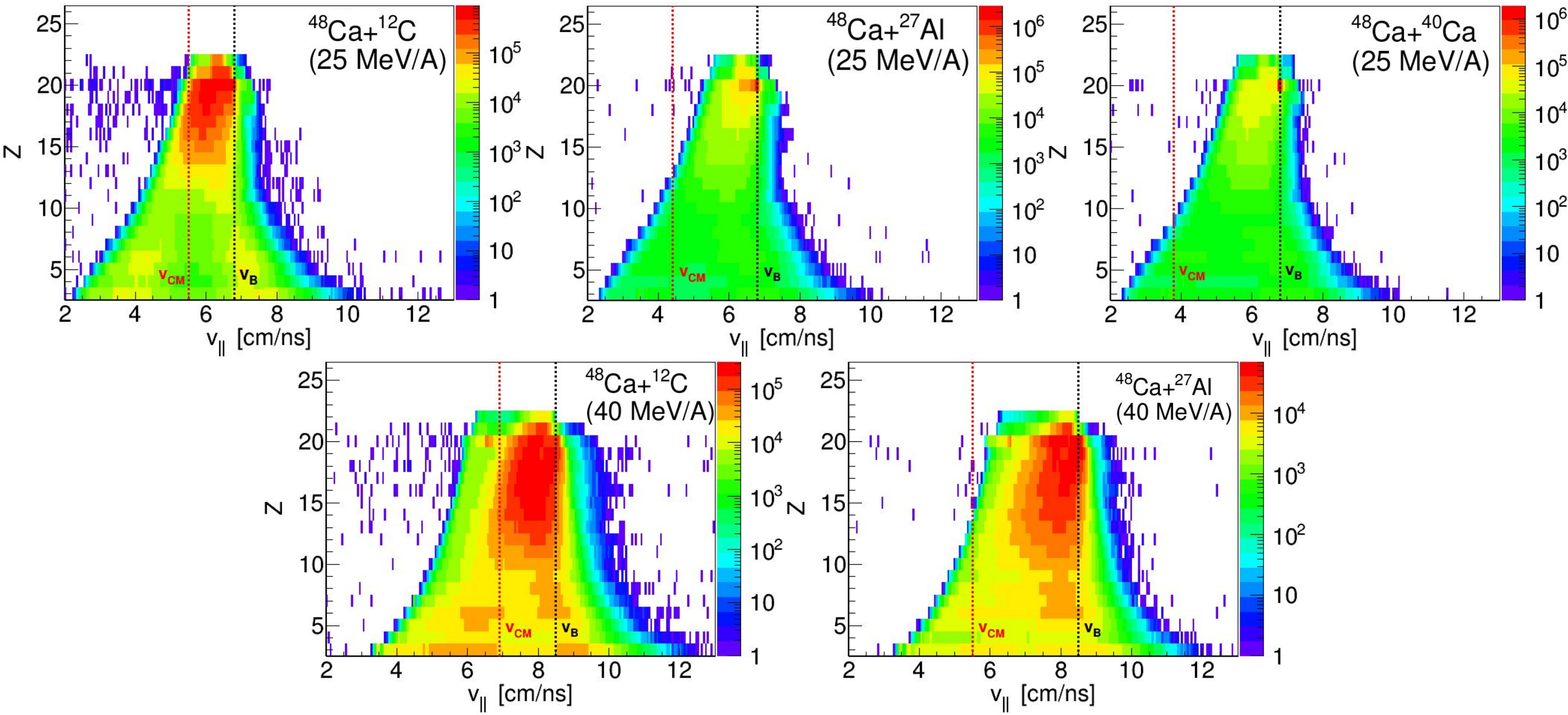
Forward angle acceptance

Only QP detected (~Z=20)

Few pre-equilibrium and neck emission also

No QT detection

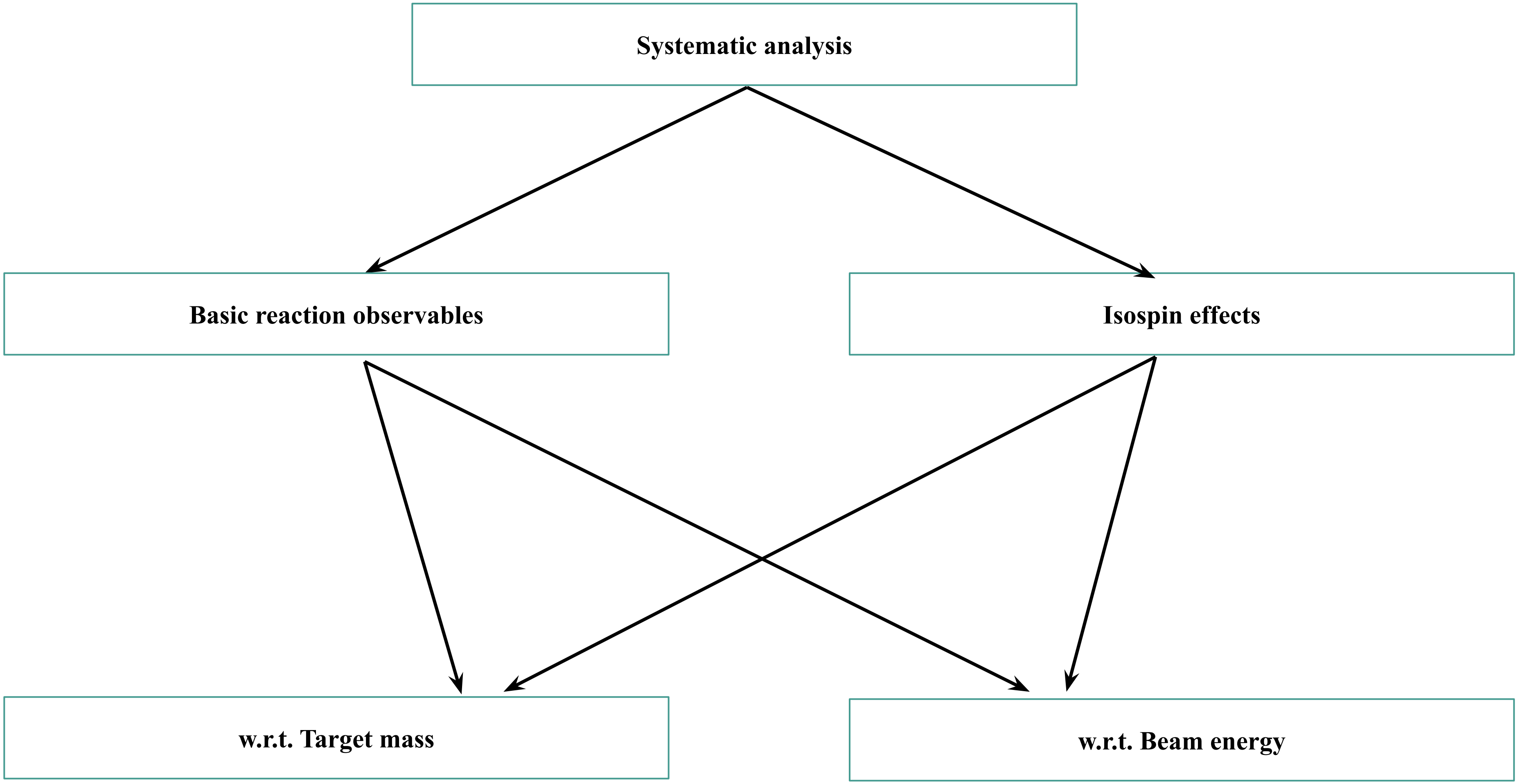
QT remains in the transverse plane



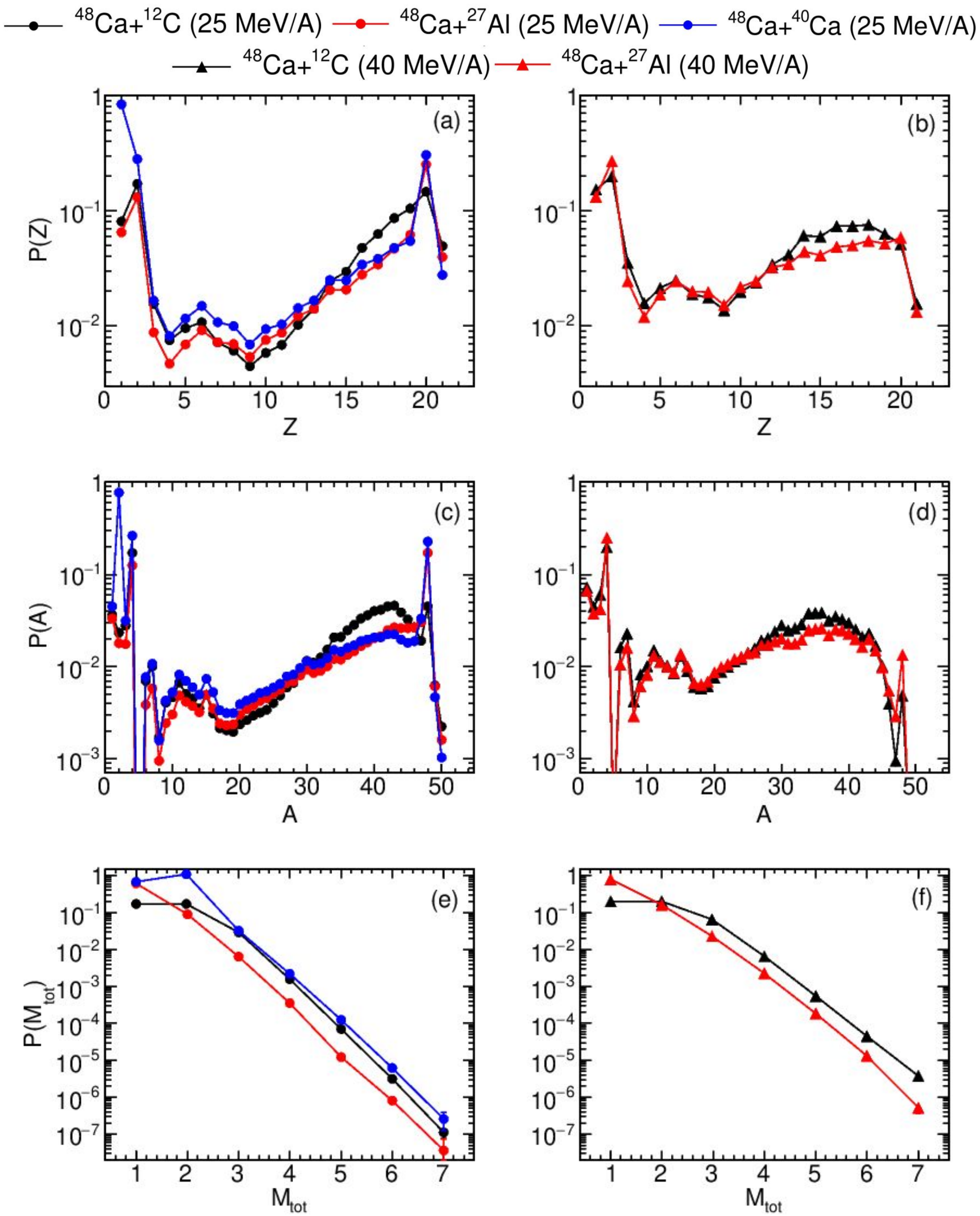
Z vs $v_{||}$ correlation, beam velocities v_B (black dashed lines) and centre-of-mass velocities v_{CM} (red dashed lines) are marked

The identification limit of FAZIA (Z~20) is sufficient to study full range of fragments here: projectile at Z=20 ($^{48}_{20}Ca$)

FAZIA-PRE Data Analysis



FAZIA-PRE Data Analysis



Basic Reaction Observables → w.r.t. Target Mass

→For $Z \lesssim 15$ ($A \lesssim 30$):

Z & A relative yield increases with target mass

Increasing fragmentation with increasing target mass due to increased number of nucleons

→For $Z \gtrsim 15$ ($A \gtrsim 30$):

Increase in PLFs and heavier fragment detection with due to increasing elastic scattering events (increasing θ_{gr})

→ For $M_{tot} = 1$:

Relative yield should also increase with target mass for same reason

→ For all data:

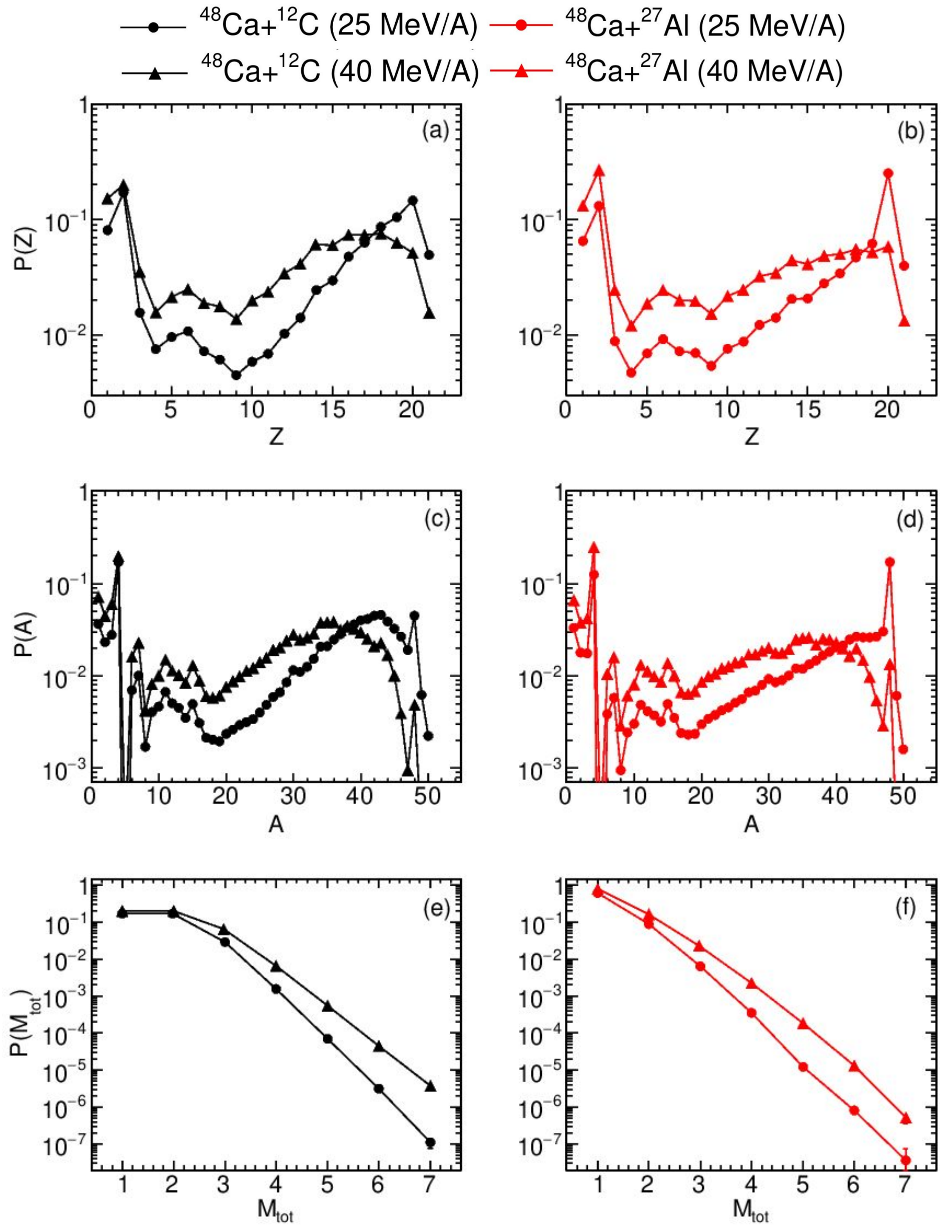
^{27}Al target data has lower relative yield for $Z \lesssim 6$, $A \lesssim 15$ and $M_{tot} > 1$

