Experimental study of the symmetry energy from ^{40,48}Ca+^{40,48}Ca reactions at 35 AMeV

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Symmetry energy in finite systems

Bethe-Weizäcker binding energy :

$$BE(N,Z) = \underbrace{-a_V A}_{\text{volume}} + \underbrace{a_s A^{2/3}}_{\text{surface}} + \underbrace{C_{sym}(A)\frac{(N-Z)^2}{A}}_{\text{symmetry}} + \underbrace{a_C \frac{Z^2}{A^{1/3}}}_{\text{Coulomb}} \quad (1)$$

Surface symmetry energy :

$$C_{sym}(A) = a_a^V + a_a^S A^{-1/3} \quad (2)$$

- a_a^V and a_a^S are constants characterizing the volume and **surface** symmetry energy, respectively [1] ;
- a_a^S not well constrained by experimental data on g.s nuclear properties [2] ;
- a_a^S is a **fundamental quantity** to describe the deformability of n-rich systems (position of the neutron drip-line, border of superheavy region, fusion/fission and rotational properties of n-rich nuclei, r-process, structure of neutron stars).

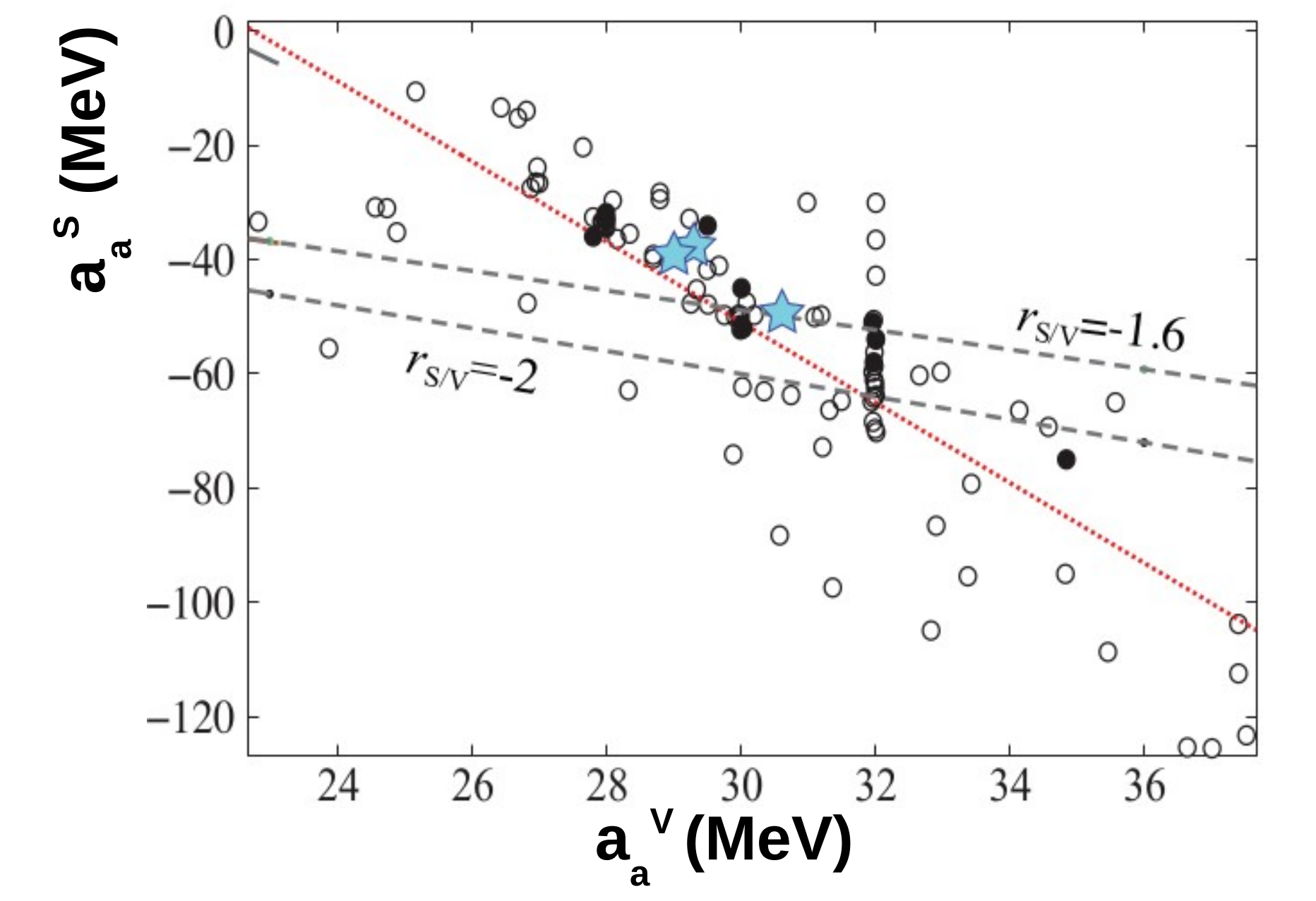


Fig.1 : Correlations between a_a^V and a_a^S from Skyrme nuclear energy density functionals [2].

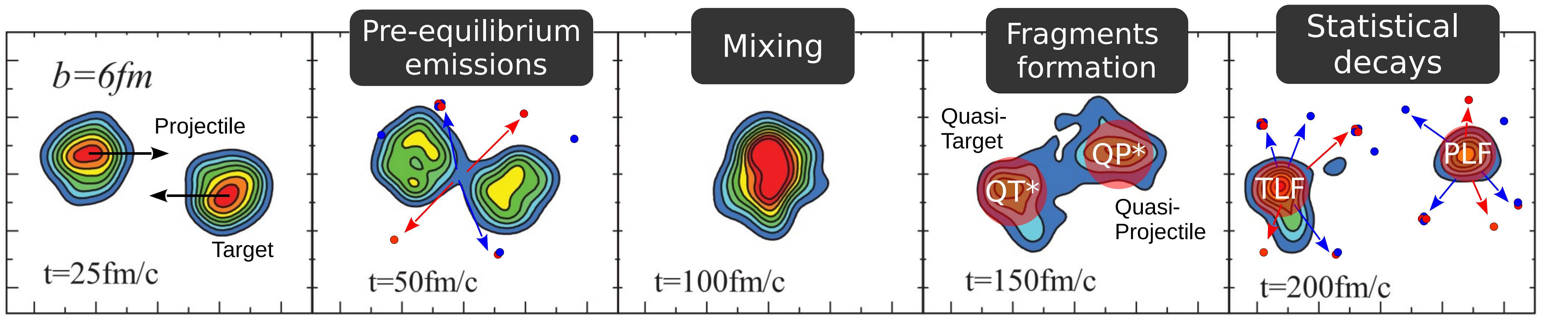


