Isospin transport phenomena and odd-even staggering in Z and N distributions in $^{84}Kr+^{112,124}Sn$ collisions at 35AMeV

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Outlook

- The physics case
- The experiment
- Isospin transport effects
- N and Z odd-even staggering
- Summary and conclusions

The physics case: the symmetry energy

- The nuclear Equation of State for asymmetric nuclear matter includes a density dependent symmetry energy term S(ρ) (not well known far from normal conditions)

$$E(\rho,I)/A = E(\rho)/A + S(\rho)\, I^2 \qquad I = N-Z/A$$

- Information on the density dependence of S(ρ) can be inferred from the investigation of isospin effects on isospin related observables.
- Such effects (known as isospin transport phenomena) arise because neutrons and protons experience different forces:

$$j_n - j_p \propto S(\rho)\nabla I + \partial S(\rho)/\partial\rho \; I \nabla\rho$$

Difference between the neutron and proton currents

V.Baran et al., Phys. Rep. 410 (2005) 335
M.DiToro et al., J.Phys.G 37 (2010) 083101

In particular:

- The isospin gradient ∇I between target and projectile (in isospin asymmetric reactions) is responsible of the isospin diffusion process, sensitive to S(ρ)
- The density gradient ∇ρ between the QP/QT region (at normal density) and the more diluted neck zone (both in symmetric and asymmetric reactions), is responsible of the isospin drift, sensitive to ∂S/∂ρ

The isospin transport phenomenon…..

- **It is still an open problem in dissipative heavy ion collisions at intermediate energies**
- **It is a challenge from the experimental point of view because it requires isotopic identification in a wide range of Z**
- **There are many papers reporting evidence of isopin drift and diffusion,**

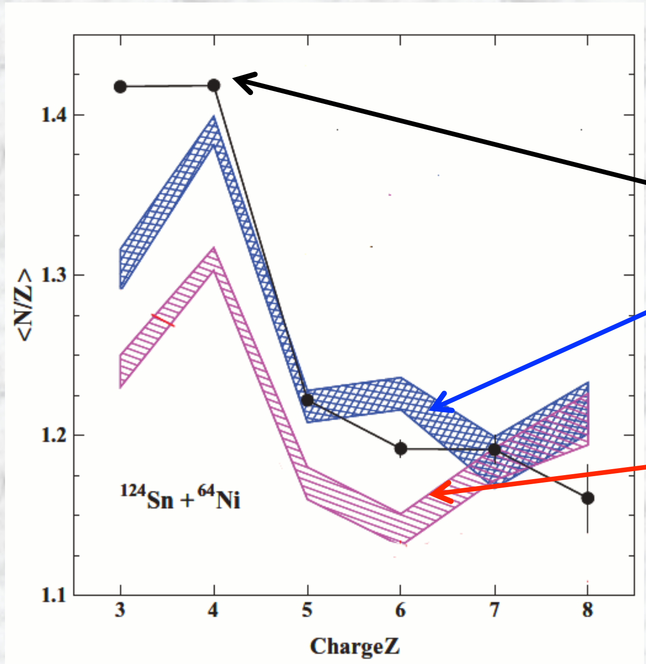
  - ✓ **by means of different observables (e.g. <N>/Z of emitted products, isotopic distribution of QP, isospin transport ratio, $Y(^{7}Li)/Y(^{7}Be)$)**

  - ✓ **by means of experimental setups with different capabilities in terms of isotopic identification (e.g. INDRA Z ≤ 4; CHIMERA Z ≤ 8; FIRST Z ≤ 14; NIMROD Z ≤ 14; LASSA Z ≤ 8; MARS spectrometer with full resolution for QP only)**

E. Galichet et al., PRC 79 (2009) 064614; M.B. Tsang et al., PRL 92 (2004) 062701; M.Veselsky et al., PRC 62 (2000) 041605; E.DeFilippo et al., PRC 86 (2012) 014610; A.B.McIntosh et al., PRC 81 (2010) 034603; T.X.Liu et al., PRC 76 (2007) 034603; Z. Kholey et al., PRC83(2011)044601 ; G.A.Souliotis et al., PLB543(2002)163; I.Lombardo et al., PRC82(2010)014608; D.Theriault et al., PRC74(2006)051602; Z.Y.Sun et al., PRC82(2010)051603; S.Hudan et al., PRC86(2012)021603

From isospin transport data to symmetry energy

- **Information on the symmetry energy term are generally obtained by means of the comparison among experimental data on isospin related observables and the predictions of theoretical models applying an afterburner (e.g. a statistical code like GEMINI, R.J.Charity, PRC82(2010)014610) to primary variables**



E.DeFilippo et al., PRC 86(2012)014610 **CHIMERA**

Exp data (neck emission)

Asystiff SMF + GEMINI

Asysoft SMF + GEMINI

SMF: V.Baran et al., NPA730(2004)329

- **It is important that the decay of primary fragments is well described by statistical codes in all its aspects, including also the staggering phenomenon**

Odd-even staggering

- Many authors report evidence of odd-even staggering in the Z distribution of the final products in a wide range of reactions, e.g.
  - low energy fission B.L.Tracy et al., PRC5(1972)222 and low energy reactions in general G.Ademard et al., PRC83(2011)054619
  - spallation and fragmentation at relativistic energies M.V.Ricciardi et al., NPA 733 (2004)299, P.Napolitani et al., PRC76(2007)064609; fragmentation at 140AMeV J.R.Winkelbauer et al., PRC88(2013)044613
  - multifragmentation reactions and semiperipheral collisions at Fermi energies G.Casini et al., PRC86(2012)011602, I.Lombardo et al., PRC84(2011)024613
  - the QP decay and central collisions in reactions under 20AMeV M.D'Agostino et al., NPA861(2011)47, M.D'Agostino et al., NPA875(2012)139
- In I.Lombardo et al., PRC84(2011)024613 the N staggering in a small range of Z is presented and discussed
- Its origin is not completely understood; it is generally attributed to the restoration of structure effects (i.e. pairing interaction) in the last step(s) of the decay.
- At present , to our knowledge, the available statistical codes are not able to reproduce the details of the phenomenon, although some gross features are reproduced.
- From the experimental point of view, in order to investigate the staggering phenomenon in an accurate way in all its aspects (including isospin effects) it is necessary to have isotopic resolution in a wide range of Z

The FAZIA (Four-π A and Z Identification Array) project

- **In order to meet the requirements in terms of isotopic identification coming from the study of isospin related observables ….**
- **…also in view of the forthcoming exotic beams…**
- **…the Fazia Collaboration started the R&D phase in 2006…**

INFN (Firenze, Napoli, LNL, LNS, Bologna), Italy

LPC, IN2P3-CNRS,ENSICAEN, Universite' de Caen, GANIL, France

CEA/DSM-CNRS, IPN Orsay, Universite' Paris-Sud XI, France

Dipartimento di Fisica Università di Firenze, Italy

Dipartimento di Fisica Università di Bologna, Italy

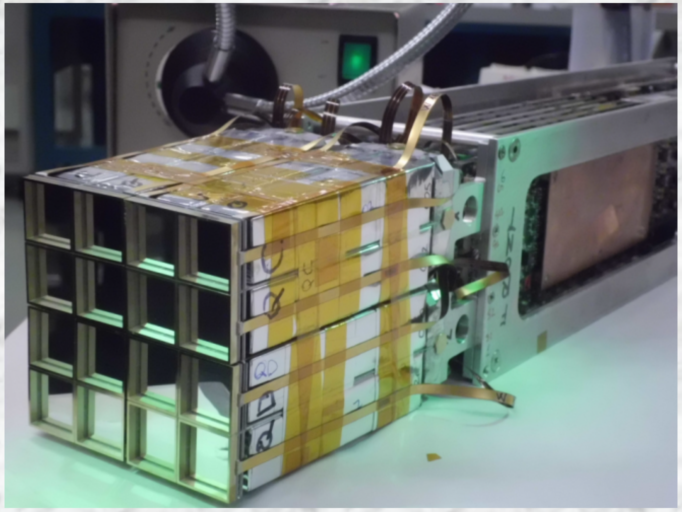
Dipartimento di Fisica Università Federico II Napoli, Italy

Jagellonian University, Institute of Nuclear Physics IFJ-Pan, Krakow, Poland

National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania

- **…aiming at the design and construction of a 4π detector for A and Z identification with high resolution and low thresholds, to be used with standard (GANIL, LNL, LNS) and radioactive (SPIRAL2, SPES, EURISOL) beams in the range 10-50AMeV.**
- **Since 2007 many tests under beam were performed, showing very good performances in terms of A and Z identification and thresholds**
- **At present the first block is in the commissioning phase**

The Fazia Project



- **Detector layout:**
  - **Blocks of 16 Si (300μm) – Si (500μm) – CsI (10 cm) (read out by a photodiode) telescopes**
  - **Fully equipped with digital electronics**
  - **Si detectors are reverse mounted for Pulse Shape Analysis**
- **Identification techniques:**
  - **ΔE –E for particles punching-through the first 300μm Si layer**

    full Z identification; A identification up to Z~23
  - **Pulse Shape Analysis for particles stopped in the first Si layer:**

    full Z identification for Z-dependent range (starting from 30μm of Si)

    A identification - up to Z~15 - for A- dependent range (> 150 μm)
  - **Time of flight**