Possible explanation from *M. Wang et al.,CPC (HEP & NP), 2012,* ***36****(12): 1603–201430* **:**

^{27}Al has lowest n and p separation energies

Light fragments escape in all directions before reaching the detector placed at forward angles

FAZIA-PRE Data Analysis



Basic Reaction Observables → w.r.t. Beam Energy

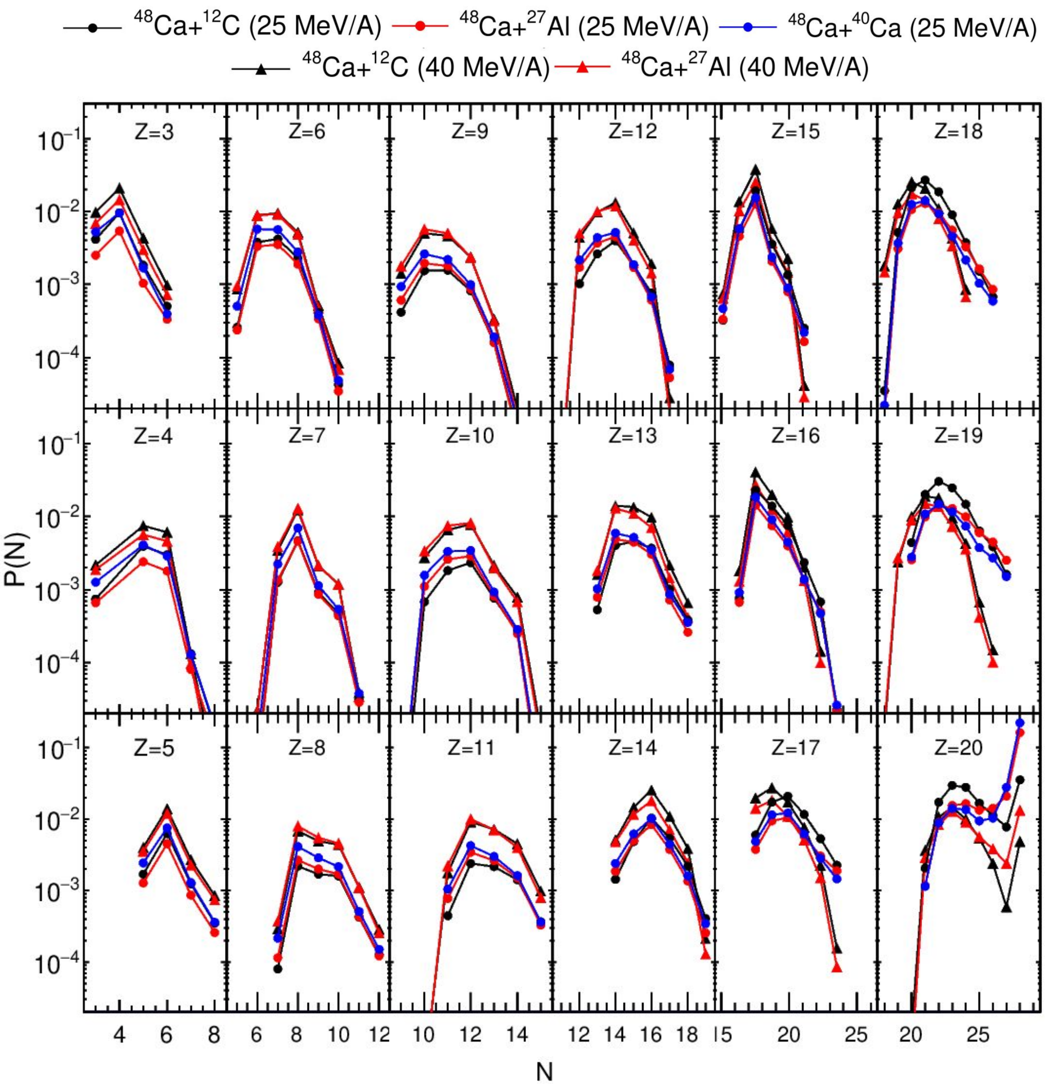
→ More projectile-like-fragments (Z~20) at 25 MeV/A due to dominance of elastic scattering

→ Increased abundance of fragments (Z<20 / A<40) shows dominance of multi-fragmentation at higher beam energy (40 MeV/A)

→ Multifragmentation increases the total charged particle multiplicity, thus 40 MeV/A systems have higher M_{tot}

FAZIA-PRE Data Analysis

Isospin effects



→ **N distribution using N = A - Z**

→ **The trends are similar to the A and Z distributions**

→ **The relative yield of neutrons increases with increasing target mass: more dissipative collisions with increasing target mass.**

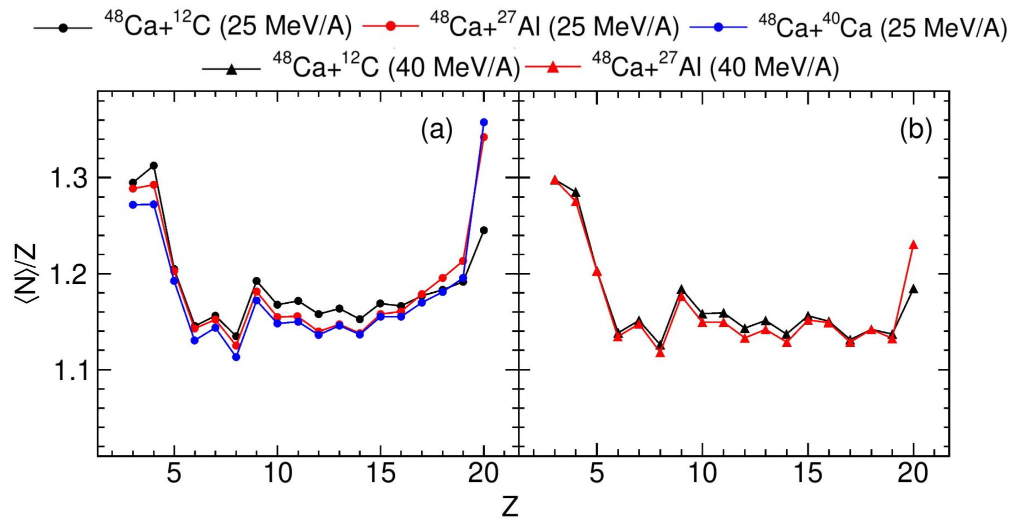
→ **Systems at 40 MeV/A have higher relative yield than systems at 25 MeV/A up to Z~16 and lesser for Z>16, as one approaches projectile Z (here, = 20): increased multi-fragmentation at higher beam energy.**

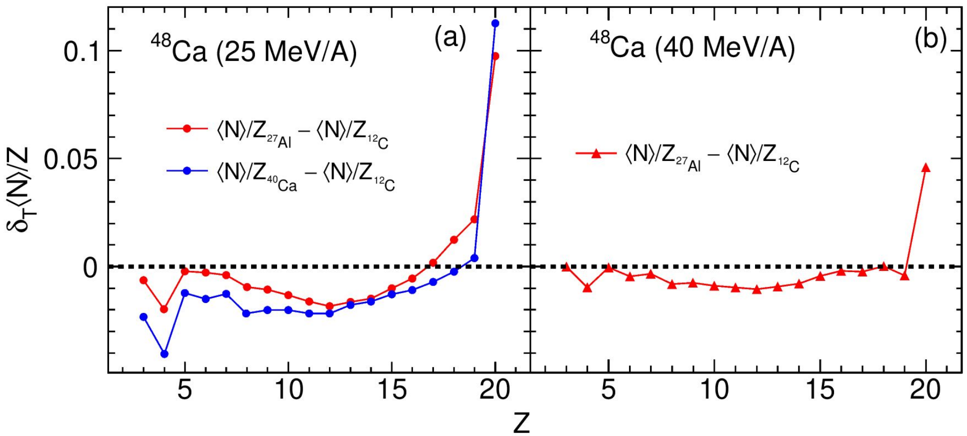
→ **For Z ≤ 6, relative yield of ^{27}Al target systems is the least at both beam energies due to its lowest proton and neutron separation energies.**

→ **For Z=20, the relative yield is highest for all systems at N=28, showing the presence of projectile-like fragments (PLFs).**

FAZIA-PRE Data Analysis

Isospin Effects → w.r.t. Target Mass





→ ⟨N⟩/Z plotted from N distributions as a function of Z

→ The range of fragment ⟨N⟩/Z stays between that of projectile and target

→ The fragment ⟨N⟩/Z observed to be decreasing with increasing target mass: with increasing target mass, more dissipative collisions lead to higher rate of isospin equilibration, decreasing the fragment ⟨N⟩/Z

→ Checking the difference between ⟨N⟩/Z of different target systems confirms the observation

→ Also confirmed from total N/Z of systems

System	N/Z total
^{48}Ca+^{12}C	1.31
^{48}Ca+^{27}Al	1.27
^{48}Ca+^{40}Ca	1.2

FAZIA-PRE Data Analysis

Isospin Effects → w.r.t. Beam Energy

→ **For beam energy dependence, the difference between fragment ⟨N⟩/Z from 25 and 40 MeV/A systems was taken:**

$$\delta_E\langle N\rangle/Z = \langle N\rangle/Z_{25} - \langle N\rangle/Z_{40}$$

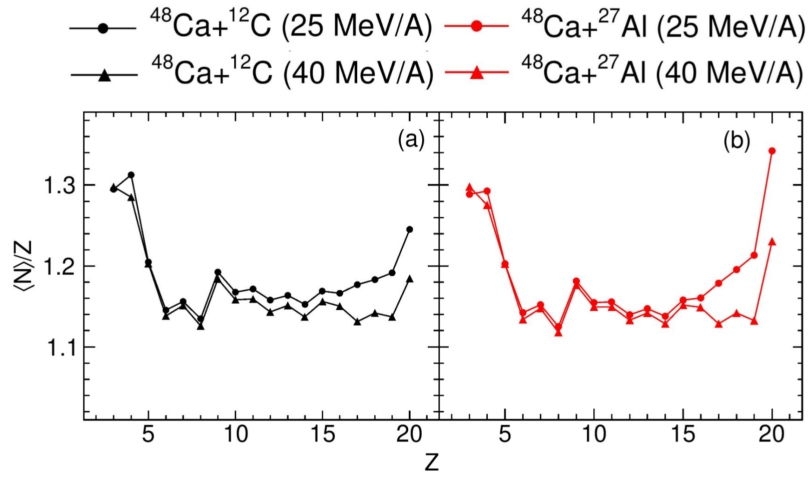
→ **Expected → interaction time and nucleon exchange between the participants reduces with increasing beam energy. Thus, an N-rich projectile should produce QP fragments with relatively higher ⟨N⟩/Z at higher beam energy.**

→ **Observed → the $\delta_E\langle N\rangle/Z$ is positive for almost all Z: the fragment ⟨N⟩/Z decreases with increasing beam energy.**

→ **Explanation from** Phys. Rev. C **55**, 1900 (1997)**:**

Rate of charged particle pre-equilibrium emission saturates at $E_B \sim 20$ MeV/A. But pre-equilibrium neutron emission increases with beam energy, thus decreasing overall N/Z of the system and consequently the fragment ⟨N⟩/Z.