Fig.2 : Illustration of Heavy Ion Collisions at intermediate energies from ImQMD transport model [3].

Peripheral/Semi-peripheral collisions

Heavy-ion collisions (HIC)

- Submit nuclei to various ρ, P and T ;
- Unique way to form exotic nuclei with a large neutron to proton asymmetry and high excitation energies.

Peripheral and semi-peripheral collisions

- Intermediate energies (15 < E_{beam} < 100 MeV/nucleon) ;
- Described as two-step processe (Fig.2) :

→ Primary excited fragments formed with properties similar to the projectile and the target (Quasi-Projectile/Target, QP/QT)
→ Decay by evaporation of Light-Charged Particles (LCP), leading to Projectile/Target-Like Fragment (PLF/TLF) residues.

- Experimentally : only the secondary fragments are detected.

Experimental details - INDRA-VAMOS coupling [4]

- ^{48,40}Ca+^{48,40}Ca at 35 MeV/A ;
- VAMOS high acceptance spectrometer (Trigger, Fig.3) :
  - → PLF identification (Z_V, N_V) (Fig.5) ;
- INDRA ~4π detector :
  - → coincident LCP identification (Fig.4) ;
- Neutrons are not detected ;
- Peripheral/semi-peripheral collisions (near-saturation density domain).