The Fazia recipe in a nutshell

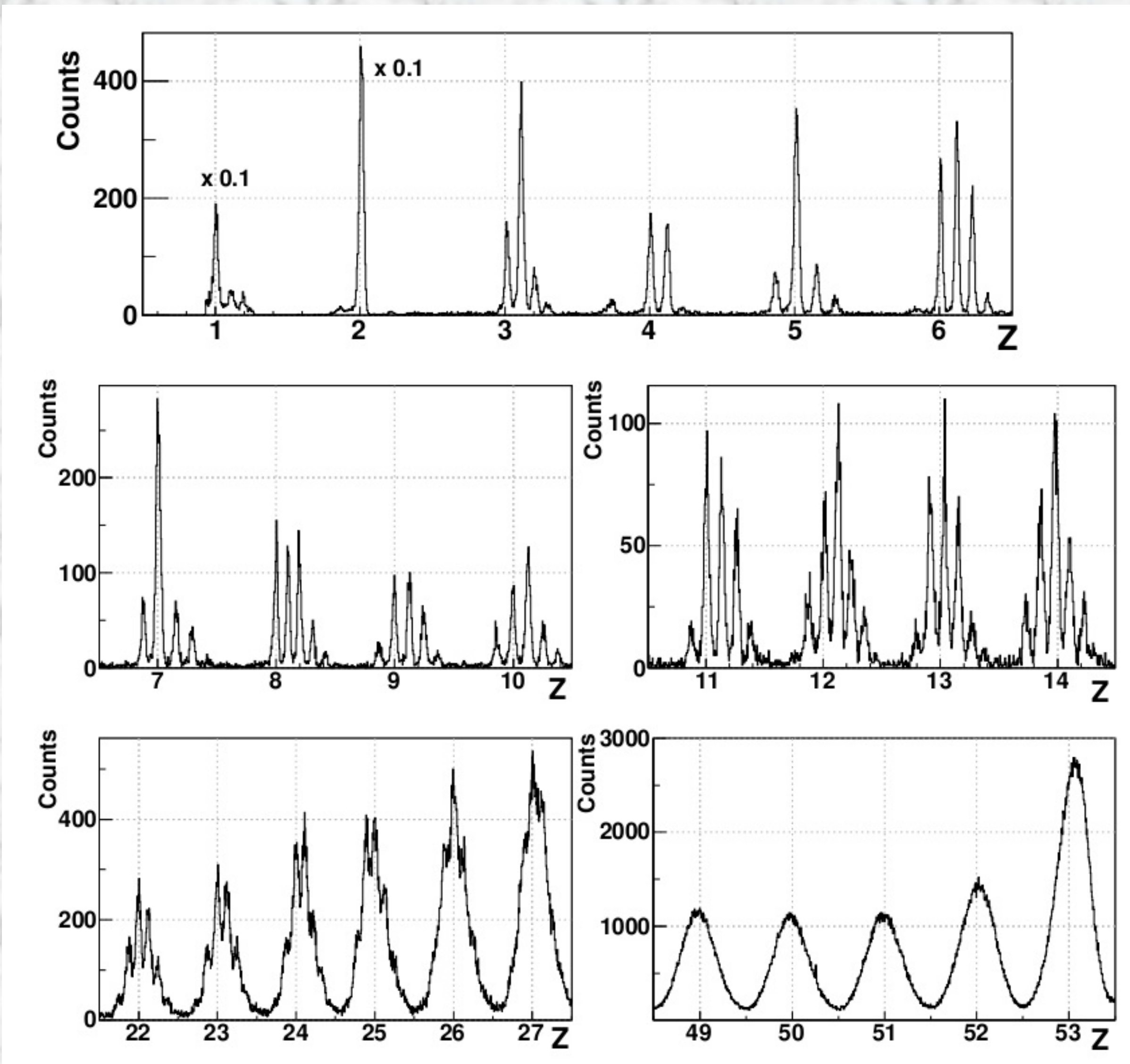
- *n-TD Si detectors with good doping uniformity (<3% FWHM)*
- *Si thickness uniformity within ~1μm (on a thickness of 300μm and 500μm)*
- *Si detectors obtained from wafers cut at 7° off the <100> axis, to minimize channeling*
- *Reverse mounting of the Si detectors*
- *30μm thick Al layer on both sides of the Si in order to reduce sheet resistance (good timing properties)*
- *Keeping constant the applied voltage across the detector*
- *Purposely developed Front End Electronics and preamp located inside the vacuum chamber (to reduce noise)*
- *Proper identification algorithms have been developped*

The results of the R&D phase are summarized in the following bibliography:

L.Bardelli et al., NIMA 491 (2002) 244
L.Bardelli et al., NIMA 521 (2004) 480
G.Pasquali et al., NIMA 570 (2007) 126
S.Barlini et al., NIMA 600 (2009) 644
L.Bardelli et al., NIMA 605 (2009) 353
S. Carboni et al., NIM A 664 (2012) 651
N.LeNeindre et al., NIMA 701 (2013) 145
G.Pasquali et al., accepted in EPJA (2014)
R.Bougault et al., EPJA 50 (2014) 47 (general review paper)
H.Hamrita et al., NIMA 531 (2004) 607
L.Bardelli et al., NIMA 560(2006) 524
L.Bardelli et al., NIMA 572 (2007) 882
L.Bardelli et al., NIMA 602 (2009) 501
L.Bardelli et al., NIMA 654 (2011) 272
G.Pasquali et al., EPJA 48 (2012) 158
S.Barlini et al., NIMA 707 (2013) 89

Example of the detector performances

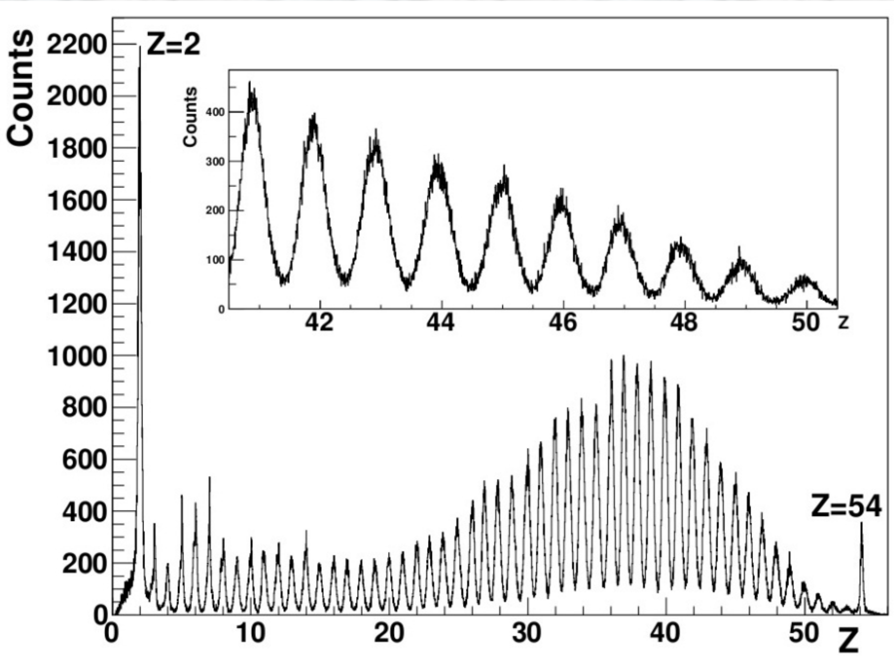
Identification spectra for particles punching through the first Si layer from ΔE-E technique