→ **⟨N⟩/Z also reduces as a consequence of secondary decays following the isospin equilibration**



FAZIA-PRE Data Analysis

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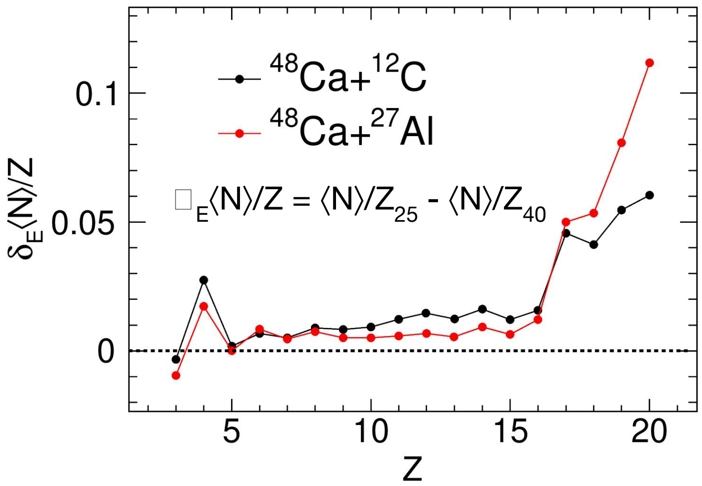
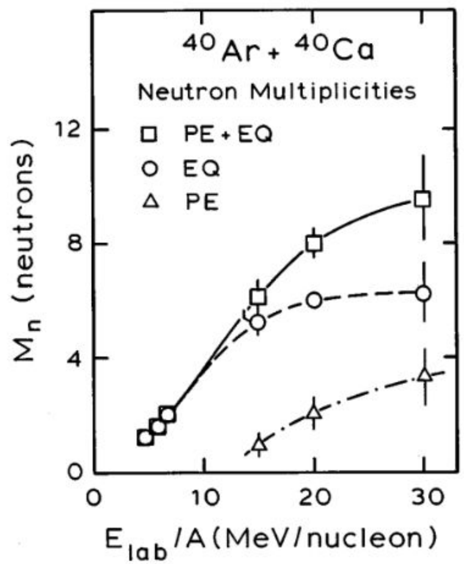


Phys. Rev. C **55**, 1900 (1997)



FAZIA-PRE Data Analysis

Isospin effects

Looking for Pre-equilibrium and Neck Emission contributions

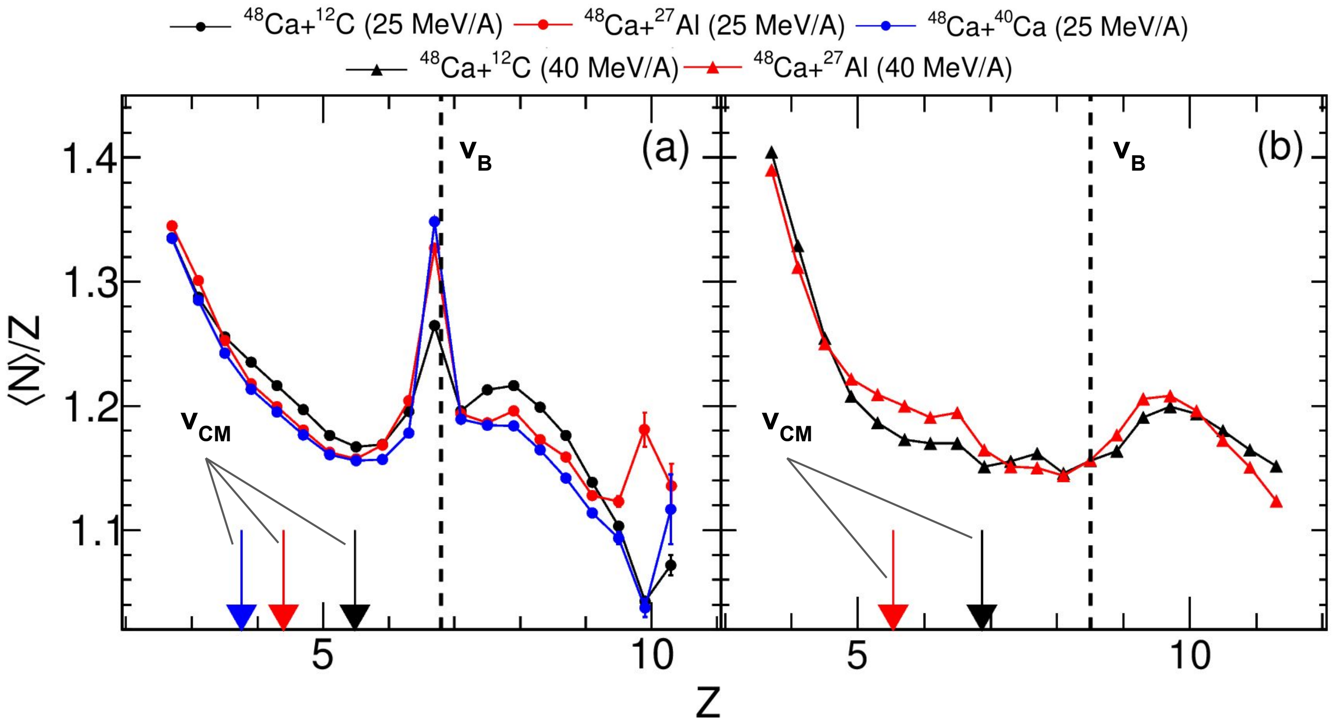
Pre-equilibrium emissions have very less contributions as the detector is far from target (1 m)

Energetic neck emissions can still reach the detector

FAZIA-PRE Data Analysis

Isospin effects

Looking for Pre-equilibrium and Neck Emission contributions



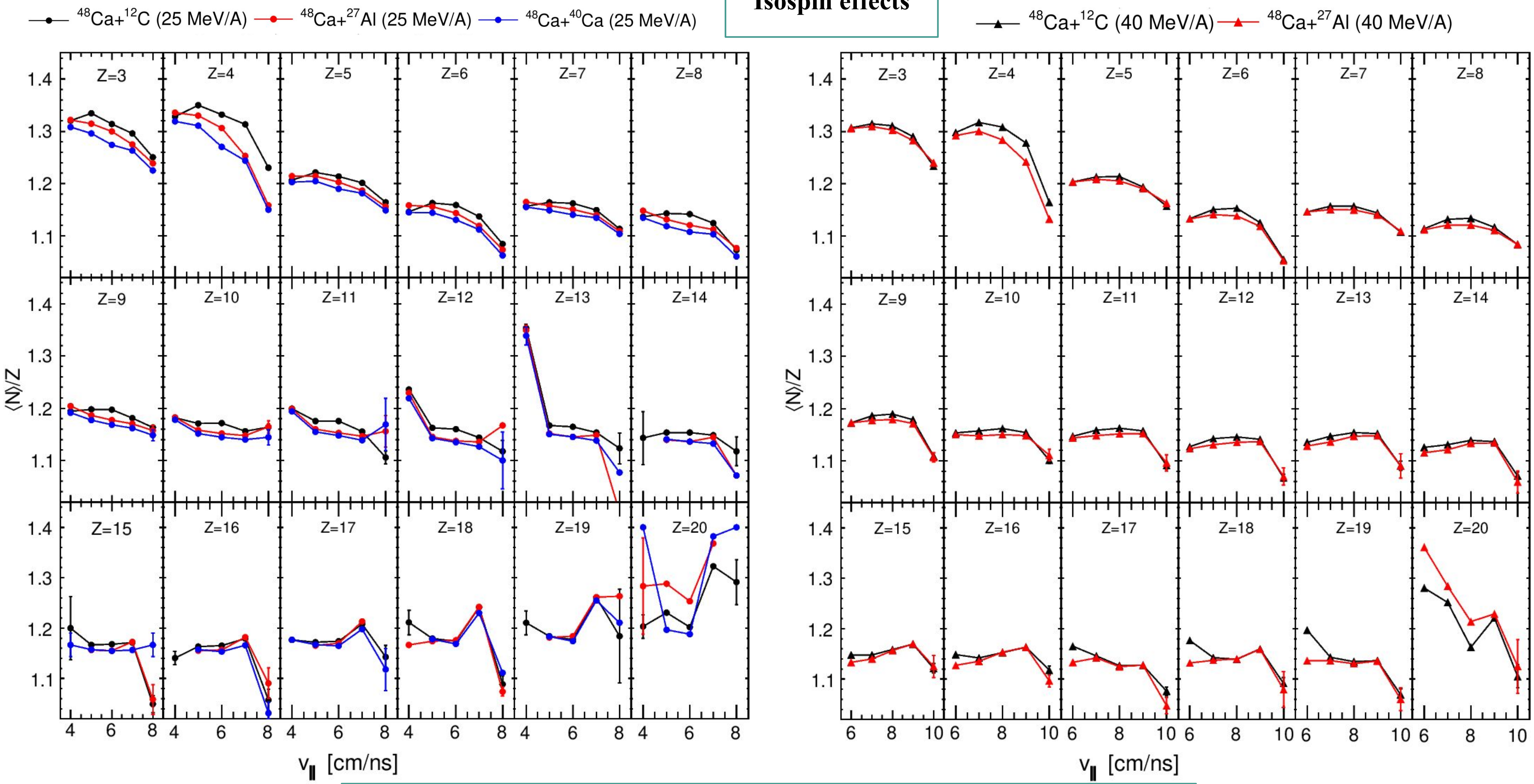
⟨N⟩/Z vs $v_{||}$ correlation shows that:

→ **Fragment ⟨N⟩/Z is relatively higher around v_{CM}**

→ **Fragment ⟨N⟩/Z is relatively higher around v_B for 25 MeV/A systems. Not seen in 40 MeV/A systems due to dominance of multifragmentation**

FAZIA-PRE Data Analysis

Isospin effects



Going deeper to search the contributions,

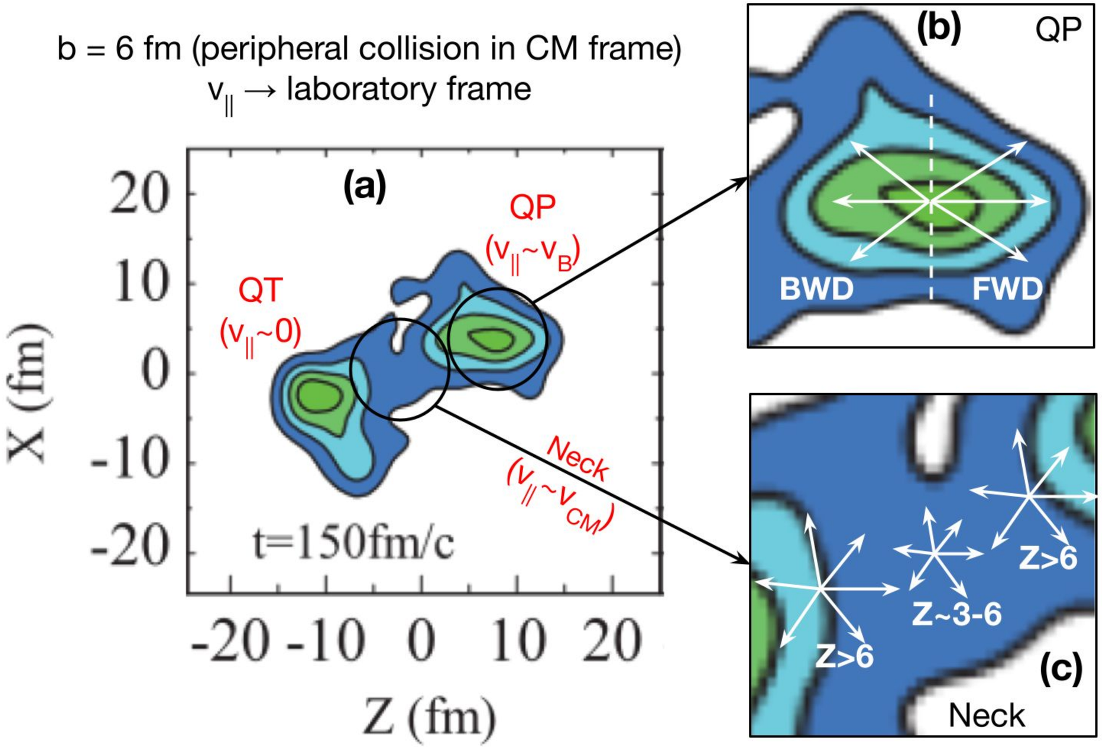
→ Plotting ⟨N⟩/Z vs $v_{||}$ for each Z = 3 - 20

→ ⟨N⟩/Z is high for Z =20 → neutron rich projectile

→ ⟨N⟩/Z is high for Z<6 around v_{CM} → must investigate emission source !

FAZIA-PRE Data Analysis

Isospin effects



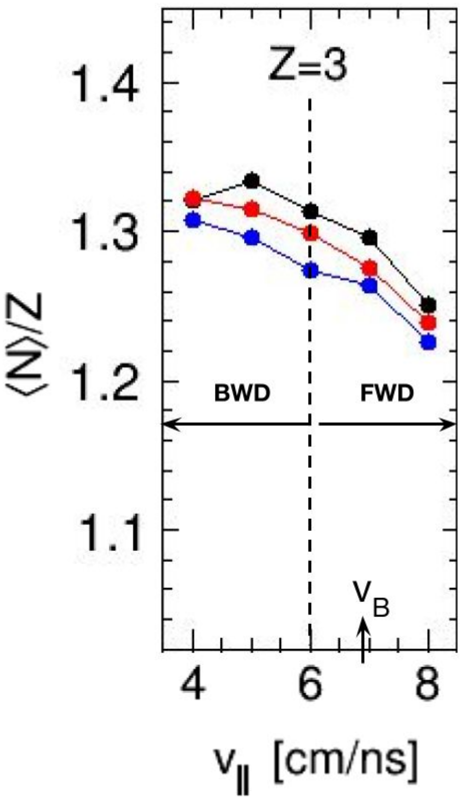
→ **The fragments with $v_{||}$ comparable to the v_B are emitted in forward direction (FWD) and the fragments with slightly lower $v_{||}$ are emitted in the backward direction (BWD) in the QP reference frame**

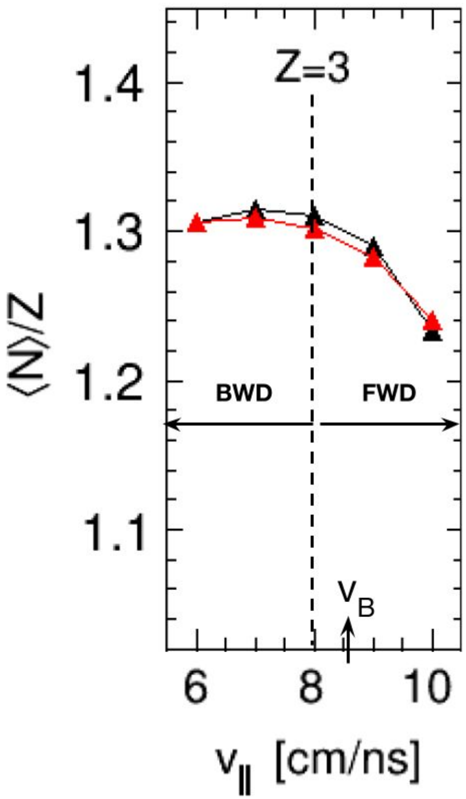
→ **The "hierarchy effect" shown by neck fragments leads to emission of light fragments (Z~3-6) with lower $v_{||}$ which is comparable to the v_{CM} from the very central dilute region of the neck.**

→ **The fragments emitted from denser parts of the neck, i.e., near QP and QT have higher $v_{||}$ than v_{CM} but lower than the BWD or FWD fragments**