VAMOS

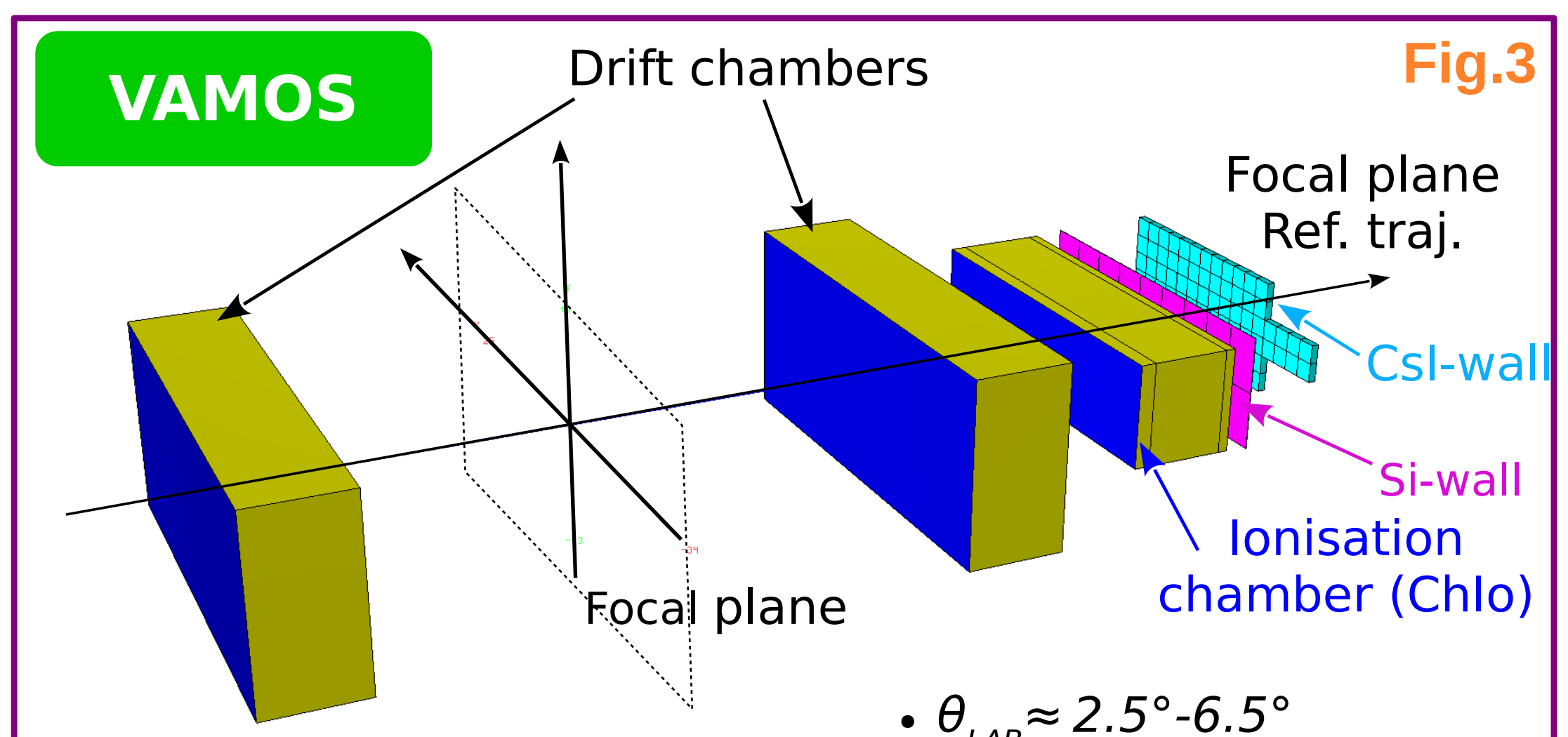


Fig.3

- $\theta_{LAB} \approx 2.5°\text{-}6.5°$
  $\varphi_{LAB} \approx 220°\text{-}320°$
- Si-wall = Acq. Trigger
- 12 Bρ settings :
  → $B\rho_0 \approx$ 0.661-2.220 T.m
- PLF identification