S.Carboni et al., NIMA 664 (2012) 251

Example of the detector performances

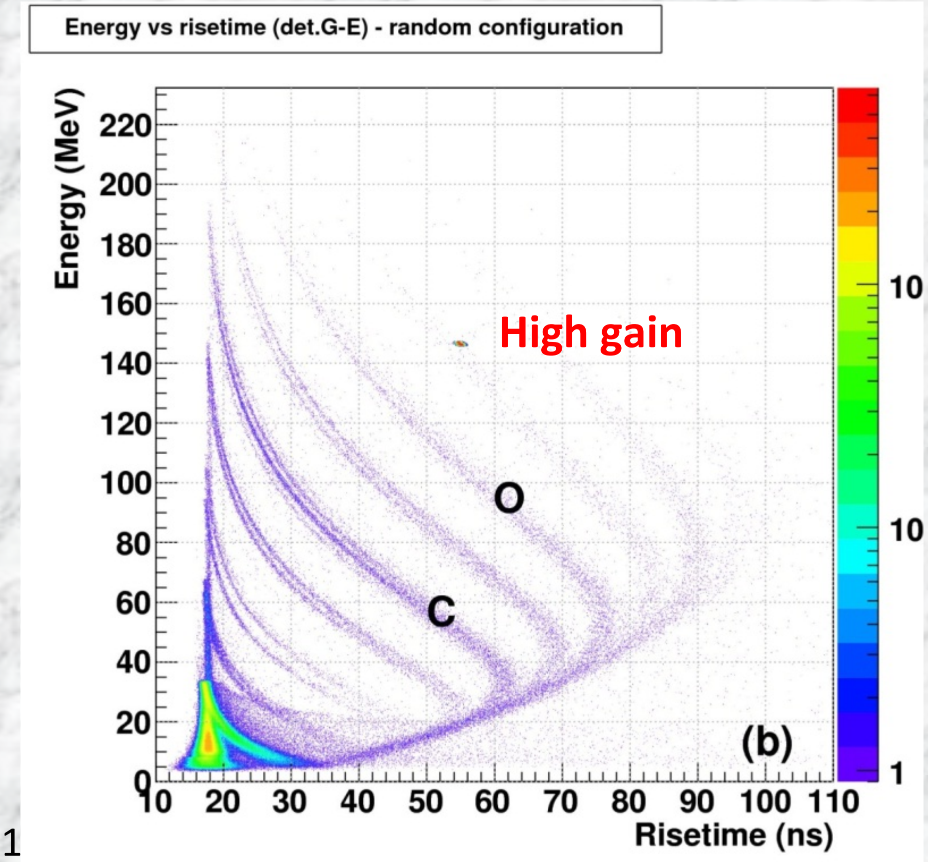
PSA for particle stopped in Si1



S.Carboni et al., NIMA 664 (2012) 251

Identification spectrum from PSA on Energy vs. Charge rise time

PSA: Energy vs. Charge Rise Time with isotopic resolution



L.Bardelli et al., NIMA 602 (2009) 501

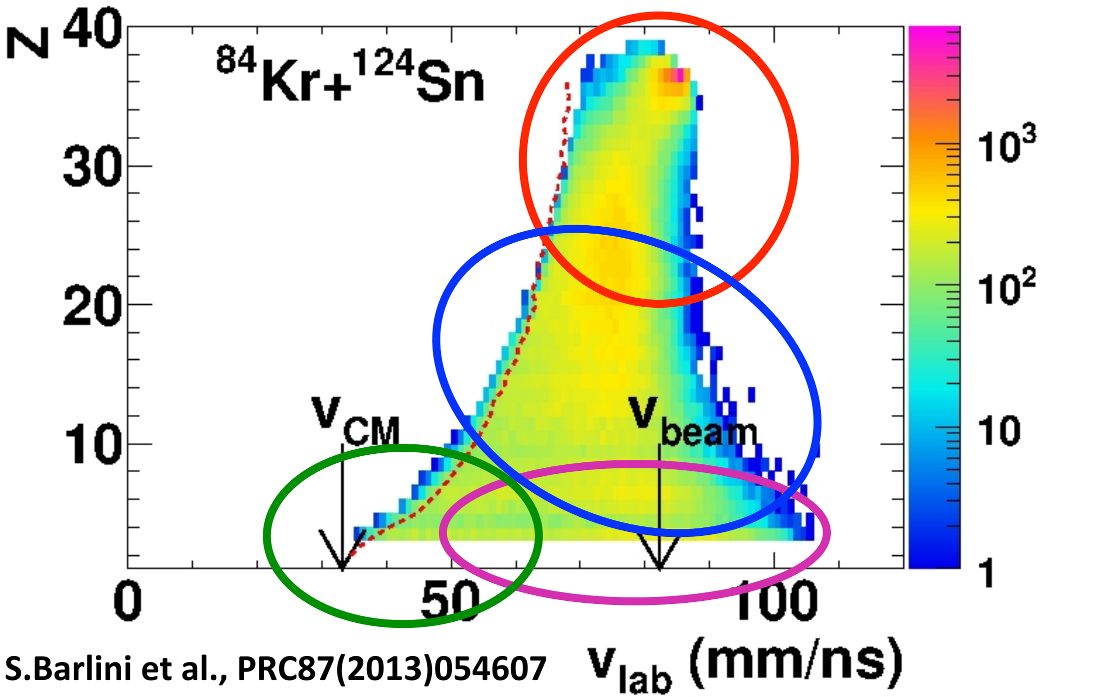
The experiment

- **Investigated reactions: $^{84}Kr+^{112,124}Sn$ at 35AMeV (beam delivered by CS at LNS – Catania in 2011 for a test experiment of the FAZIA Collaboration)**
- **Isopin content:**
  - ❖ **1.33 for the projectile ^{84}Kr**
  - ❖ **1.48 for ^{124}Sn**
  - ❖ **1.24 for ^{112}Sn**
- **Grazing angles:**
  - ❖ **4.1° for n-poor reaction ($^{84}Kr+^{112}Sn$)**
  - ❖ **4.0° for n-rich reaction ($^{84}Kr+^{124}Sn$)**
- **A single FAZIA telescope was located just beyond the grazing angle for both reactions (angular coverage: 4.8°- 6°) in the Ciclope scattering chamber**
- **Only inclusive measurements (no coincidences)**

Event characterization

Since the telescope is located just beyond the grazing angle for both reactions, *some kind of event selection is done by the geometry itself:*

- **Only fragments forward-emitted in the centre of mass can be detected, i.e.**
    - **QP residues (Z>20)**
    - **QP fission fragments (Z=7-20)**
    - **Neck emission**
    - **QP evaporation**
- **QT contamination is negligible**



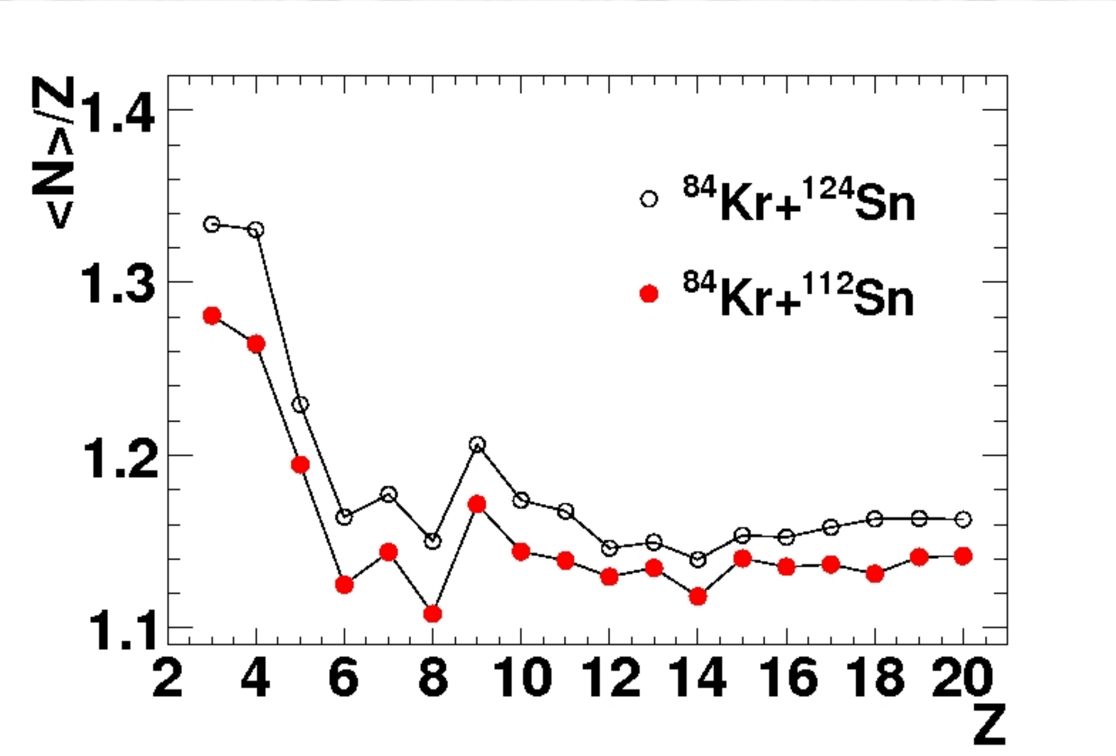
S.Barlini et al., PRC87(2013)054607

Since

- **the kinematics is very similar for both reactions,**
- **the projectile is the same ^{84}Kr**
- **targets are different (^{112}Sn and ^{124}Sn)**
- **and we can detect only fragments coming from the QP phase space**

any difference seen in the isotopic composition of the detected reaction products should be attributed to a transport of isospin between projectile and target

<N>/Z of the detected products

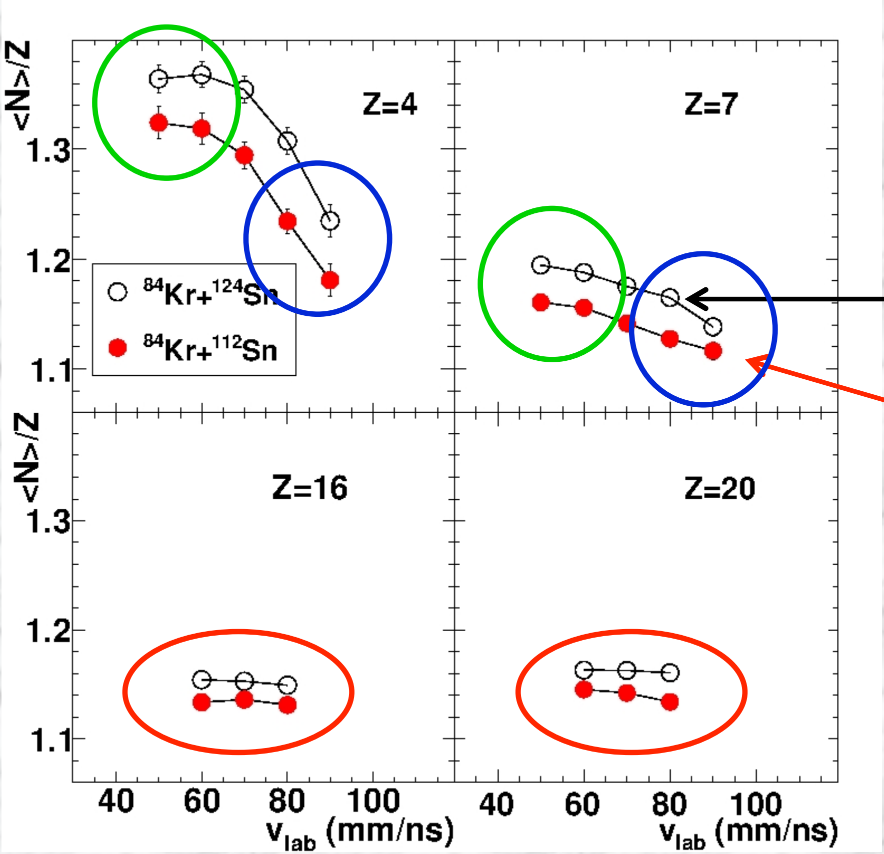


The <N>/Z of the products detected in the n-rich case is systematically higher than the <N>/Z of the n-poor case

Since our telescope detects mainly fragments coming from the QP phase space and the projectile does not change, this difference is due to the isospin diffusion between target and projectile

S.Barlini et al., PRC87(2013)054607

Velocity dependence of <N>/Z:

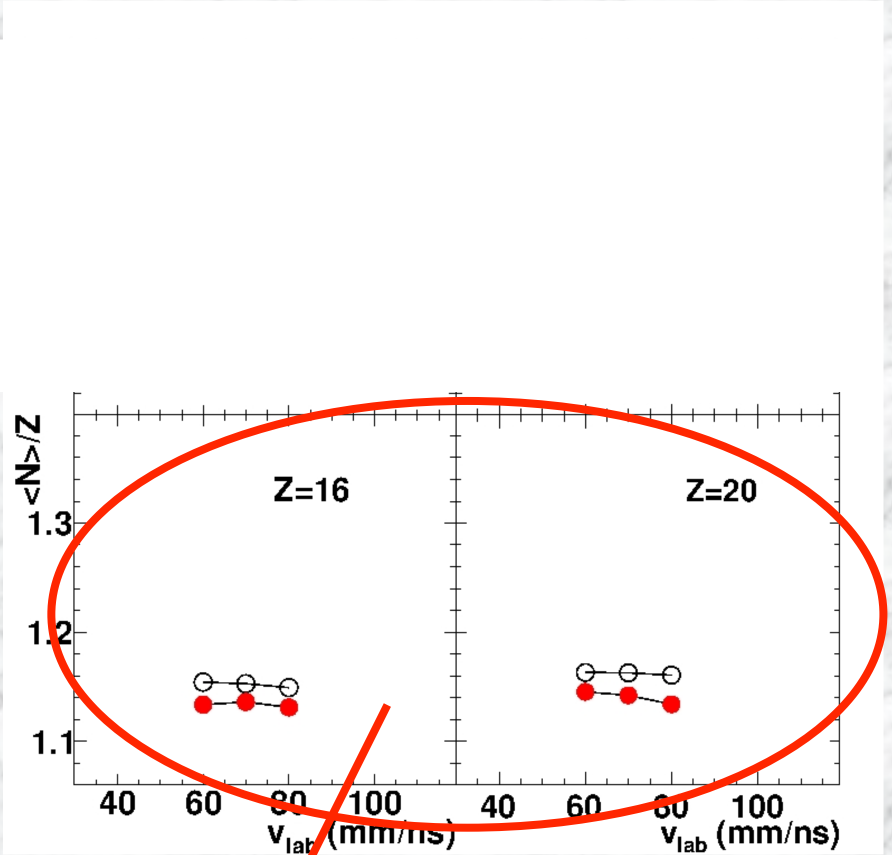


Light fragments: strong dependence on v_{lab}

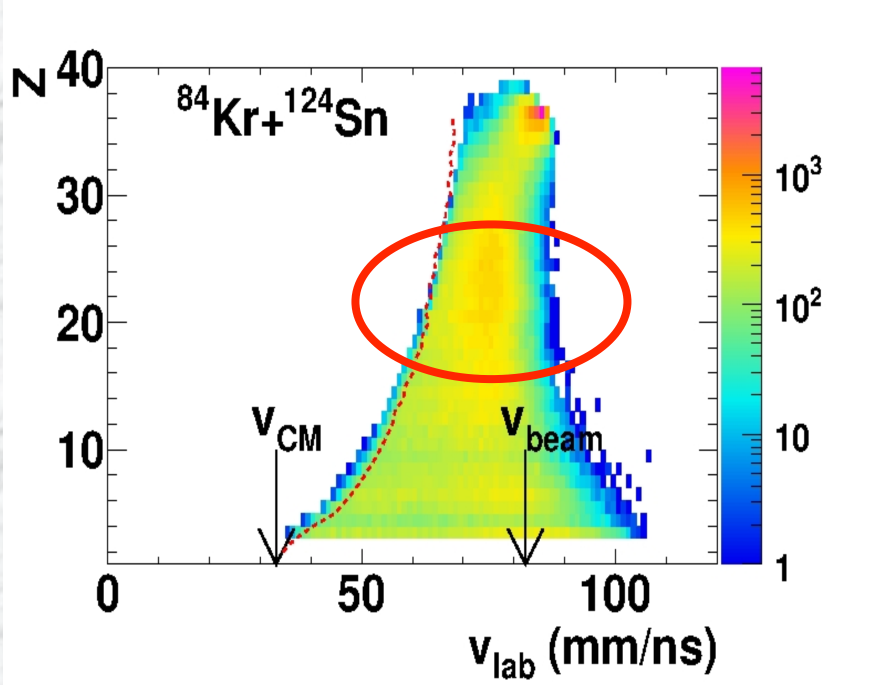
<N>/Z of n-rich case sistematically higher at all v_{lab} values

Heavy fragments: almost no dependence on v_{lab}

Velocity dependence of <N>/Z: heavy fragments



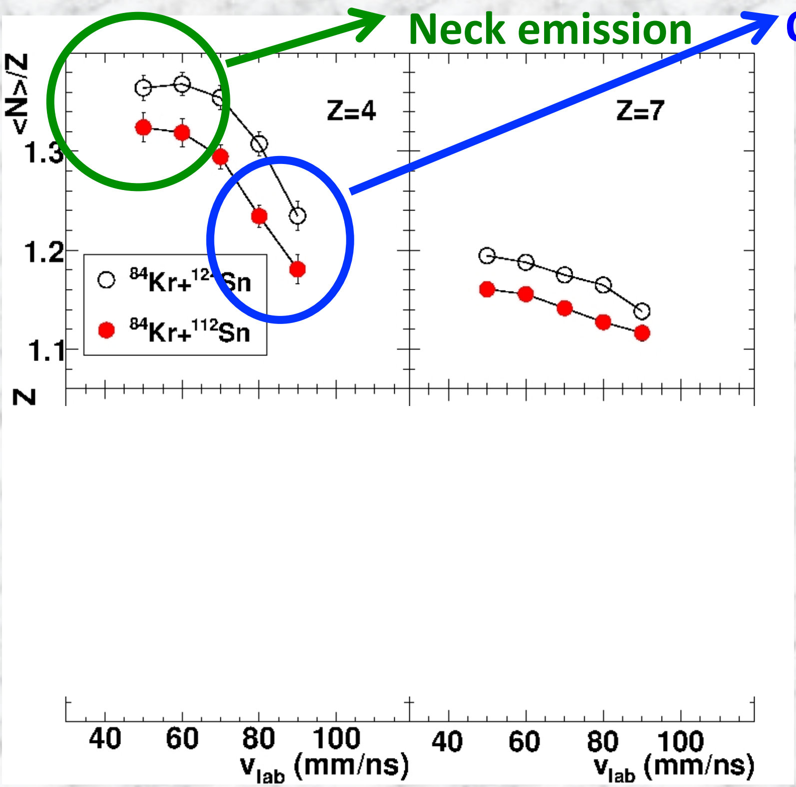
QP Fission fragments

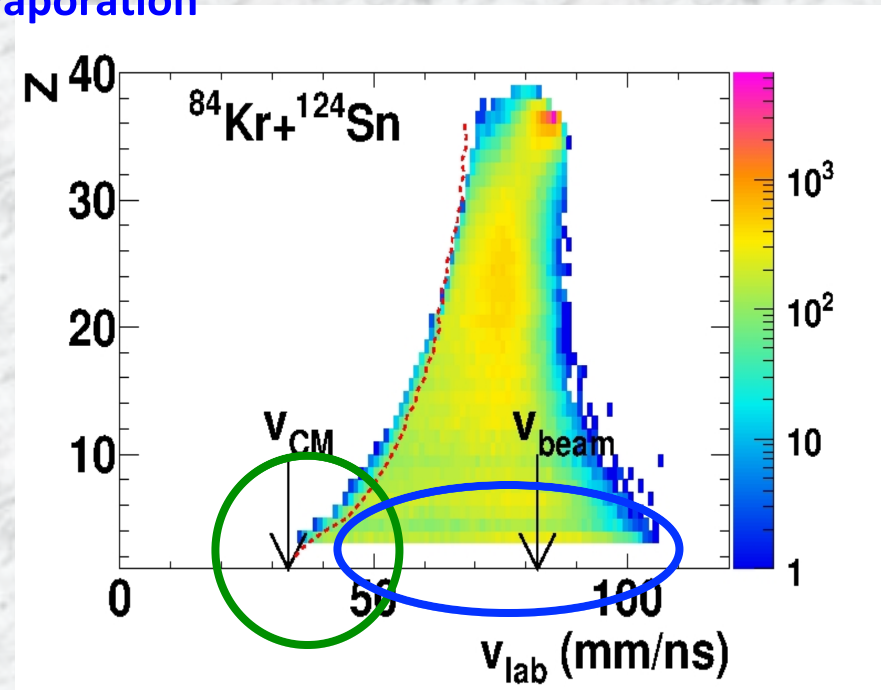


- Heavy fragments come from a unique mechanism (QP fission)

We can expect that <N>/Z is independent of the lab velocity

Velocity dependence of <N>/Z: light fragments





Neck fragments are more neutron rich than those coming from QP decay

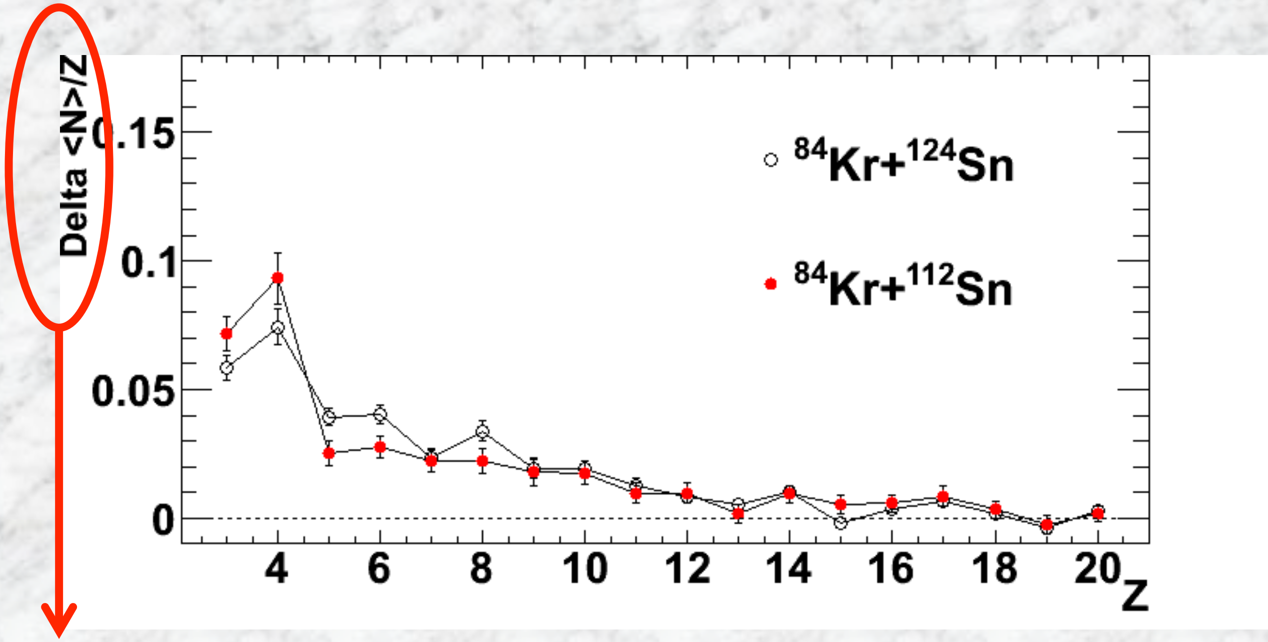
Possible evidence of isospin drift from the QP/QT region at normal density towards the more diluted neck zone

2 production mechanisms for light fragments:

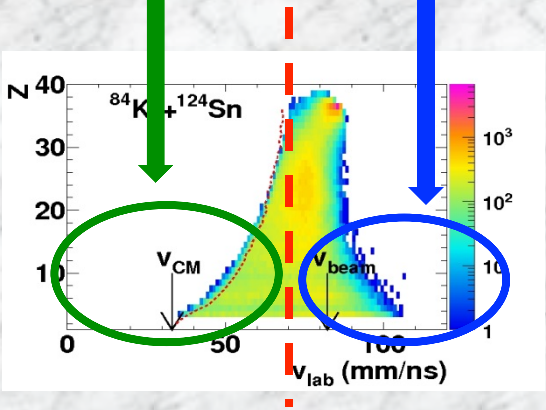
- QP evaporation
- Neck emission

We can expect a difference in the <N>/Z

A better way to put into evidence the isospin drift



Delta= <N>/Z backward - <N>/Z forward



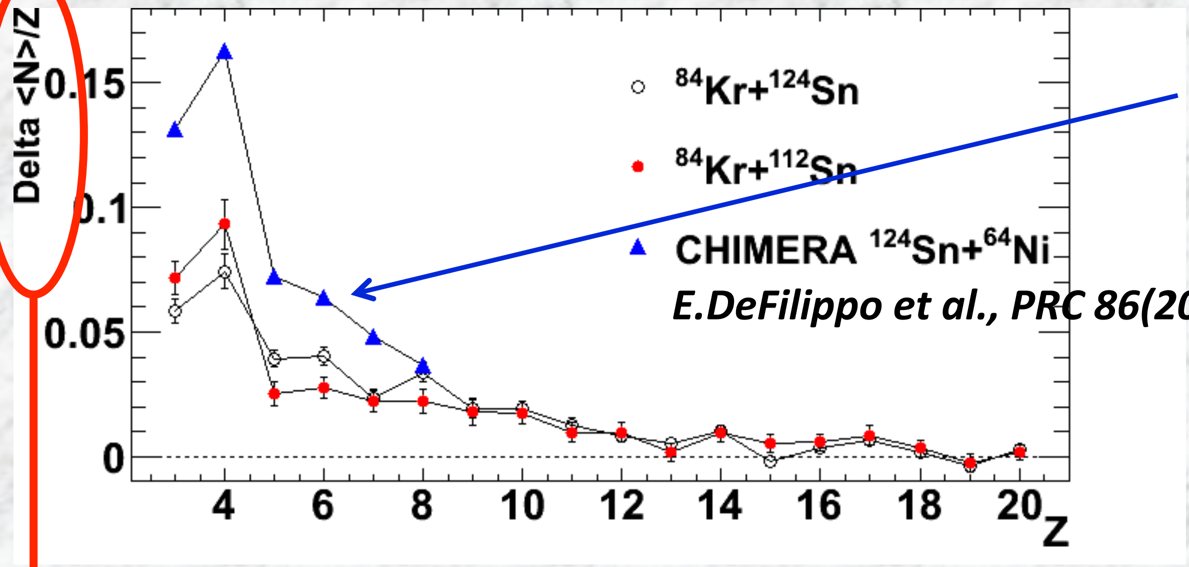
The isospin diffusion effect is canceled out