FAZIA-PRE Data Analysis

Isospin effects





To verify, we split the QP phase space for BWD and FWD fragments

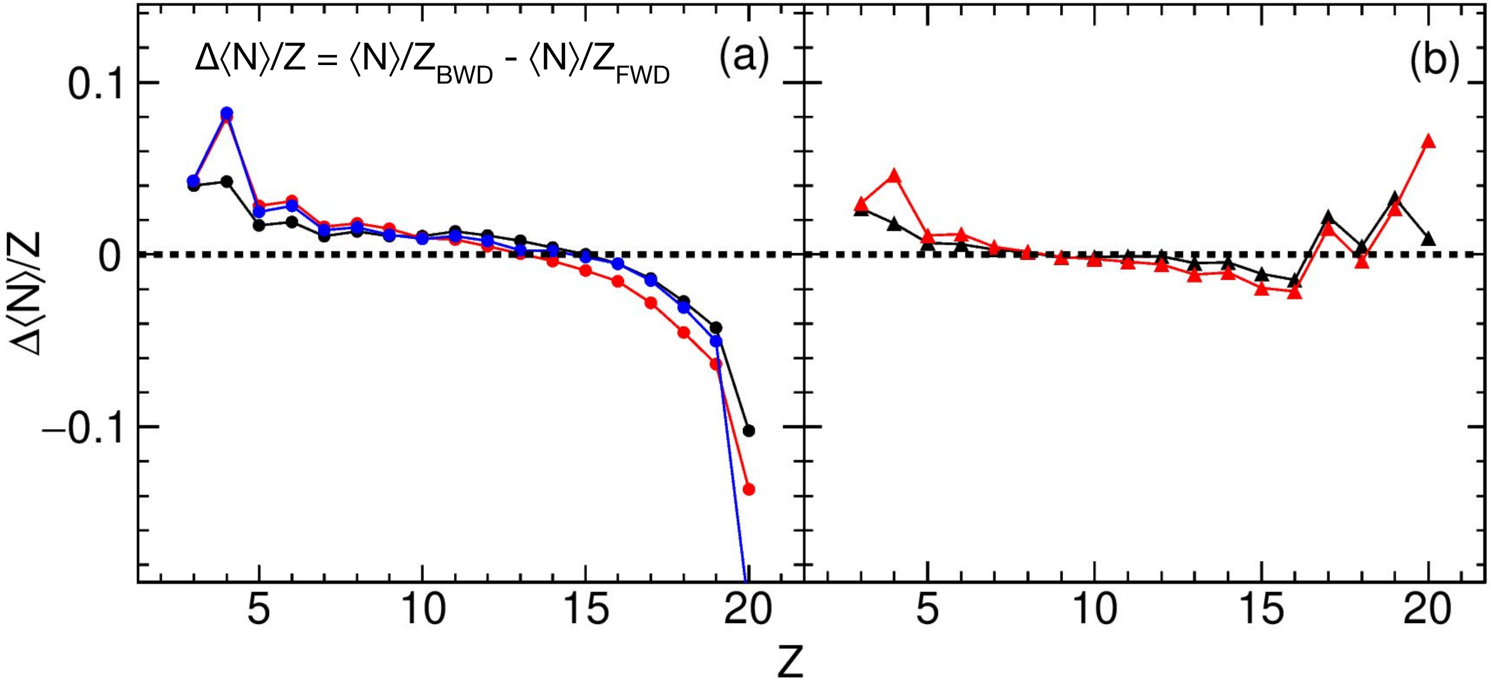
Split point slightly lower than v_B: E_B = 25 MeV/A → 6 cm/ns ; E_B = 40 MeV/A → 8 cm/ns

If v|| ≤ 6/8 cm/ns → fragment is emitted in backward direction in QP phase space → BWD + neck emissions

If v|| > 6/8 cm/ns → fragment is emitted in forward direction in QP phase space → FWD

FAZIA-PRE Data Analysis

Isospin effects



$\Delta\langle N\rangle/Z = \langle N\rangle/Z_{BWD} - \langle N\rangle/Z_{FWD}$ vs Z

→ Isospin equilibration should have equal effects for BWD and FWD fragment ($\Delta\langle N\rangle/Z \cong 0$)

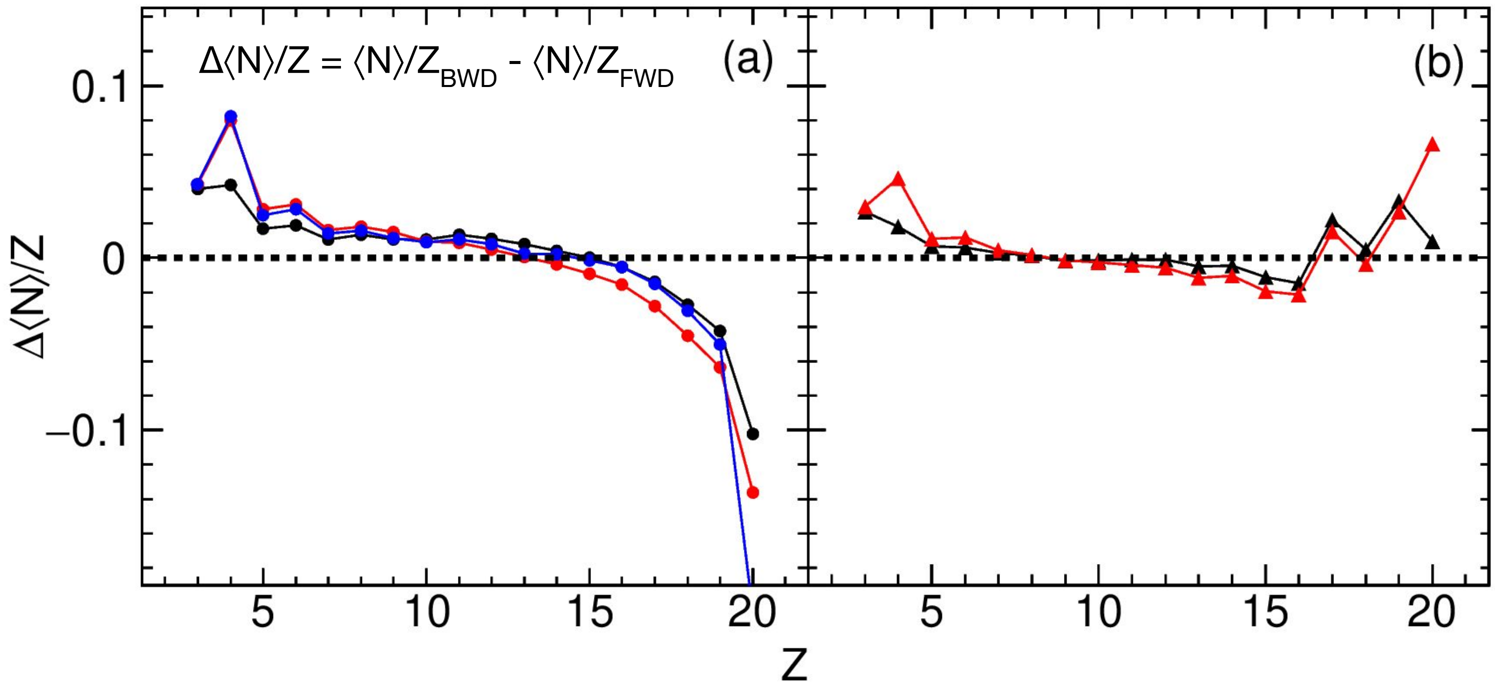
→ $\Delta\langle N\rangle/Z > 0$ for fragments Z ≲ 7: Confirming that these lighter fragments in the backward phase space with high $\langle N\rangle/Z$ come from neck

→ These fragments with $v_{||} \sim v_{CM}$ have high $\langle N\rangle/Z$ → neutron enrichment of the neck region

This confirms the observation of Isospin Drift !

FAZIA-PRE Data Analysis

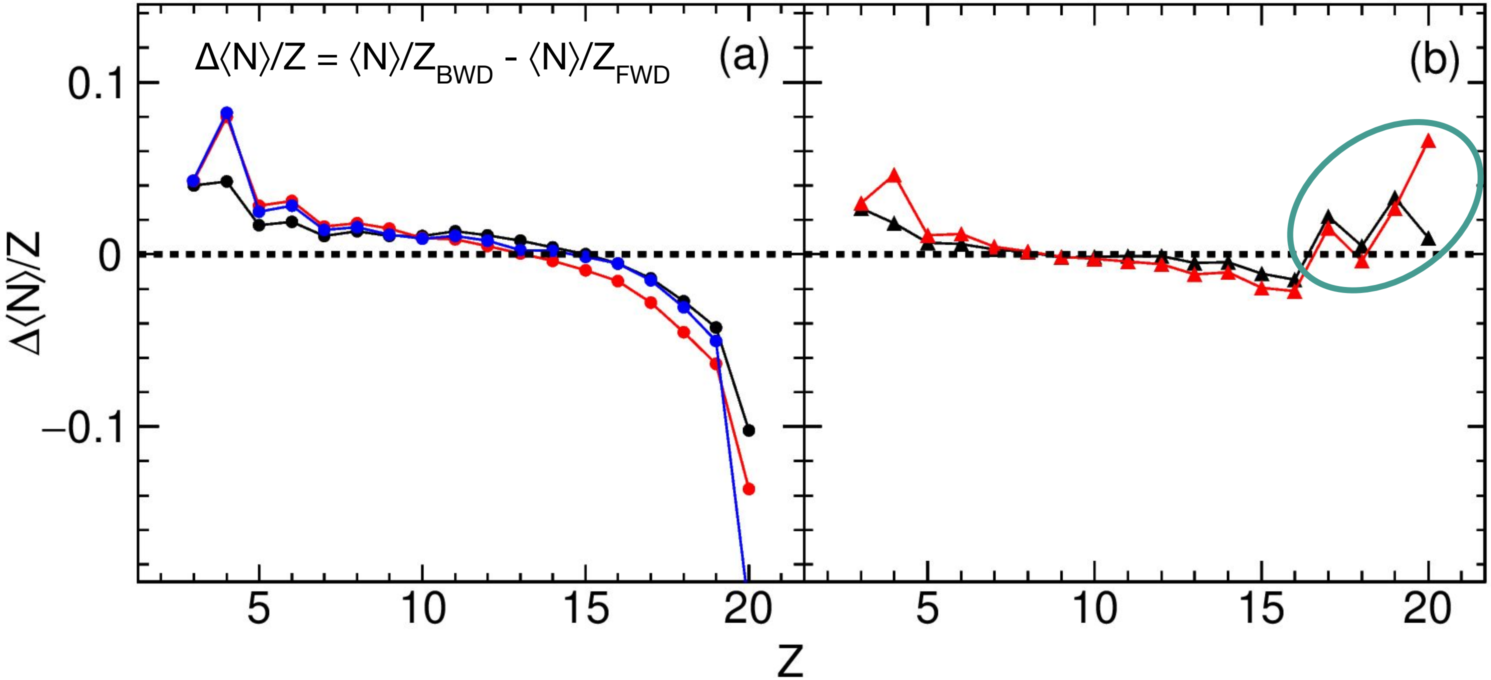
Isospin effects



Isospin diffusion cannot be observed in this data because we also need a ^{40}Ca beam to compare the data on the basis of isospin asymmetry

FAZIA-PRE Data Analysis

Isospin effects



→ Δ⟨N⟩/Z < 0 for heavier fragments → FWD fragments have higher ⟨N⟩/Z due to presence of neutron rich PLFs and heavier fragment

→ But the trend changes in the 40 MeV/A systems: Possible reason because of pre-equilibrium neutron emissions from projectile reducing the overall ⟨N⟩/Z in PLFs → thus reducing ⟨N⟩/Z of FWD fragments than BWD

HIPSE Event Generator

HIPSE Event Generator

HIPSE (Heavy-Ion Phase-Space Exploration) is a phenomenological event generator able to simulate heavy ion collisions at the intermediate energy range (20-100 MeV/A).

It can easily perform nuclear simulations at all impact parameter ranges and thus is a valuable tool for the understanding of nuclear reaction processes.

LACROIX, VAN LAUWE, AND DURAND PHYSICAL REVIEW C **69**, 054604 (2004)

not ensure a general agreement with the data collected in the intermediate energy range. Indeed, the free parameters of the model have been adjusted with help of a limited set of data and additional studies leading to the same values of these parameters are necessary to confirm the validity of our scenario.

In the near future, we plan to extend the model to mass asymmetric systems. Note also that the calculation gives the final charge to mass ratio of fragments created during the reaction and could be a valuable tool to explore the N/Z effects in nuclear collisions in the Fermi-energy range.

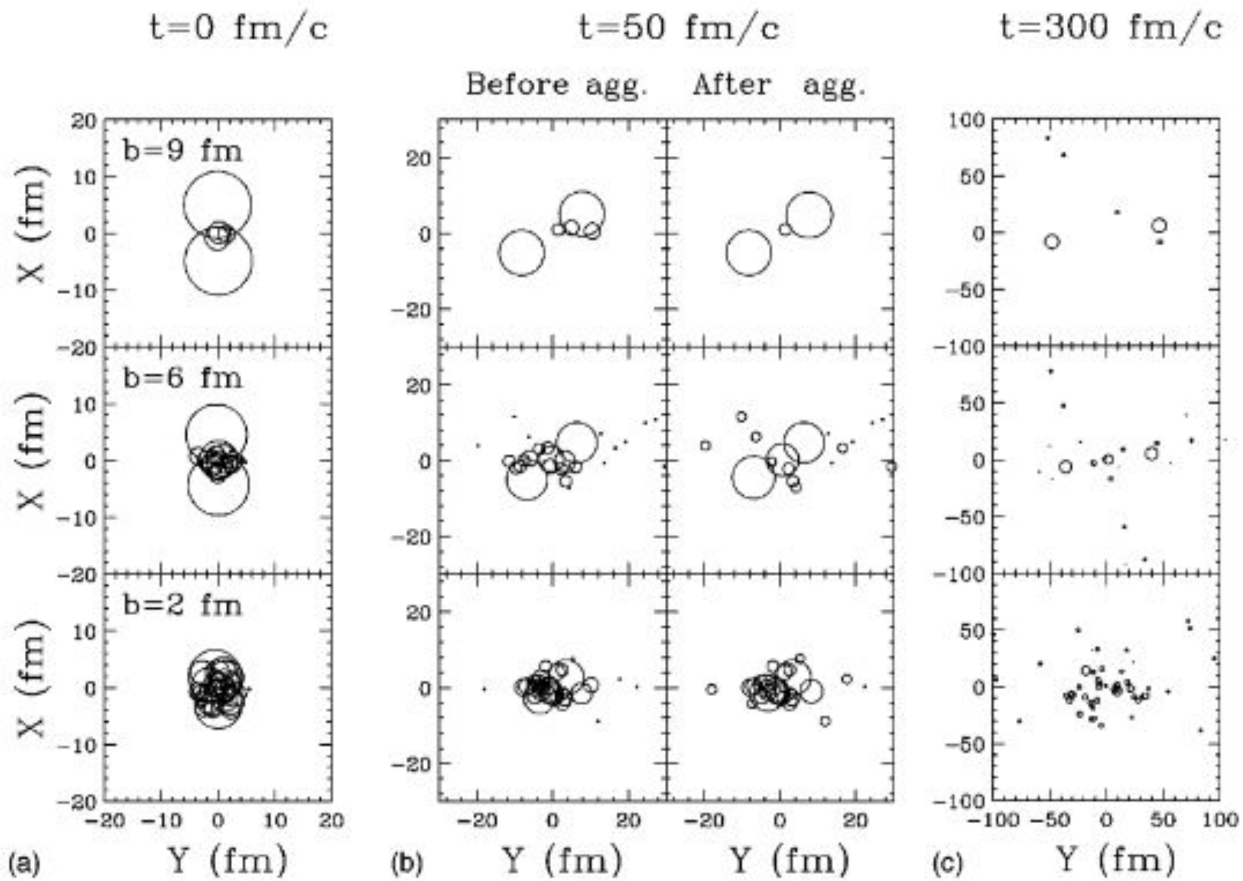
Finally, it is worth noting that the technique of exploration of phase space described in this paper is flexible enough to test rapidly other (possibly thermalized) nucleon momentum distributions to describe nuclear fragmentation.