INDRA

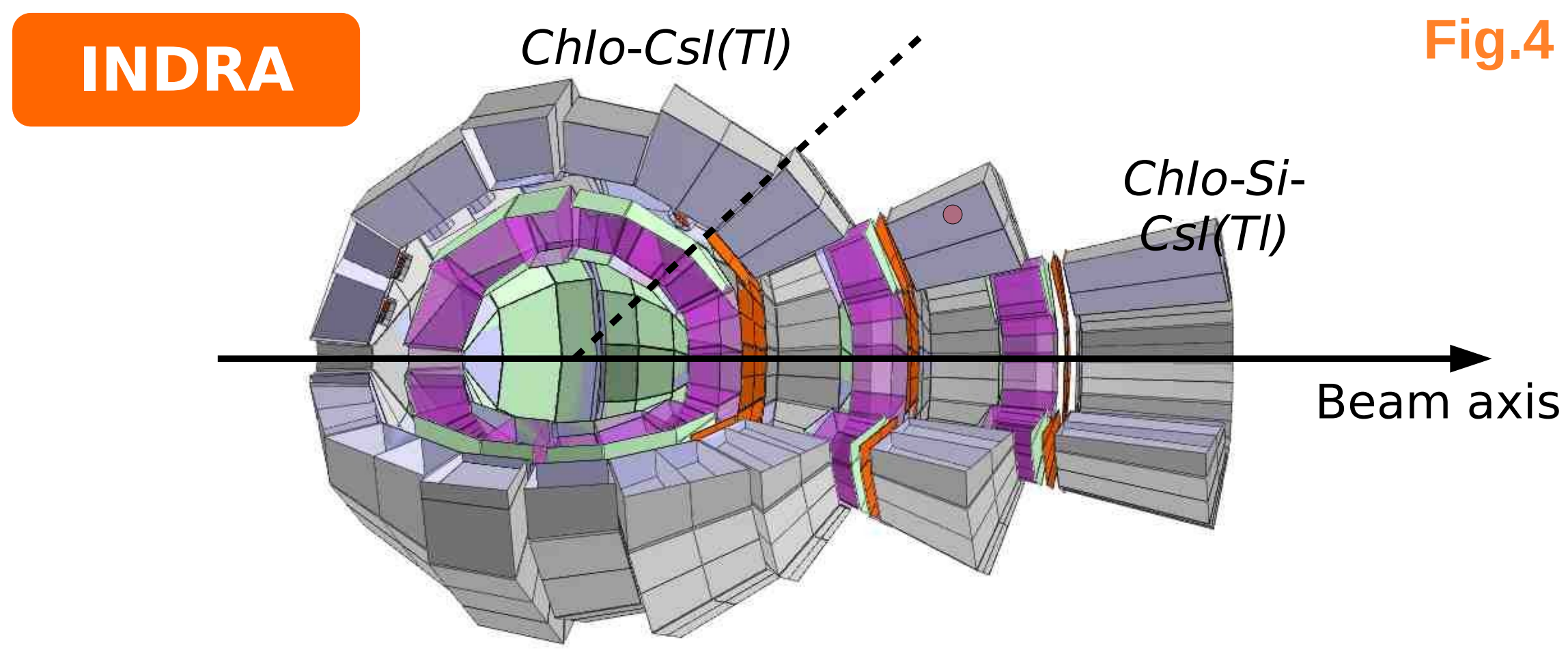


Fig.4

- 14 rings centered around beam axis (~300 identification modules)
- Identification :
  → (Z,A) for Light Charge Particles (Z≤2)
  → Z up to Z~25
- $\Theta_{LAB} \approx 7°\text{-}176°$
- Event characterization (*impact param, E*, T,...*)