Only the isospin drift effect remains

The isospin drift is observed mainly for light fragments

S.Barlini et al., PRC87(2013)054607

Our interpretation concerning the neck origin of backward emitted light fragments is supported by the comparison with the data of a more complete experiment with a cleaner event selection:

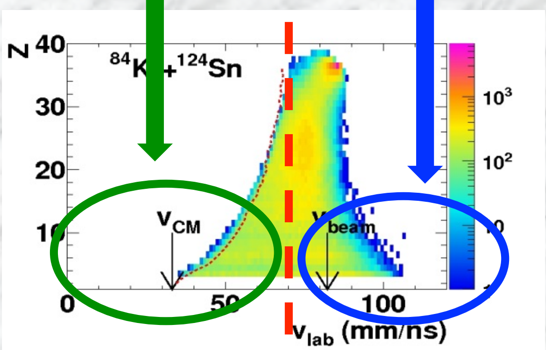


E.DeFilippo et al., PRC 86(2012)014610

$(\langle N\rangle/Z)_{neck} - (\langle N\rangle/Z)_{QP}$

Delta= <N>/Z backward - <N>/Z forward

In the superposition region (Z<9) the behaviour is similar



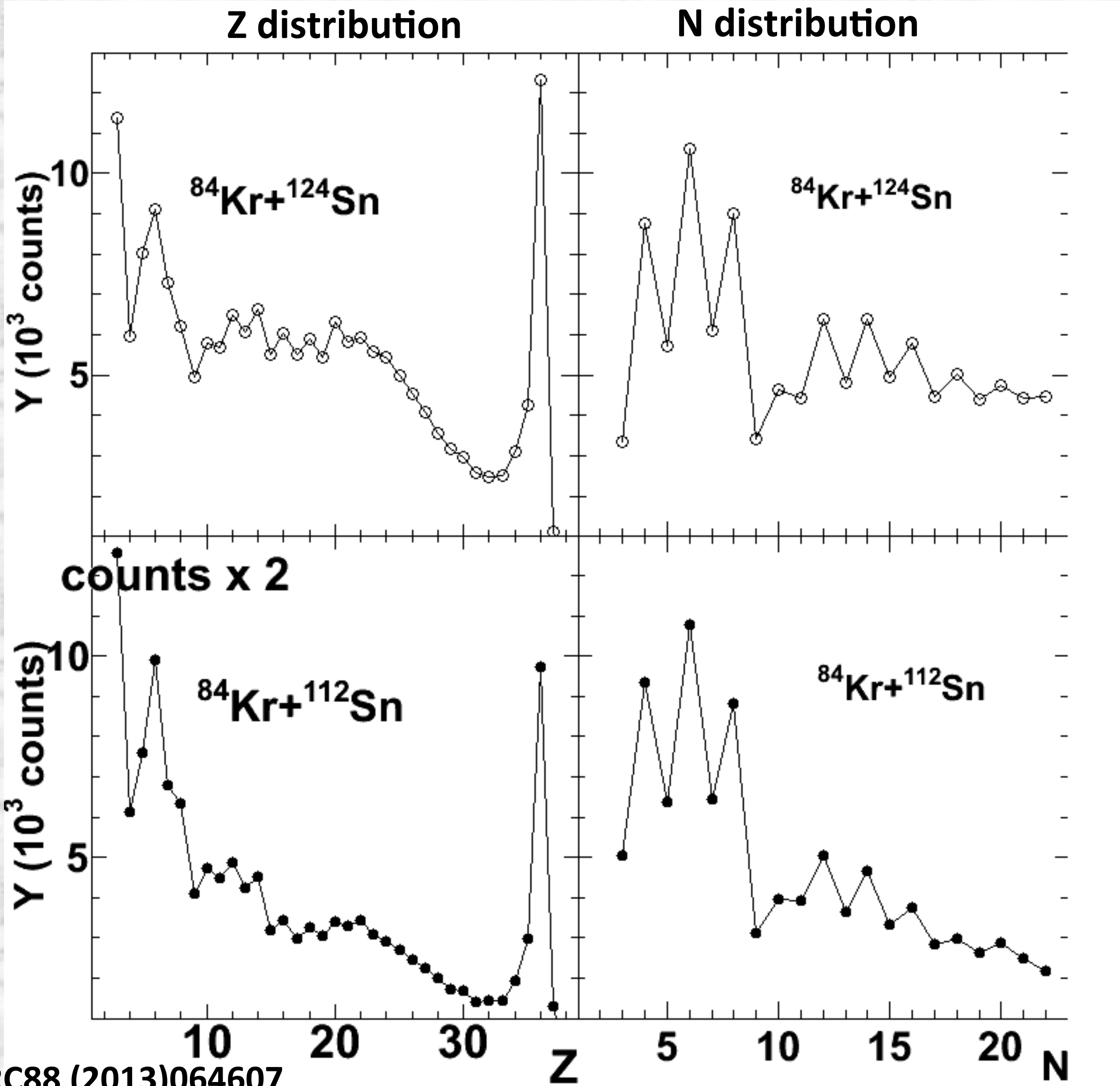
Other evidences of isospin enrichment of the midvelocity emission:

e.g. D.Theriault et al., PRC74(2006)051602;
I.Lombardo et al., PRC82(2010)014608;
E.Plagnol et al., PRC61(1999)014606;
Y.Larochelle et al., PRC62(2000=051602;
J.F.Demspey et al., PRC54(1996)1710;
for H isotopes S.Piantelli et al., PRC 76(2007)061601

Odd Even staggering

- **Since we have Z and N distributions, it is possible to investigate the staggering effect in both variables as in I.Lombardo et al., PRC84(2011)024613**
- **How can we exctract the staggering from the experimental yields? (i.e. we have to remove the average smooth behaviour)**

Experimental yields



S.Piantelli et al., PRC88 (2013)064607

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- **How can we exctract the staggering from the experimental yields? (i.e. we have to remove the average smooth behaviour)**
- **How can we evaluate in a quantitative way the staggering amplitude?**

We can use the prescription of B.L.Tracy et al., PRC 5 (1972) 222, where the parameter δ (which gives the local deviation of the cross section from a gaussian-like distribution) calculated on 4 neighbouring elements is introduced:

$$\delta(Z+3/2) = 1/8\,(-1)^{Z+1}\,[\ln Y(Z+3) - \ln Y(Z) - 3(\ln Y(Z+2) - \ln Y(Z+1))]$$

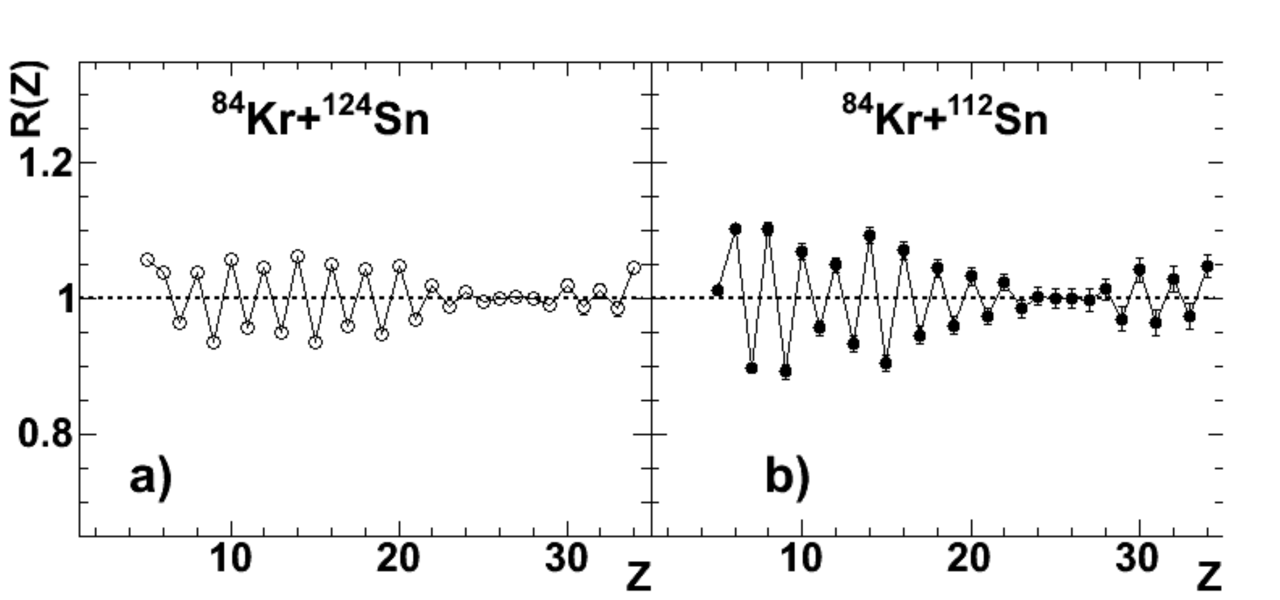
With a modification to evaluate the staggering amplitude in Z (or N) (i.e. we use 5 neighbouring elements):