ACKNOWLEDGMENT

We thank warmly INDRA Collaboration for permission to use its data.

It says here that HIPSE “could be a valuable tool” for N/Z studies but it has never been directly checked !!

HIPSE Event Generator



Approaching Phase

Initialisation of n and p position and momentum according to Thomas-Fermi distribution for each nucleus in the centre-of-mass frame

Re-aggregation Phase

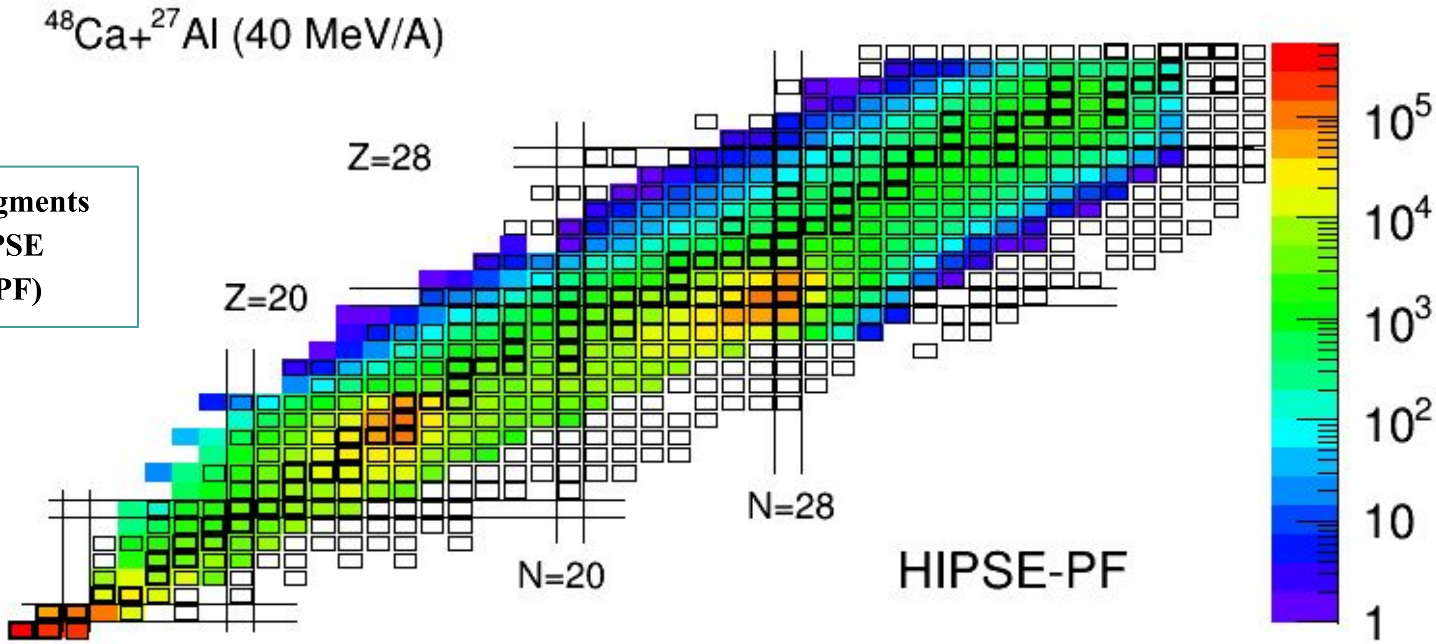
Propagation of entrance channel, make pre-equilibrium partition and QP-QT regions and energy distribution among fragments

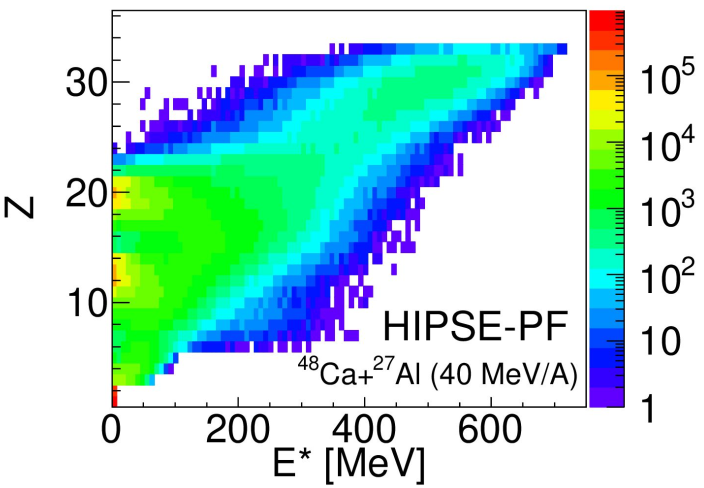
After-burner Phase

in-flight final de-excitation using secondary de-excitation codes like SIMON or GEMINI++

HIPSE Event Generator

Primary fragments from HIPSE (HIPSE-PF)

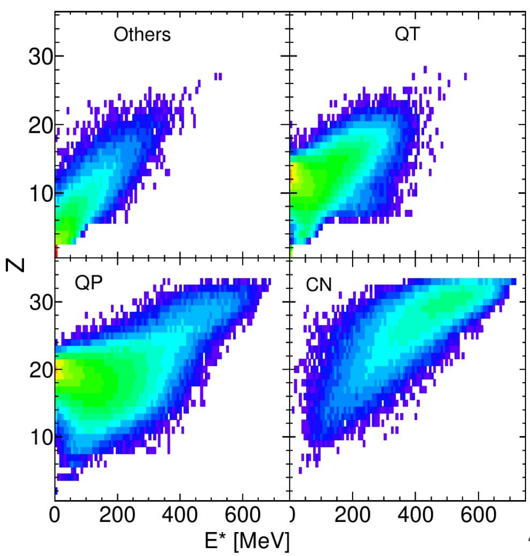




← **Excitation energy of HIPSE-PF**

Split in to contributions of various emission sources →

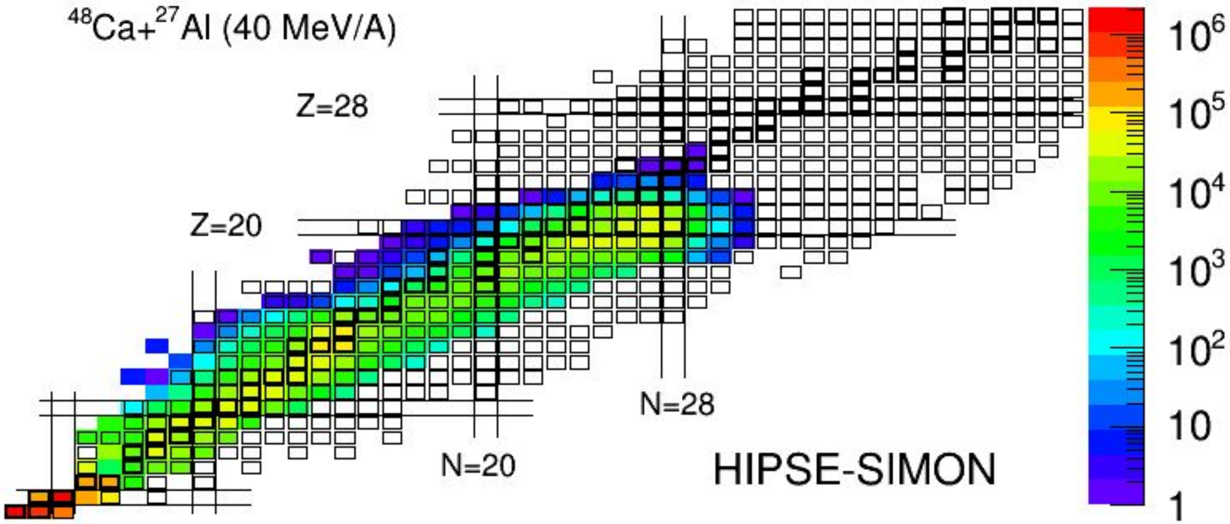
QP, QT, compound nucleus (CN) and other sources like pre-equilibrium emissions, etc



HIPSE Simulations

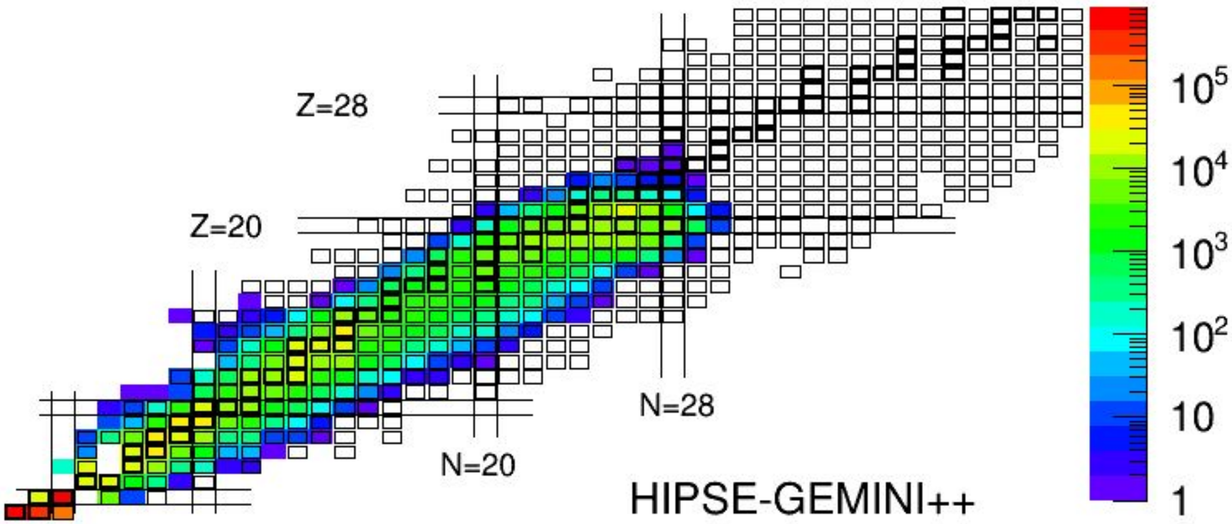
SIMON code

Simulation of pre-equilibrium emissions from entrance channel and a transition to a model based on simultaneous multifragmentation instead of successive binary decay

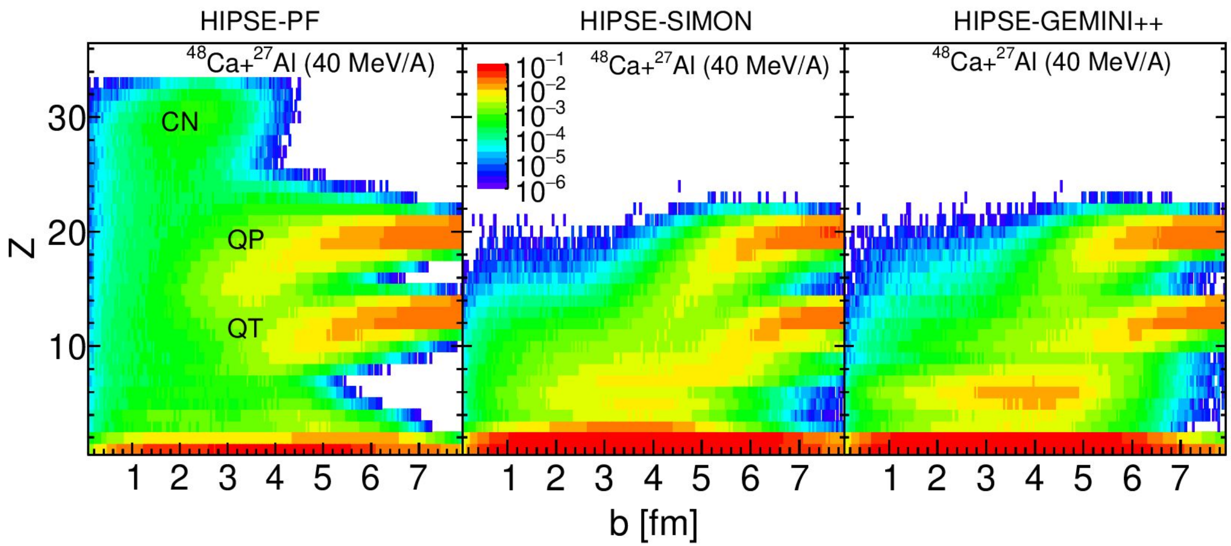


GEMINI++ code

Follows the decay of a compound nucleus by a series of binary divisions. Useful in cases where the excitation energy and spin distributions of the compound nuclei are well defined.