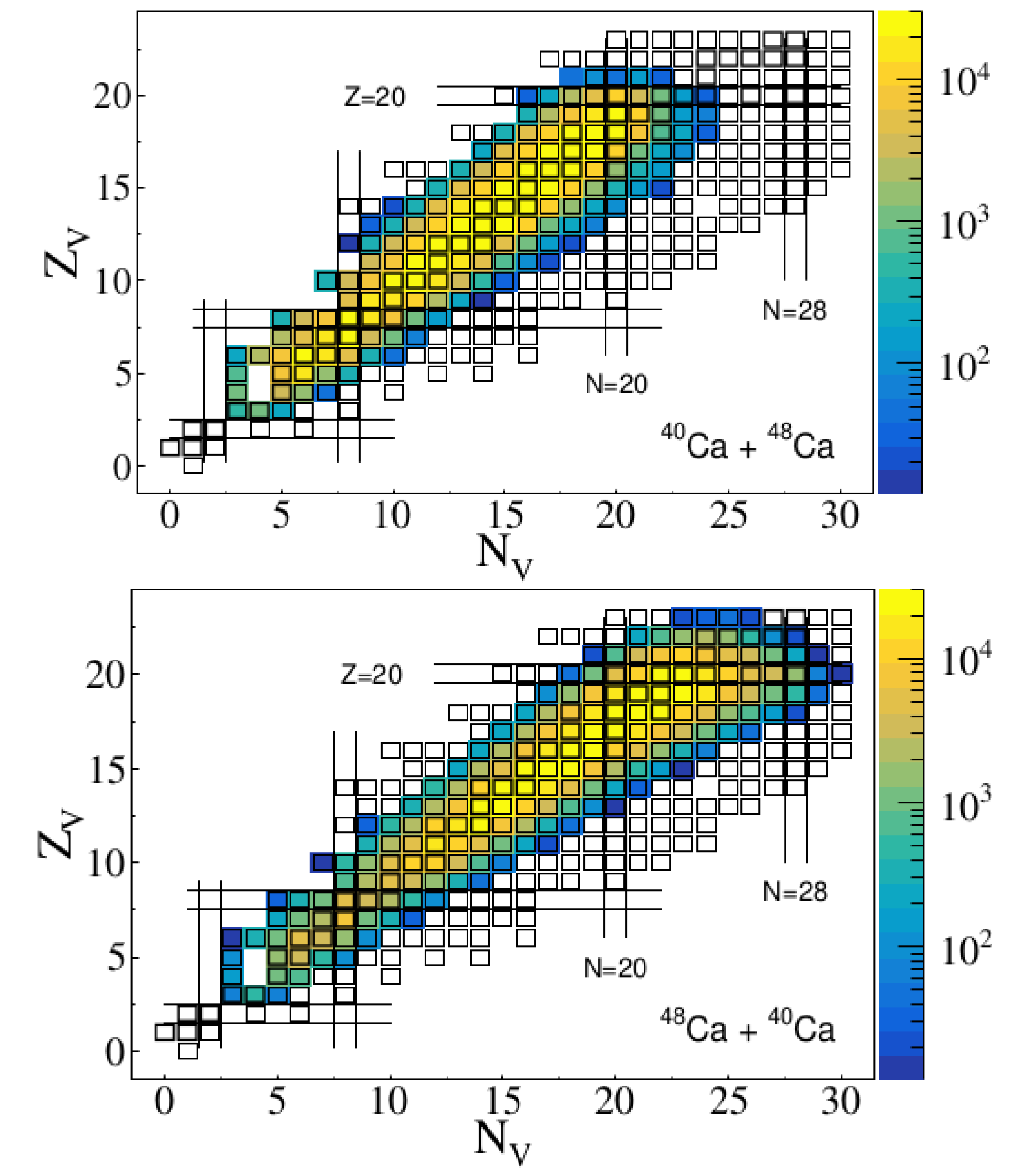


Fig.5 : Chart of the nuclides identified in VAMOS.

Isoscaling and Quasi-Projectile reconstruction

Isoscaling is a scaling behaviour observed in a variety of HIC [5], such as :

$$R_{21}(N,Z) = \frac{Y_{(2)}(N,Z)}{Y_{(1)}(N,Z)} \propto exp\left[\alpha N + \beta Z\right]$$

Where $Y_{(i)}$ is the yield of the same isotope (*N*,*Z*) measured in two reactions (1) and (2).

Assuming a thermal & chemical equilibrium is reached during the interaction, the isoscaling coefficients (*α*,*β*) can be linked to the neutron and proton chemical potentials $\mu_{n,p(i)}$:

$$\alpha = \Delta\mu_n/T \qquad \beta = \Delta\mu_p/T$$

A Gaussian approximation of the fragments yields in the grand-canonical approximation allows to link the isoscaling parameters to C_{sym} and the temperature *T* of the system [6] :