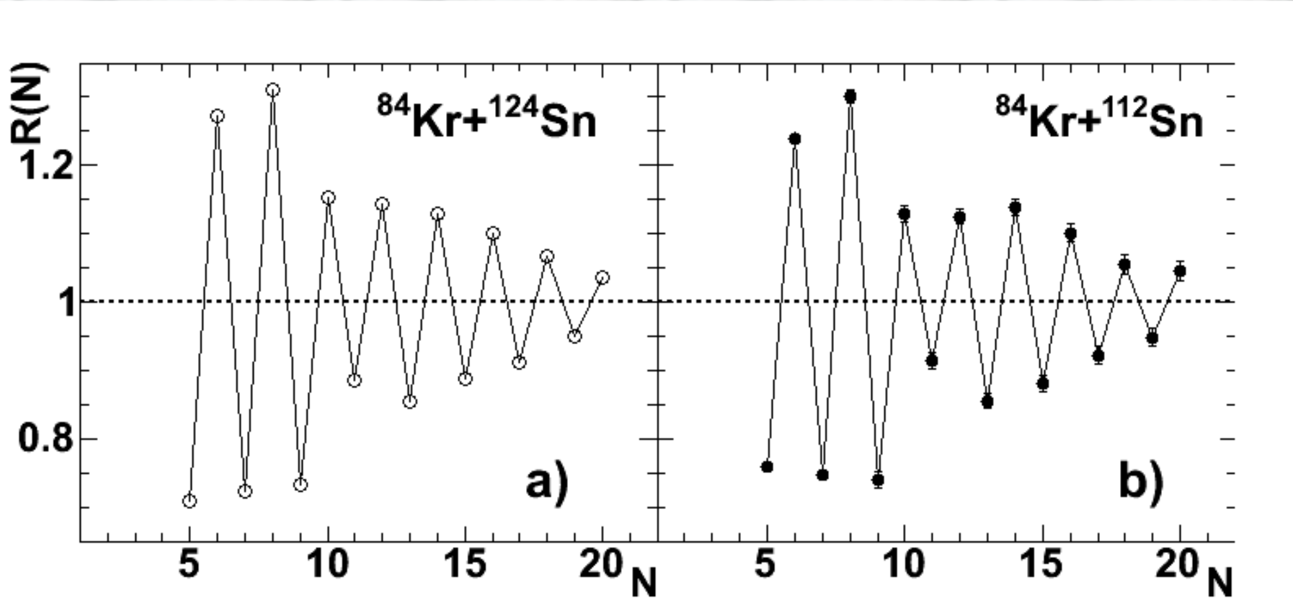
$$\delta(Z) = 0.0625(-1)^{Z}\,[\ln Y(Z+2) - 4\ln Y(Z+1) + 6\ln Y(Z) - 4\ln Y(Z-1) + \ln Y(Z-2)]$$

- **δ=0 no staggering**
- **δ>0 staggering (even N/Z yields > odd ones)**
- **δ<0 anti-staggering**

$R(Z)=(-1)^{-Z}\,\delta(Z)+1$ gives a ″sawteeth″ distribution (around 1) in presence of staggering

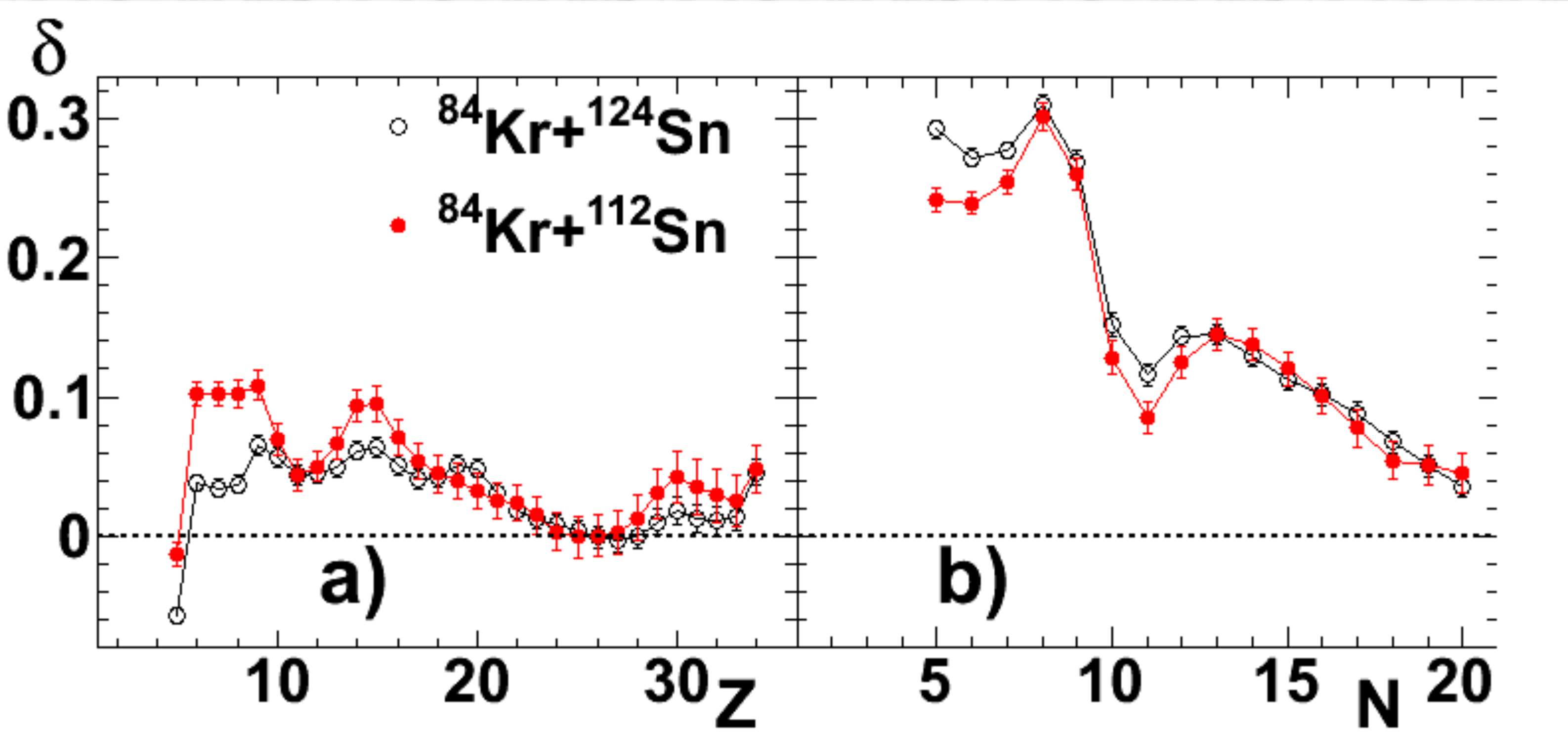
R distribution: a first glance at the staggering





S.Piantelli et al., PRC88 (2013)064607

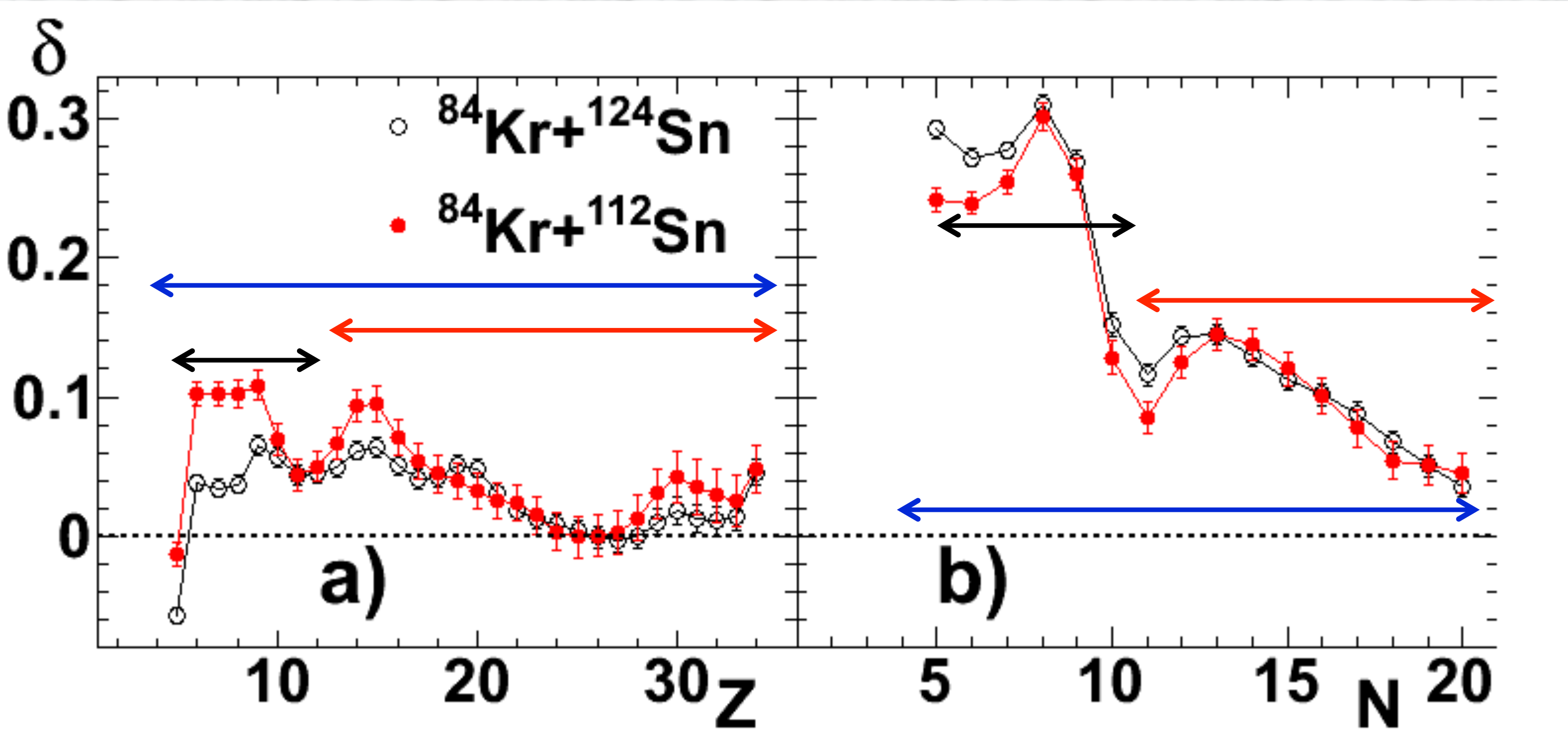
δ distribution: quantitative evaluation



- N staggering greater than Z staggering for our systems
- Z staggering greater for n-poor system
- N staggering more similar for both systems
- The staggering decreases when the size of the fragments increases ,with some bumps e.g. around Z=30 see also G.Casini et al., PRC86(2012)011602