HIPSE Simulations



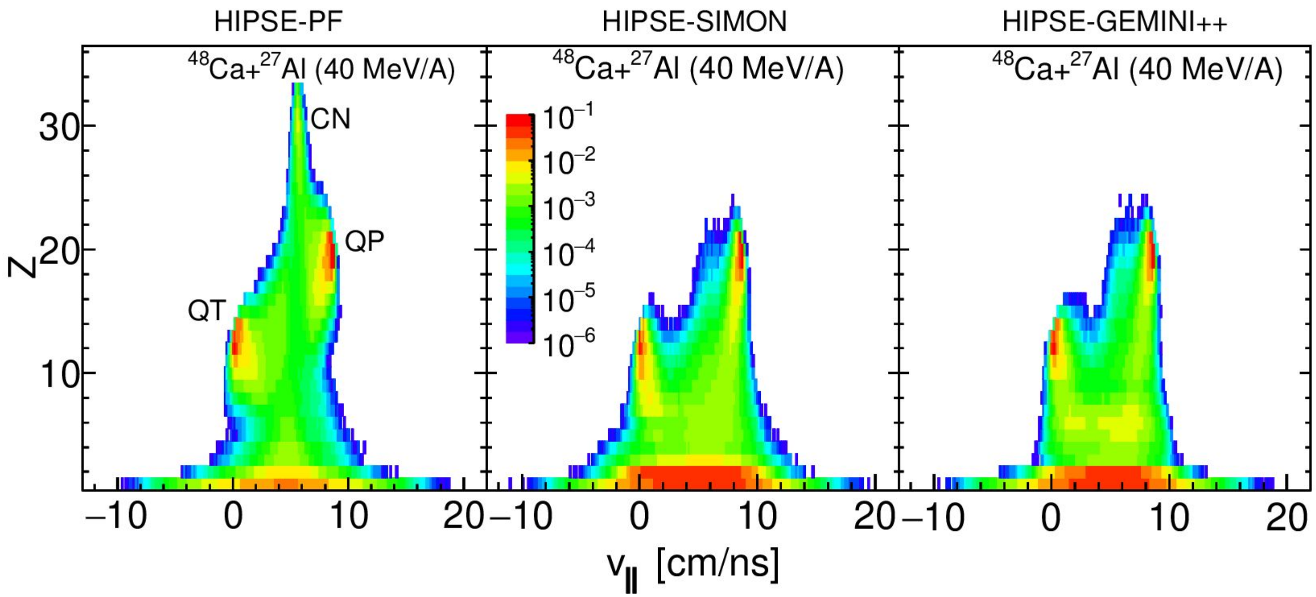
HIPSE calculates the reaction dynamics for full 4π solid angle in the CM frame

b_{max} = 8 fm
Simulations till semi-peripheral region
Ultra-peripheral region → no QP and QT

Z vs $v_{||}$ (lab frame)

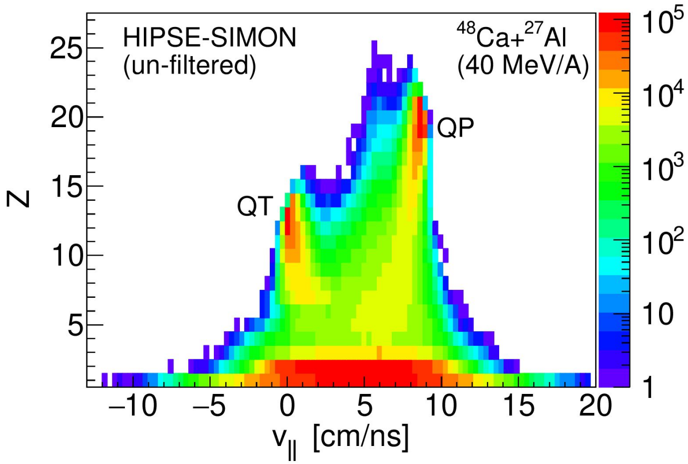
HIPSE-PF → QT, QP, CN marked

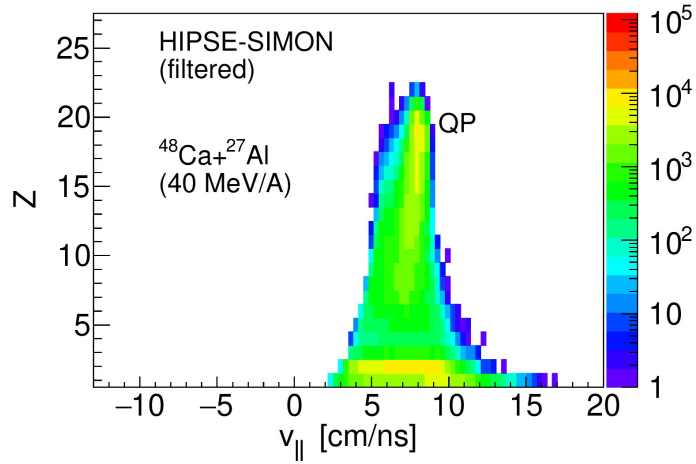
Secondary fragments → for HIPSE-SIMON and HIPSE-GEMINI++ fragments



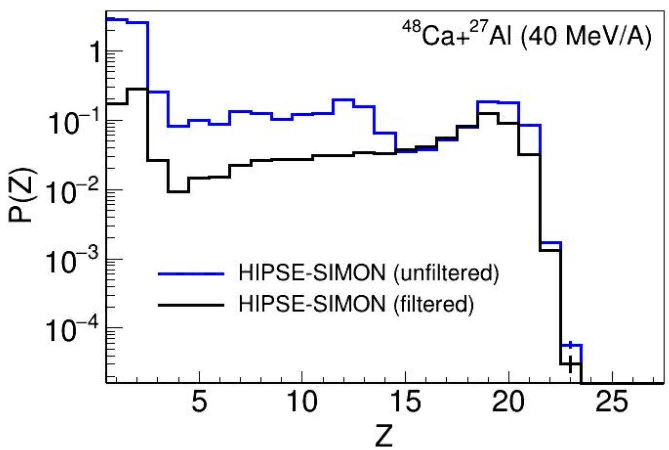
HIPSE Simulations

HIPSE full 4π simulations cannot be directly compared to the experimental data due to experimental constraints
HIPSE data is filtered w.r.t. the FAZIA-PRE experimental constraints for comparison





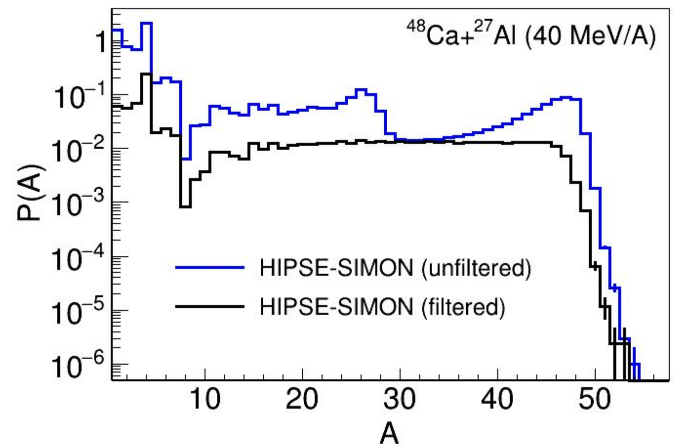
FAZIA-PRE detector arrangement → Very forward angles → Mostly QP detected QT stays in transverse plane



Z distribution shows the QP peak

A distribution slightly disrupted around heavier masses

Filter tries to replicate the FAZIA detector identification capabilities (A identification up to Z~20)



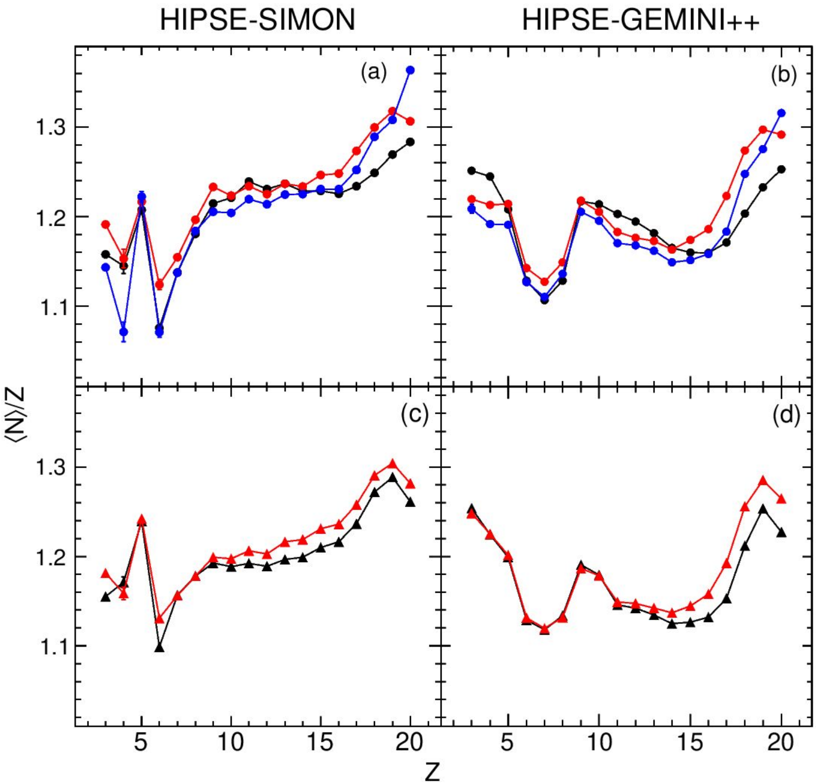
HIPSE Simulations

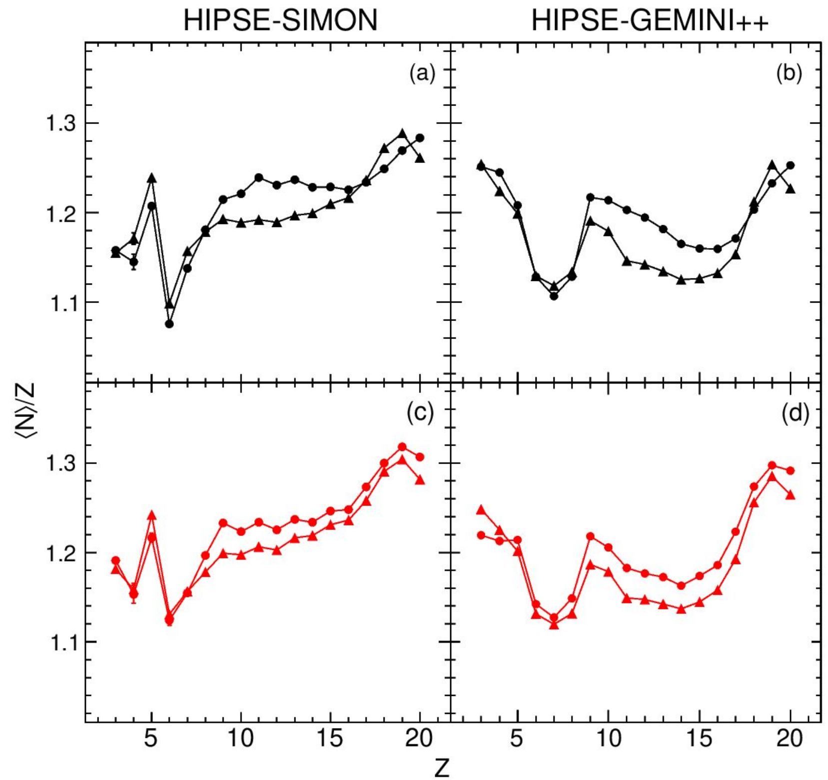
Before a direct comparison with experimental data, HIPSE filtered data was analysed for target mass and beam energy dependence

w.r.t. Target Mass

^{48}Ca+^{12}C (25 MeV/A) ^{48}Ca+^{27}Al (25 MeV/A) ^{48}Ca+^{40}Ca (25 MeV/A)
^{48}Ca+^{12}C (40 MeV/A) ^{48}Ca+^{27}Al (40 MeV/A)

w.r.t. Beam Energy





No consistent dependence on target mass is seen

Discussion about the shape of distribution and isospin transport during comparison with experimental data

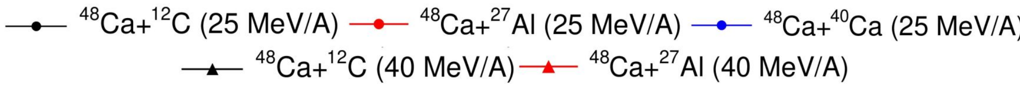
Beam energy dependence is seen in the HIPSE data

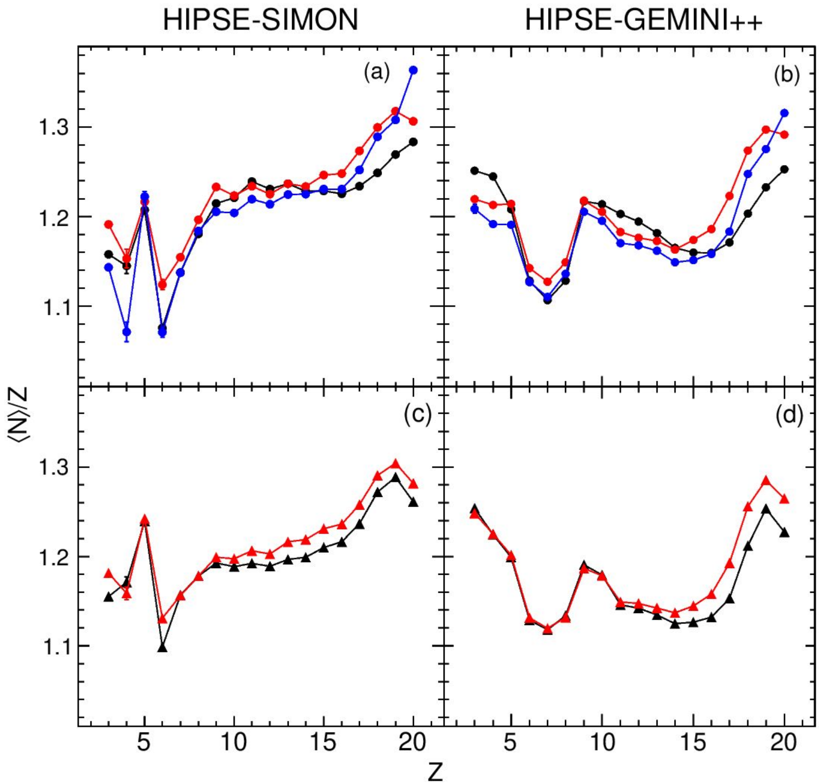
HIPSE Simulations

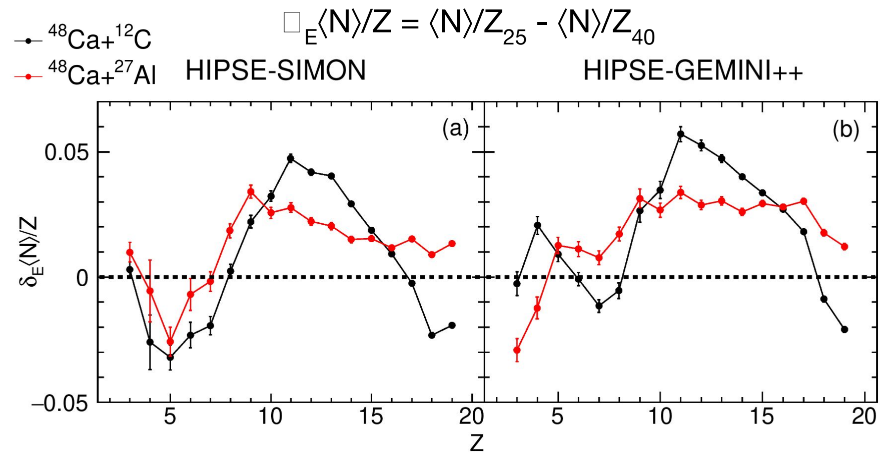
Before a direct comparison with experimental data, HIPSE filtered data was analysed for target mass and beam energy dependence

w.r.t. Target Mass

w.r.t. Beam Energy







No consistent dependence on target mass is seen

Discussion about the shape of distribution and isospin transport during comparison with experimental data