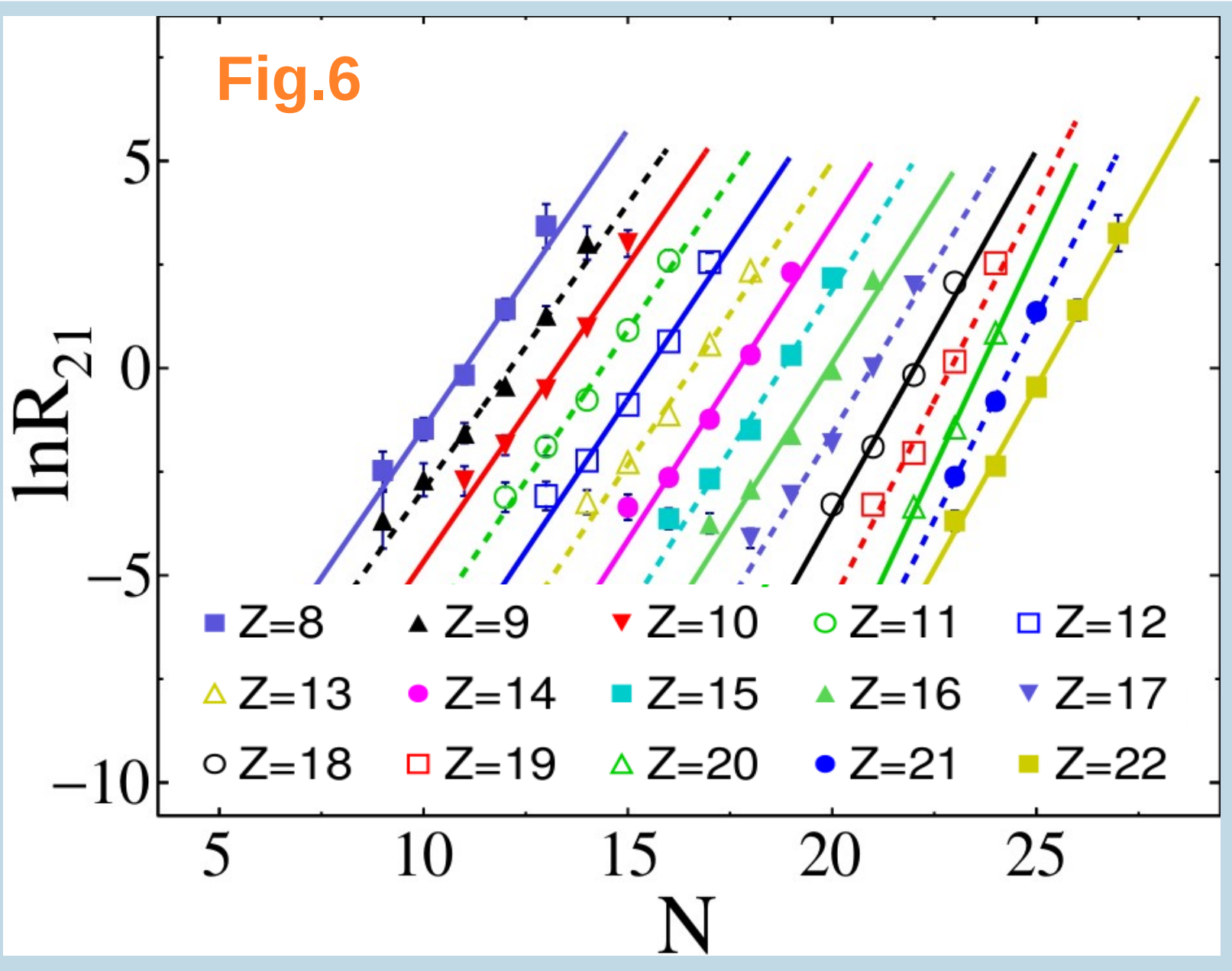
$$\frac{4C_{sym}(Z)}{T} = \frac{\alpha(Z)}{\left(\frac{Z}{\langle A_1(Z)\rangle}\right)^2 - \left(\frac{Z}{\langle A_2(Z)\rangle}\right)^2}$$

QP reconstruction based on the relative velocities between the reaction products detected with INDRA and the PLF detected identified with VAMOS.

- Neutron estimated from AMD + GEMINI filtered models ;
- QP reconstruction is mandatory to extract meaningful values from isoscaling (Fig.6).

Apparent temperatures extracted by fitting the slope of the proton kinetic energy spectra in the forward domains of the QP (Fig.7), using « 3D Calorimetry » [7].