S.Piantelli et al., PRC88 (2013)064607

Comparison among different systems

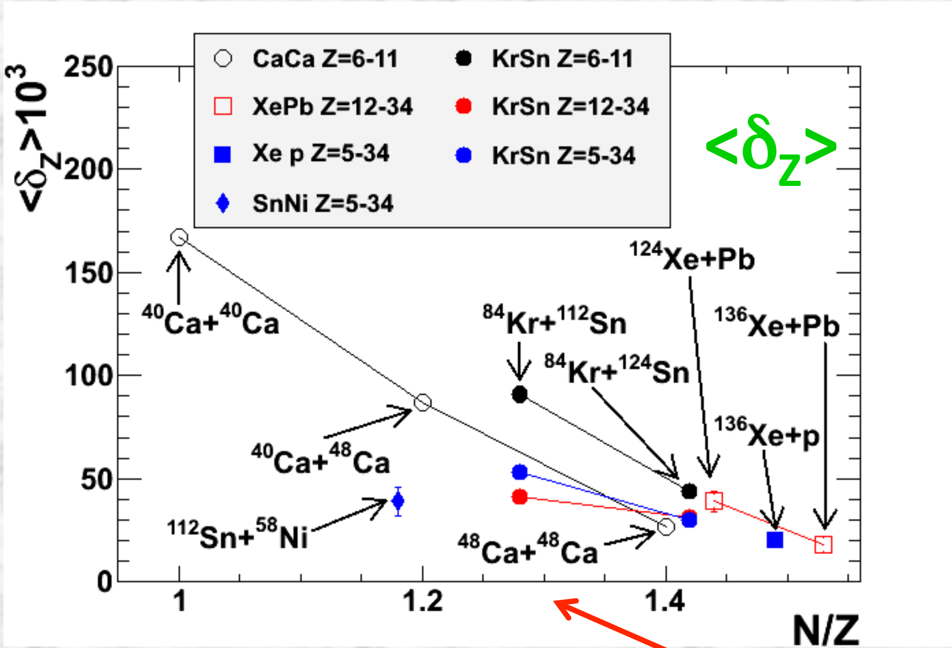


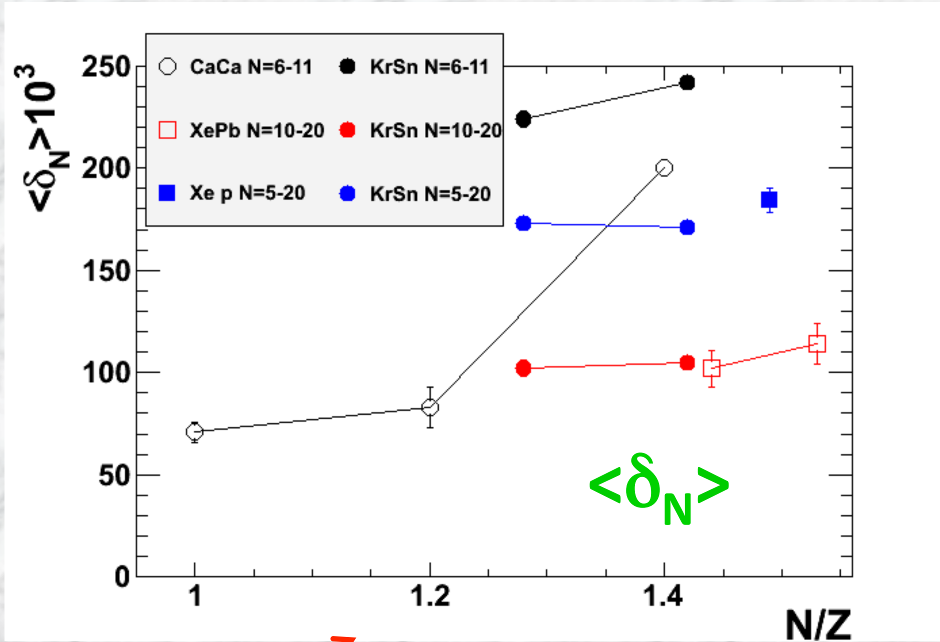
We calculate the <δ> in different regions (corresponding to common ranges in data of different experiments)

- **Z=6-11**
- **Z=12-34**
- **Z=5-34**

- **N=6-11**
- **N=10-20**
- **N=5-20**

Comparison among different systems: <δ>





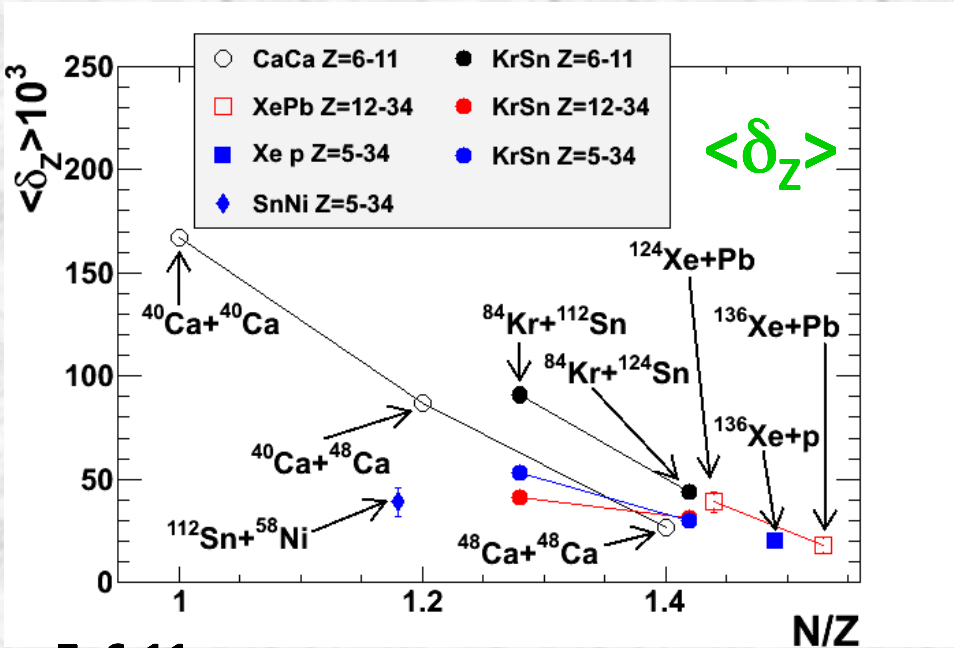
Z=6-11
Z=12-34
Z=5-34

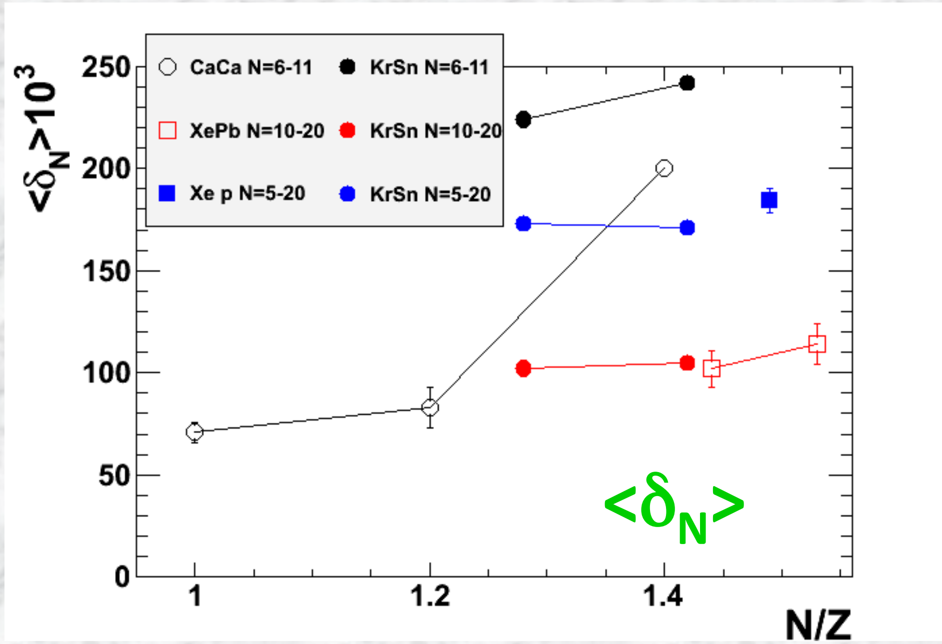
Warning: N/Z of the total system!
Not necessarily equal to the N/Z of the source

N=6-11
N=10-20
N=5-20

- ^{40,48}Ca+^{40,48}Ca@25AMeV: CHIMERA data at LNS I.Lombardo et al., PRC84(2011)024613
- ^{124,136}Xe+Pb@1AGeV: FRS at GSI D.Henzlova et al., PRC78(2008)044616
- ^{136}Xe+p@1AGeV: FRS at GSI P.Napolitani et al., PRC76(2007)064609
- ^{84}Kr+^{112,124}Sn@35AMeV: FAZIA telescope at LNS S.Piantelli et al., PRC88(2013)064607
- ^{112}Sn+^{58}Ni@35AMeV: CHIMERA data at LNS G.Casini et al., PRC86(2012)011602