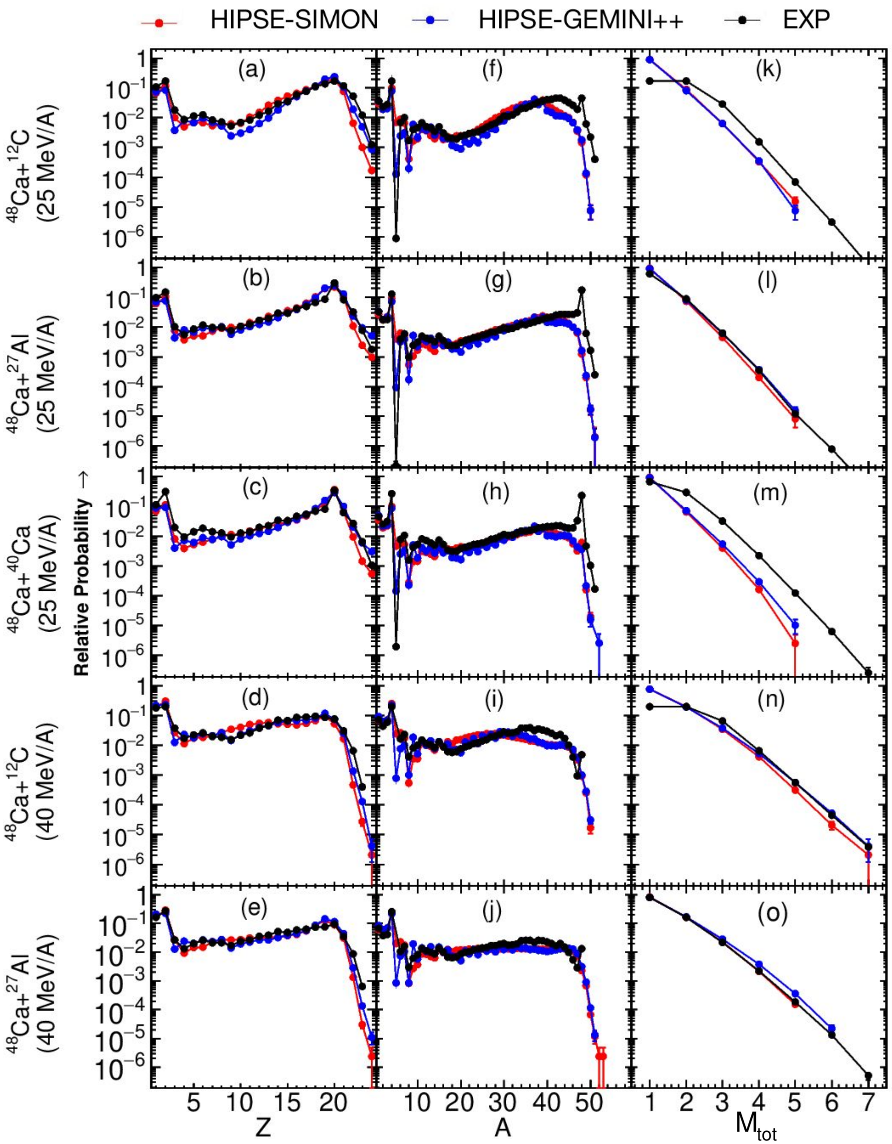
Beam energy dependence is seen in the HIPSE data

$\delta_E\langle N\rangle/Z = \langle N\rangle/Z_{25} - \langle N\rangle/Z_{40}$ also shows that most of the fragment Z have $\delta_E\langle N\rangle/Z > 0$

Confirms the dependence on beam energy

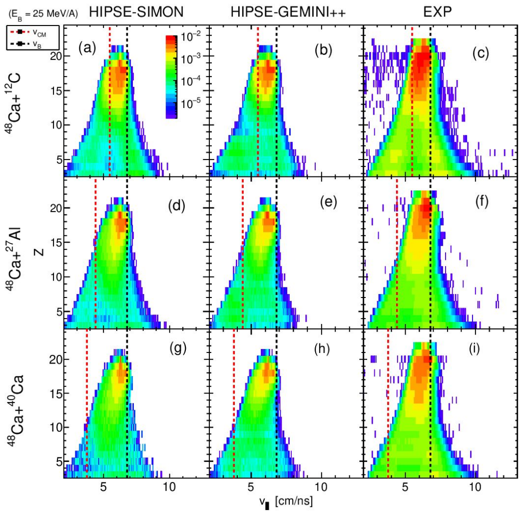
Data Comparison

Basic reaction observables

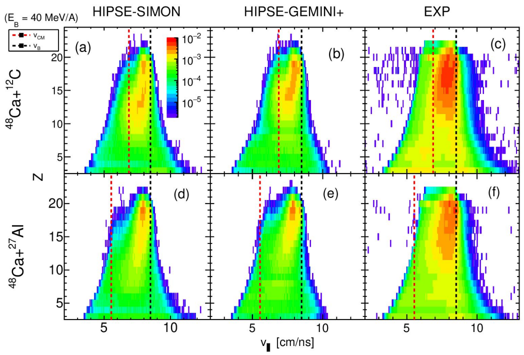


→ **Fragment Charge (Z), Fragment Mass (A), Multiplicity of Charged Particles (M_{tot}) and Parallel Velocity ($v_{||}$) are reasonably well reproduced by HIPSE**

→ **A qualitative agreement is observed for all systems between HIPSE and experimental data (EXP)**

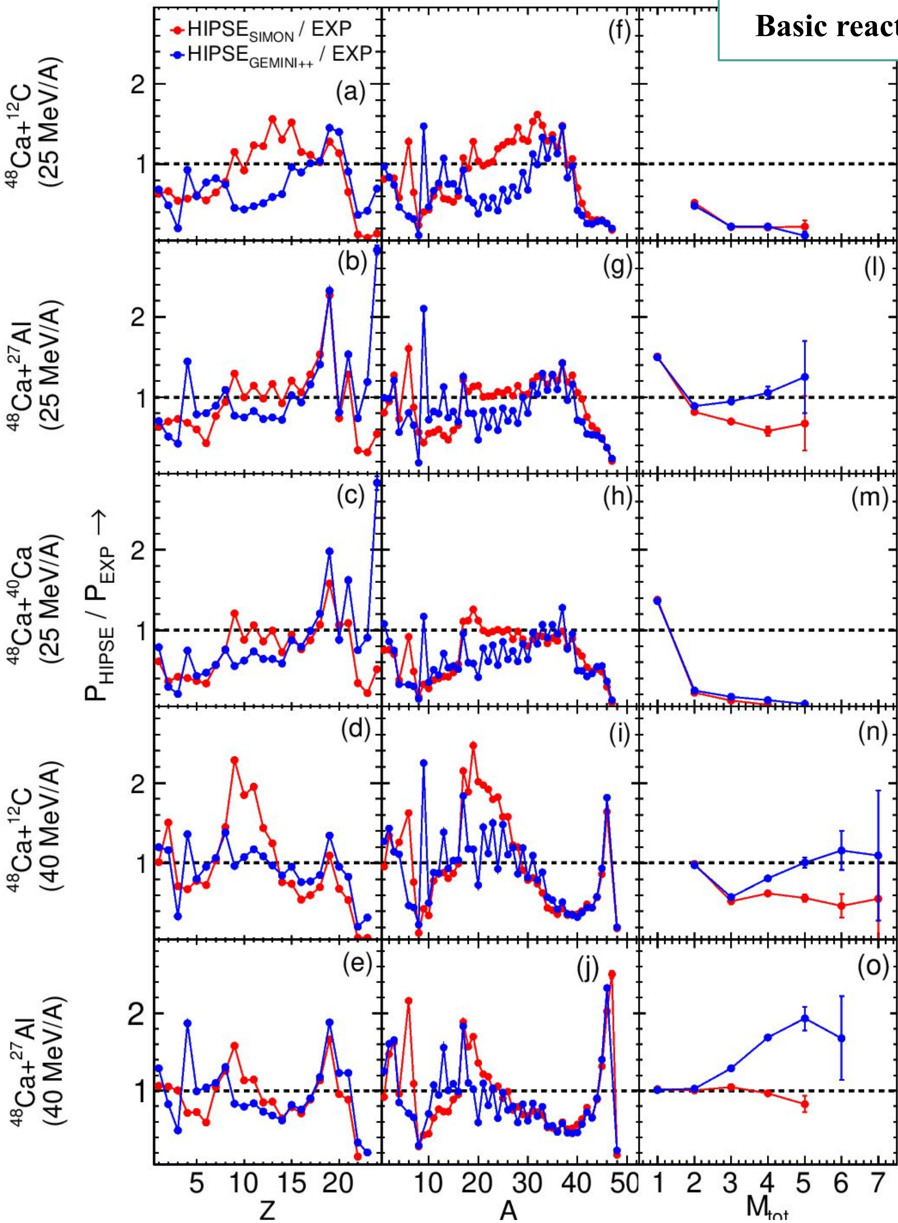


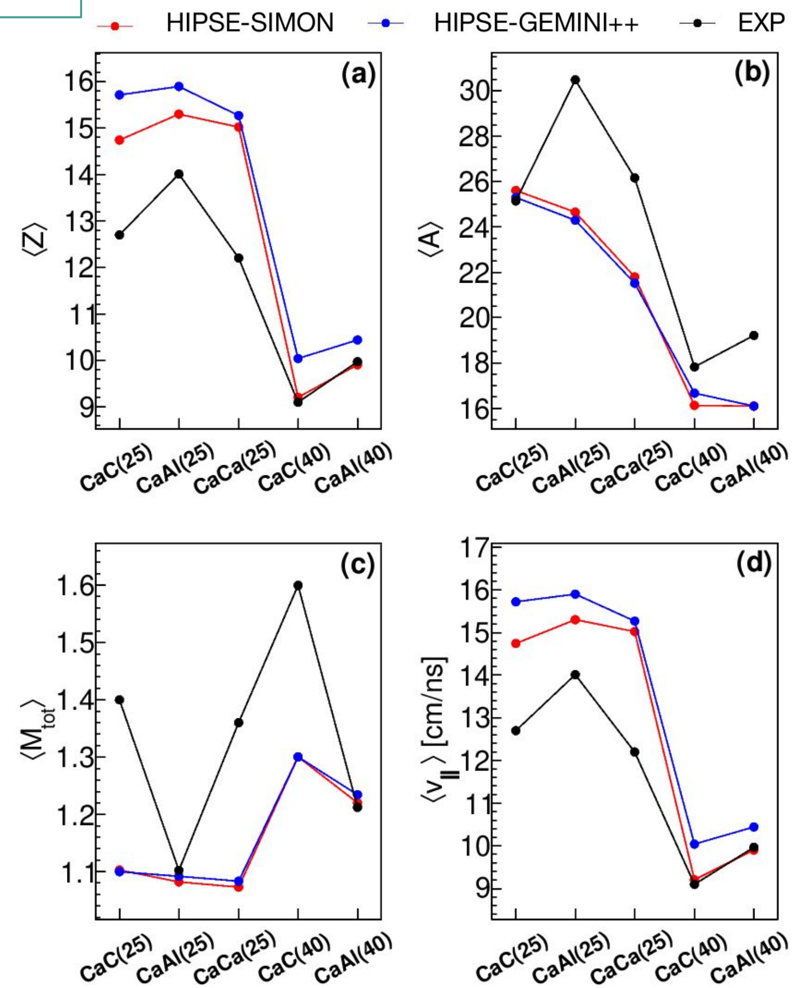
Dominance of elastic scattering events not seen in HIPSE due to choice of b_{max} only up to semi-peripheral region