Fig.6



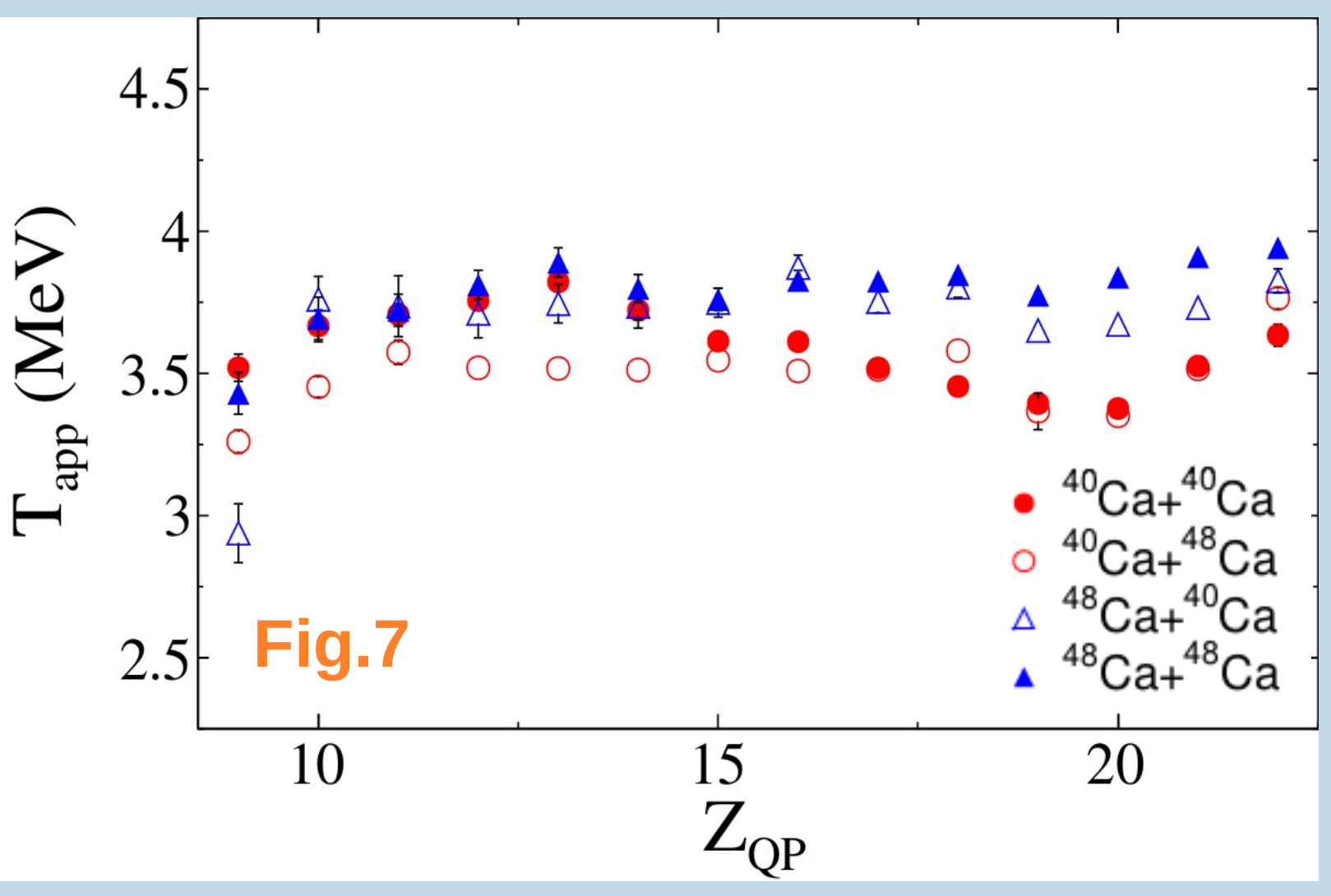


Fig.7

Conclusion

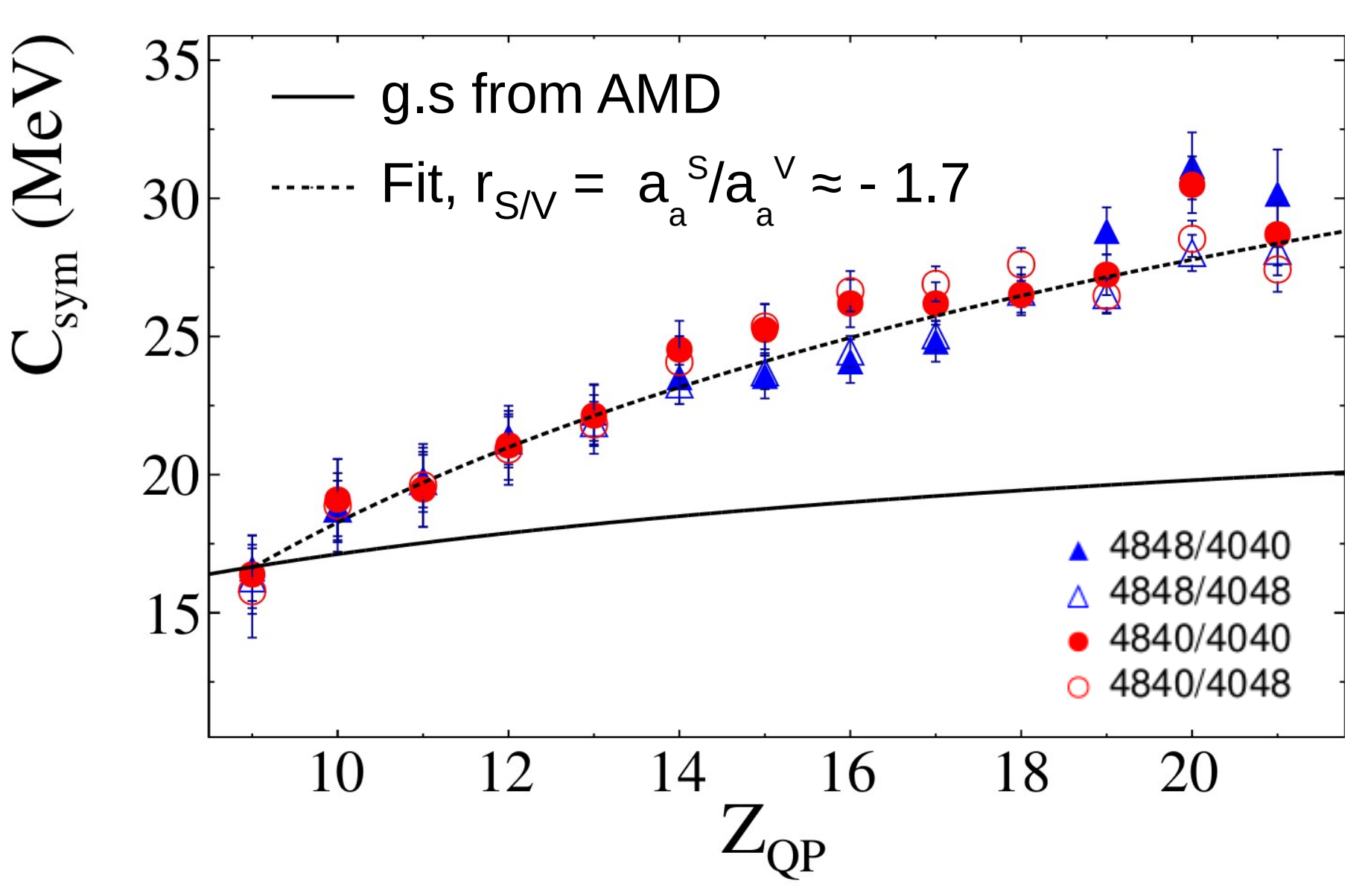


Fig.8 : Experimental symmetry energy of the reconstructed primary fragment as a function of its charge , extracted from the isoscaling method.

The **experimental symmetry energy** of the primary fragments formed in HIC peripheral collisions at intermediate energies were extracted using the **isoscaling method** :

- The Quasi-Projectile reconstruction (based on the relative velocities between the reaction products detected in INDRA and the PLF detected in VAMOS) is mandatory to extract meaningful values from isoscaling ;
- Temperatures around 3.6 *MeV* for all the systems were extracted from Maxwellian fits to the protons kinetic spectra ;

A gradual decrease of the symmetry energy of the hot primary fragments is observed with decreasing charge, from ***27 MeV*** for the most peripheral collisions (Z close to the projectile) towards ***16 MeV*** for the most dissipated.

These findings highlight the importance of **surface contribution** :

- A fit of Eq.(2) to the data leads to a surface-to-volume ratio $r_{S/V} = a_a^s/a_a^v \approx -1.7$ (Fig. 8) ;
- These results are consistent with the idea that the fragments formed a sub-saturation density and finite temperature behave differently than the bulk nuclear matter.

The observed isosaling parameters as well as the *Z/A* ratios (from PLF and reconstructed QP) are of first interest to study the isospin transport phenomena [4].

[1] P. Danielewicz, J. Lee, Nuc. Phys. A 818 (2009)
[2] N. Nikolov et al., Phys. Rev. C 83, 0343305 (2011)
[3] Y. Zhang et al., Phys. Rev. C 85, 024602 (2012)
[4] Q. Fable, Ph.D thesis, Université de Caen Normandie (2018)
[5] M. B. Tsang et al., Phys. Rev. Lett. 86, 5023 (2001)
[6] Ad. R. Raduta, F. Gulminelli, Phys. Rev. C 75, 044605 (2007)
[7] E. Vient et al., Phys. Rev. C 98, 044611 (2018)