Comparison among different systems: $<\delta>$



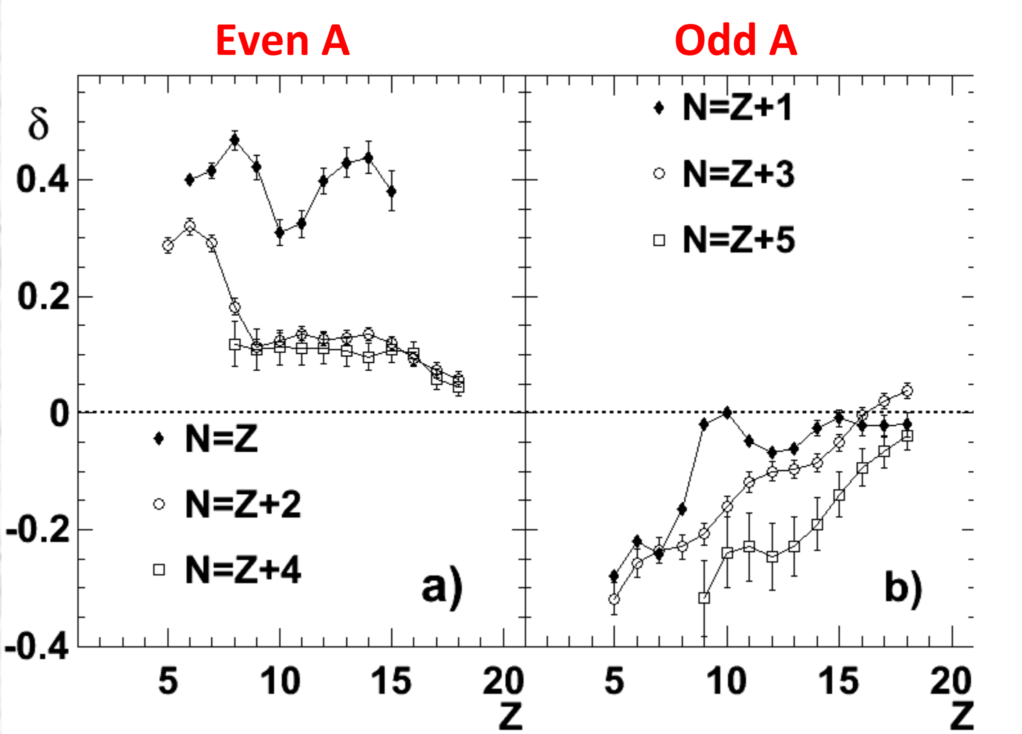


Z=6-11
Z=12-34
Z=5-34

N=6-11
N=10-20
N=5-20

- Staggering weakly dependent on the reaction mechanism (last step(s) effect?)
- Z staggering wider for n-poorer systems
- Less evident dependence of N staggering on the N/Z of the total system

Chains with N-Z=k



- There is a hierarchy in k
- N=Z chain has the largest staggering
- Antistaggering for odd N-Z
- Similar results observed in
  P.Napolitani et al., PRC76(2007)064609
  M.V.Ricciardi et al., NPA 733 (2004)299
  M.D'Agostino et al., NPA861(2011)47

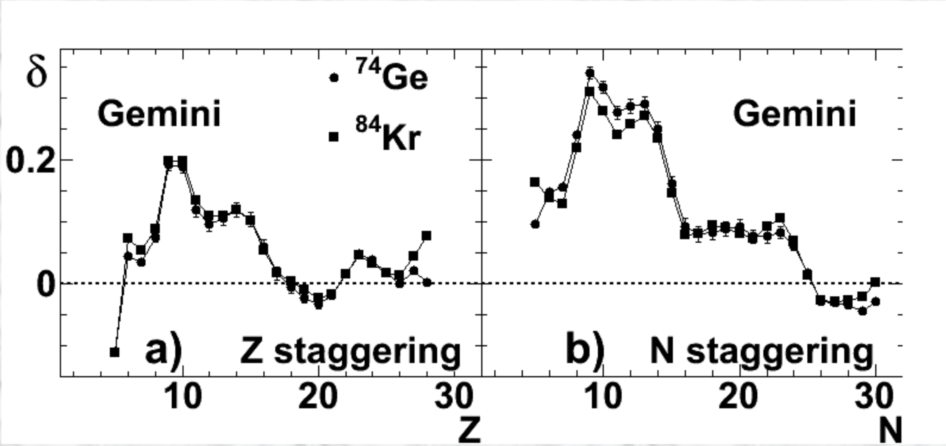
This behaviour is due to the fact that there is staggering both in N and in Z and the effect is larger in N

The staggering is larger for even N-Z chains formed by even-even (enhanced in Z and N) and odd-odd (depressed in Z and N) nuclei

Odd N-Z chains are formed by odd-even or even-odd nuclei: Z and N staggering works in opposite directions. Even Z depressed by the prevalent effect of odd N; odd Z enhanced by the prevalent effect of even N => apparent antistaggering

S.Piantelli et al., PRC88 (2013)064607

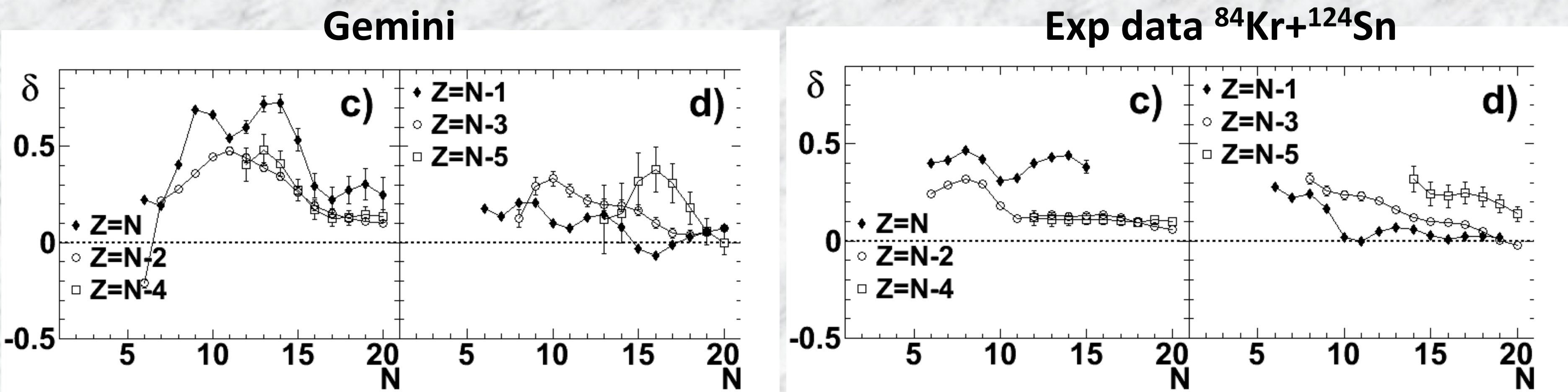
Staggering in a statistical code: GEMINI++



^{74}Ge and ^{84}Kr E*=2.7AMeV J=50$\hbar$

- N staggering greater than Z staggering

Chains Z-N=k



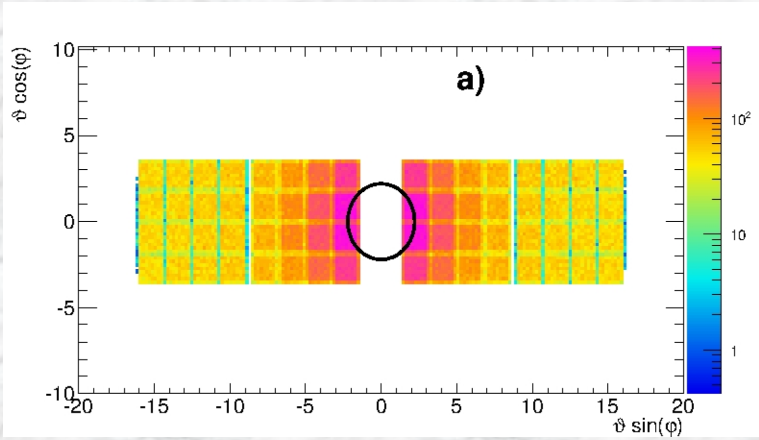
- Hierarchy almost reproduced

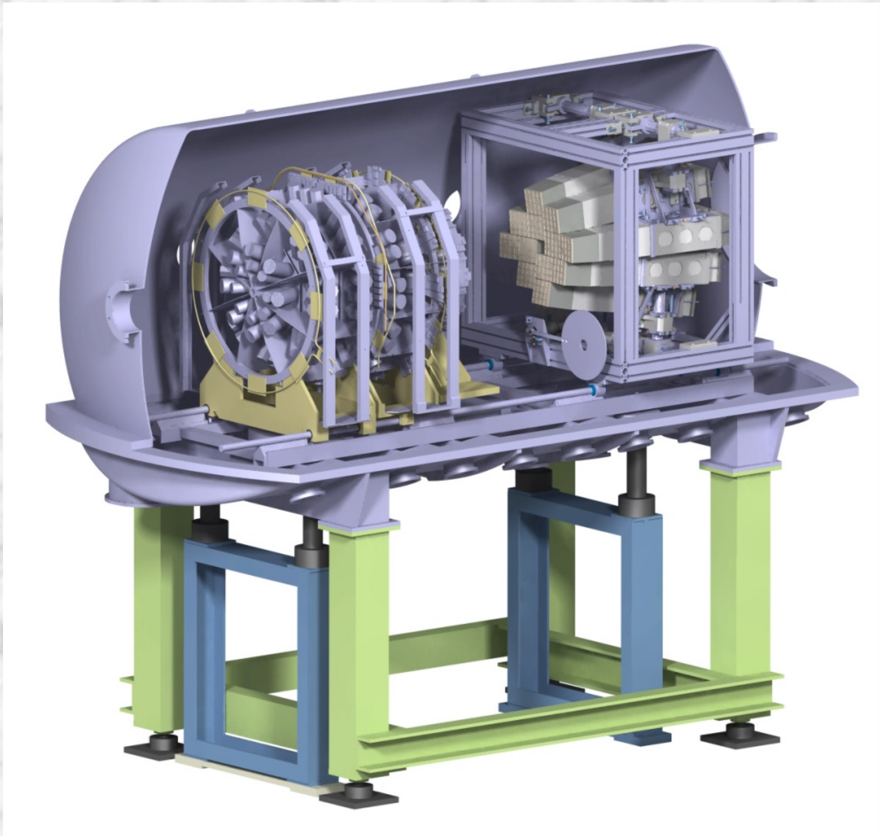
Some general features of the staggering are reproduced by GEMINI++
Details are not reproduced

Summary and Conclusions

- **Experimental data collected by a single FAZIA telescope with high performances in terms of A and Z identification during a test experiment on the systems $^{84}Kr+^{112}Sn$ and $^{84}Kr+^{124}Sn$ at 35AMeV have been presented**
- **The angular coverage of the detector gave access to products coming from the QP phase space**
- **Difference in the <N>/Z as a function of Z of the emitted products in the two reactions => since the projectile is the same and targets are different this is an evidence of isospin diffusion**
- **The <N>/Z of light products is higher for particles emitted closer to the center of mass => evidence of isospin drift (neutron enrichment of the midvelocity emission)**
- **Z staggering is smaller than N staggering and depends on the isospin of the system**
- **N staggering seems more independent of the N/Z of the system**
- **The staggering is almost independent of the kind of reaction => it seems to be a product of the last step (or the last few steps) of the reaction**
- **Some general characteristics of the staggering phenomenon are reproduced by GEMINI++**

Next future….





- **One experiment approved by the LNS PAC concerning the isospin transport phenomenon with 4 blocks of FAZIA**

- **LoI Indra + Fazietto (12 blocks of FAZIA) presented at the last GANIL PAC and concerning the N and Z staggering phenomenon for systems of different isospin**

Thank you for your attention!