Data Comparison

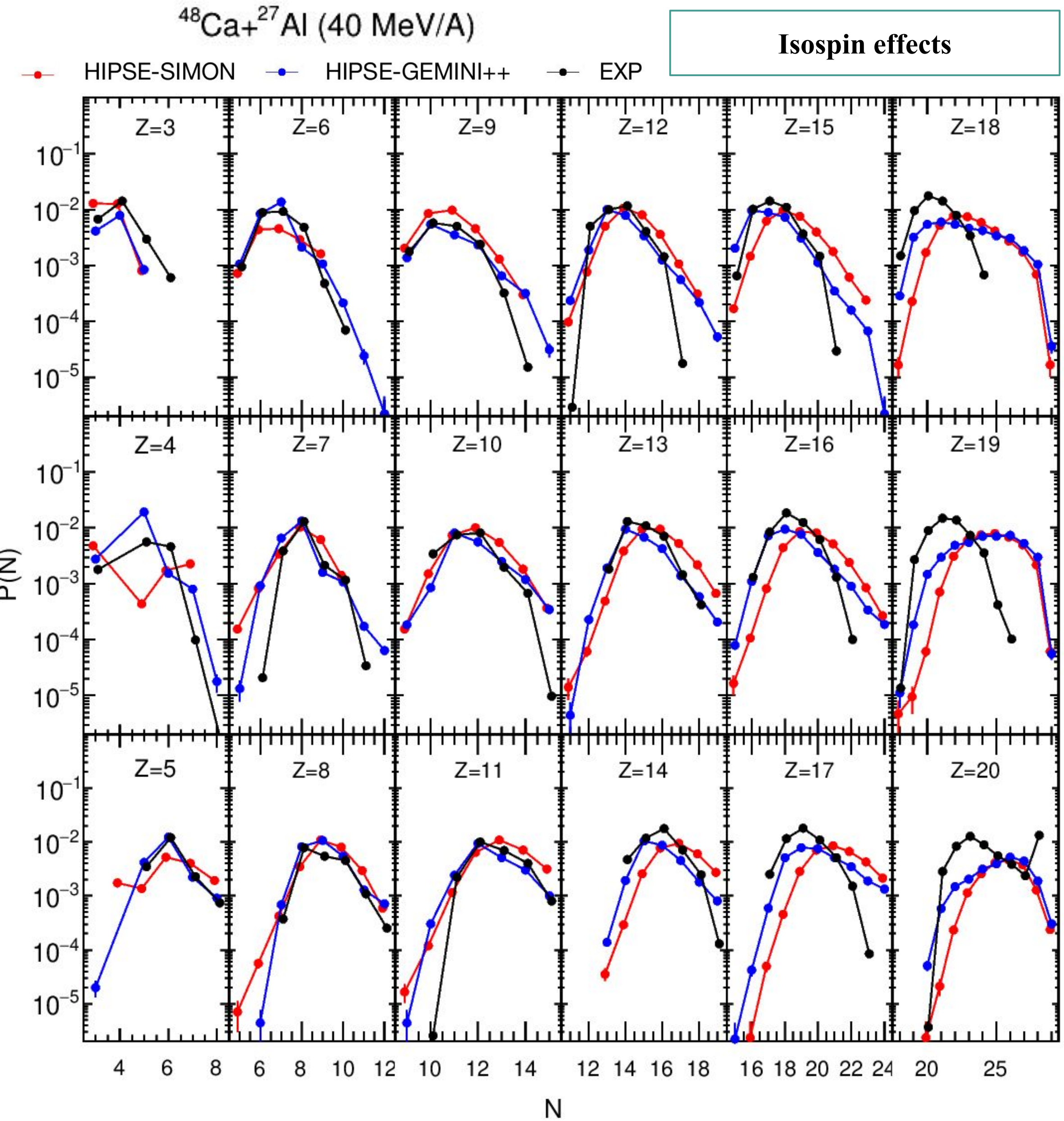
Basic reaction observables





But a quantitative comparison shows slight disagreement between HIPSE and EXP

Data Comparison



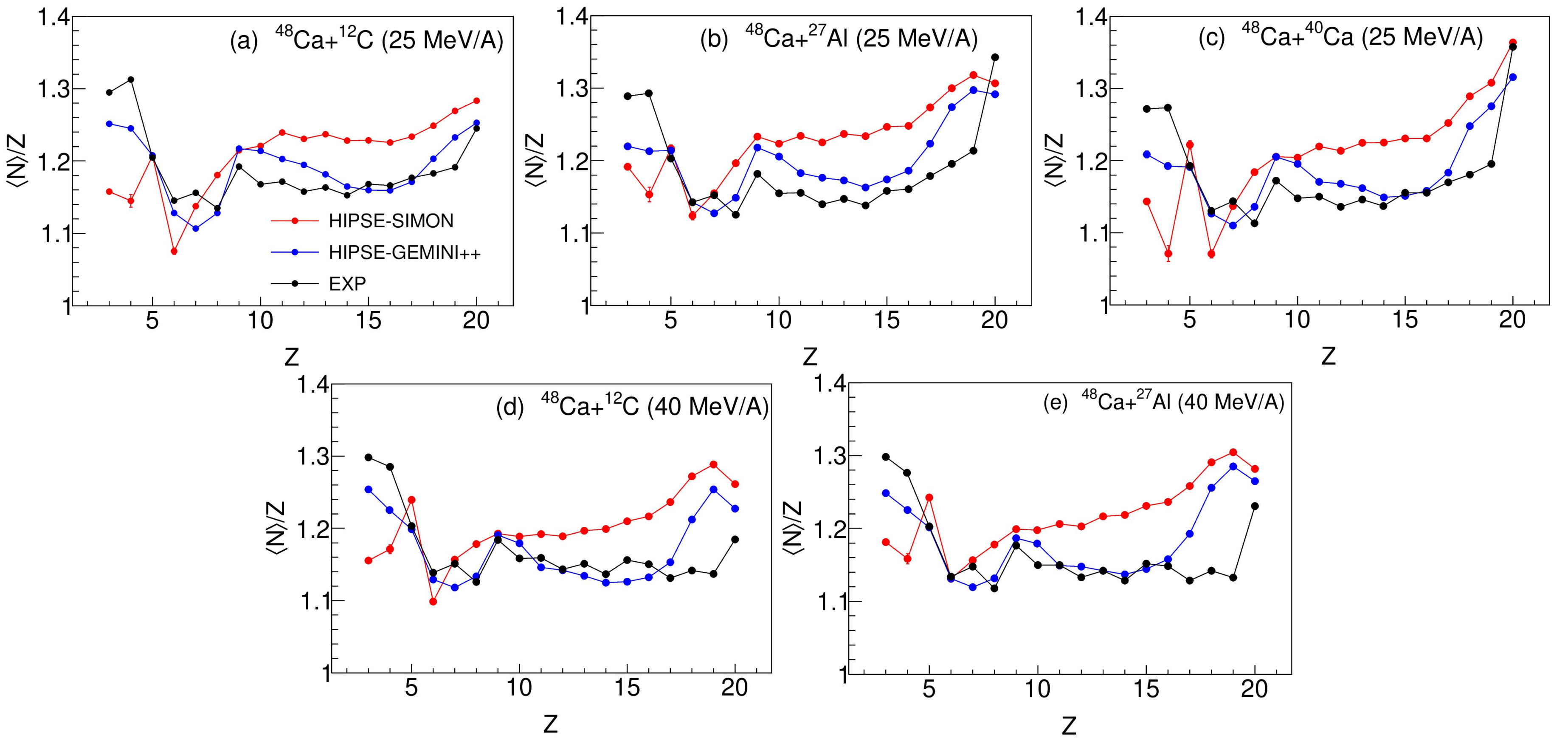
Isospin effects

Fine reproduction of N distribution up to Z~16

Similar results are observed for all systems

Data Comparison

Isospin effects

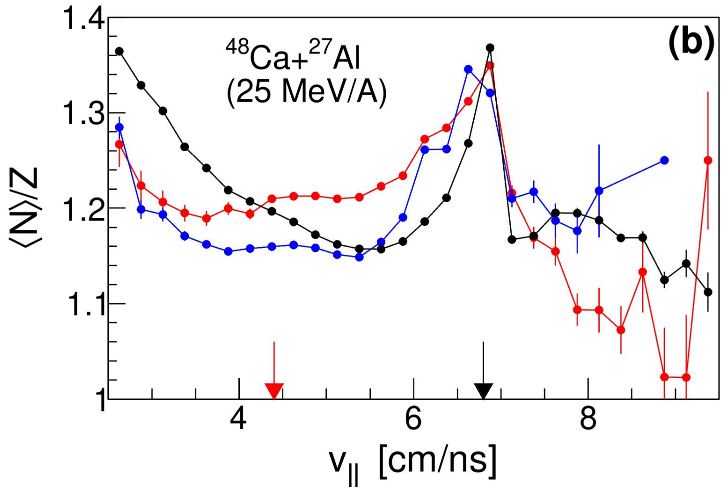


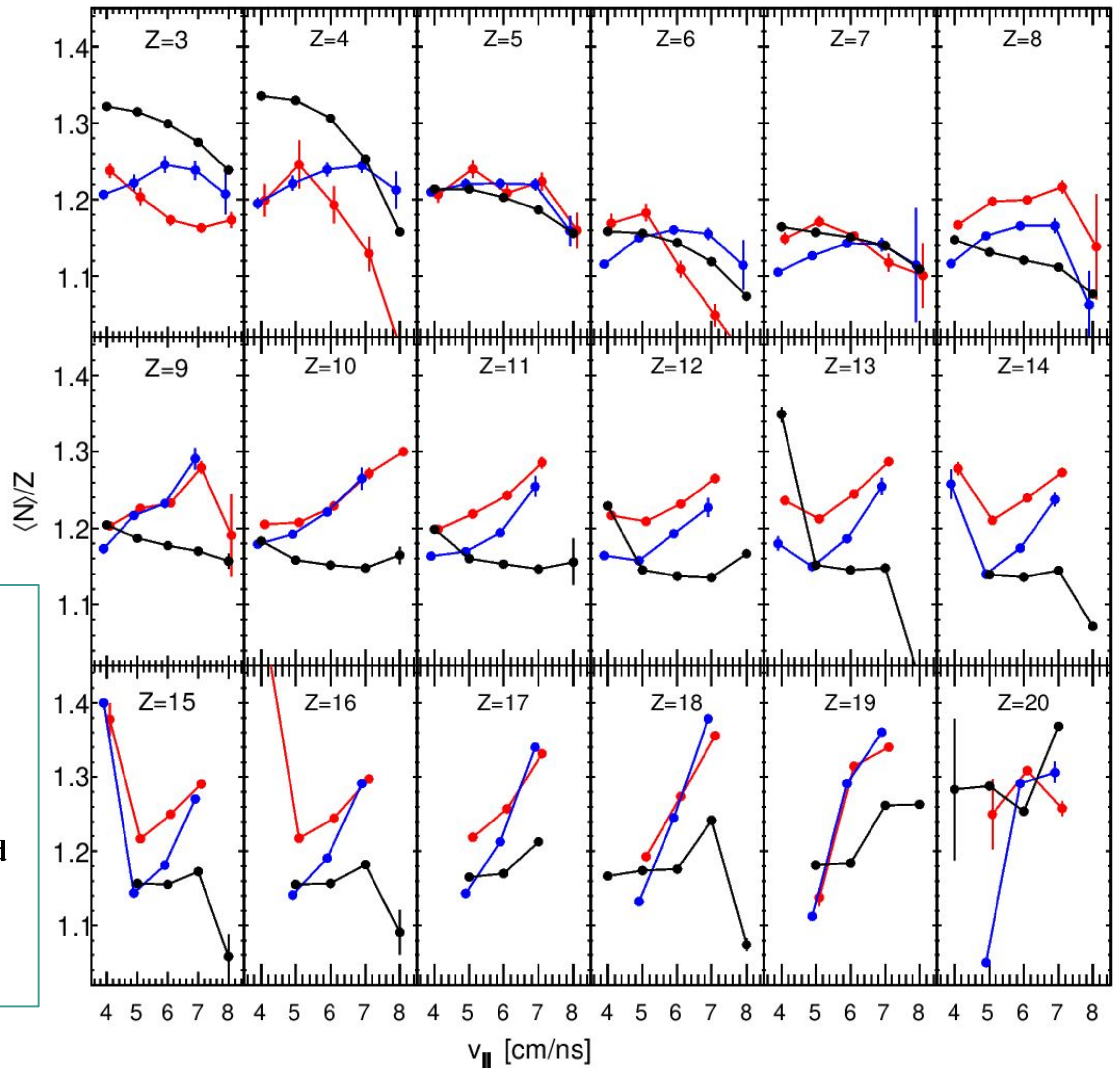
Reasonable reproduction (overall shape) of fragment ⟨N⟩/Z vs Z

Detailed structure of ⟨N⟩/Z not observed

Data Comparison

Isospin effects





⟨N⟩/Z vs v$_{||}$ for all fragments (Z>2) confirms a reasonable fragment ⟨N⟩/Z reproduction

⟨N⟩/Z vs v$_{||}$ for each Z=3 to Z=20 confirms that a detailed structured ⟨N⟩/Z distribution is not produced

Similar results are observed for all systems

Summary and conclusions

→ Heavy-ion collisions at intermediate energies can help to study isospin transport in peripheral collisions.

→ FAZIA is a charged particle multi-detector with an excellent mass resolution of up to Z~25.

→ The research work presented here mainly focused on the analysis of the data from the FAZIA-PRE experiment performed using 6 FAZIA blocks at LNS-INFN, Catania, Italy in February 2018.

→ ^{48}Ca projectile was bombarded on ^{12}C, ^{27}Al and ^{40}Ca targets at 25 MeV/A and on ^{12}C and ^{27}Al targets at 40 MeV/A.

→ The aim of the experiment was to study the effects on the fragment N/Z due to initial neutron abundance and pre-equilibrium neutron emissions from the projectile.

→ Mainly QP fragments detected as the detector setup had an angular acceptance of ~ $2^o - 18^o$.

→ Dependence on the target mass and beam energy for various basic reaction observables such as charge (Z), mass (A), multiplicity of charged particles (M_{tot}), parallel velocity ($v_{||}$) and isospin observable $\langle N \rangle/Z$ was observed.

→ A full range of N distributions for Z=3-20 was obtained for all reaction systems from N=A-Z

→ The fragment $\langle N \rangle/Z$ was found to be decreasing with increasing target mass.

→ The fragment $\langle N \rangle/Z$ was found to be decreasing with increasing beam energy.

→ Isospin drift is also observed in the FAZIA-PRE experimental data

Conclusions from comparison

→ A detailed study of HIPSE simulations with SIMON and GEMINI++ de-excitation codes in comparison with FAZIA-PRE experimental data for 5 different systems has lead to the following conclusions:

→ No dependence on the mass of the target is observed in HIPSE data.

→ Effects of beam energy dependence on fragments is observed in HIPSE data.

→ HIPSE gives an overall qualitative reproduction of the experimental data with respect to basic reaction observables (Z, A, M_{tot} and $v_{||}$).

→ A low quantitative agreement is observed.

→ HIPSE is able to produce the fragment ⟨N⟩/Z with a reasonable agreement to the experimental data. But it cannot give a detailed structure of the fragment ⟨N⟩/Z.

HIPSE event generator is a fine tool to generate the fragments from nuclear reactions at intermediate energy range with respect to the basic reaction observables and to have an idea of the overall dynamics. But due to its inability to produce a detailed structure of fragment N/Z, it is not advisable to use HIPSE to study N/Z effects. One would rather continue to use Antisymmetrized Molecular Dynamics (AMD) model or Constrained Molecular Dynamics (CoMD) model to investigate isospin and symmetry energy related studies.

FAZIA

The FAZIA Collaboration

THANK YOU