# Excitation of baryon resonances in isobar charge-exchange reactions at relativistic energies

J. Benlliure

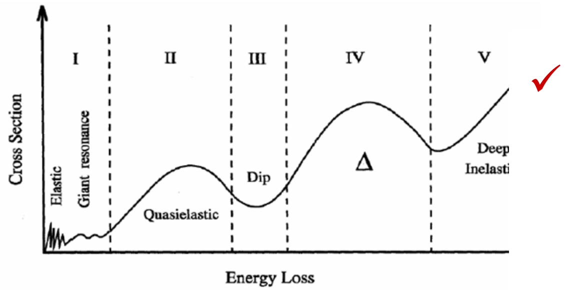
Univ. Santiago de Compostela
Spain

NUSTAR collaboration meeting, March 2014

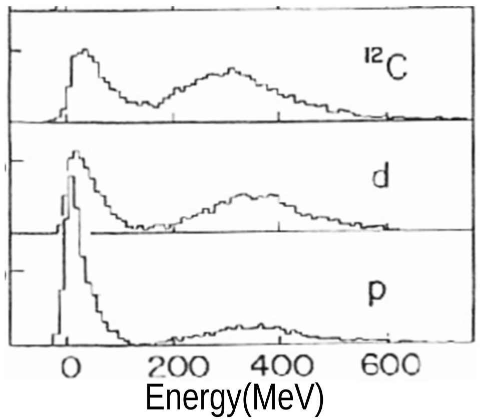
# Charge-exchange reactions

Charge-exchange reactions are governed by the $V_{\sigma\tau}$ term in the nucleon-nucleon interaction so they are particularly interesting for investigating the spin-isopin dependence of the nuclear force. Moreover, some of these excitations have been proven to be sensitive to the radial distributions of protons and neutrons in the nucleus.

Charge-exchange reactions led to spin-isospin excitations in two different energy domains:



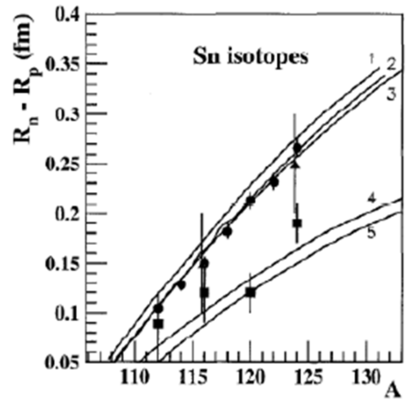

$^{20}Ne(X,Y)^{20}Na$ @ 900 MeV/u




C. Bachelier et al. PLB 172 (1986) 23

✓ at low energies: particle-hole excitations (Gamow-Teller, spin-dipole, spin- quadrupole or quasi-elastic).

- Gamow-Teller: $B_{GT}$ transition strengths
- spin-dipole: radial distributions of protons and neutrons




A. Krasznahorkay et al. NPA 731 (2004) 224

✓ at high energies: excitation of a nucleon into a Δ resonance

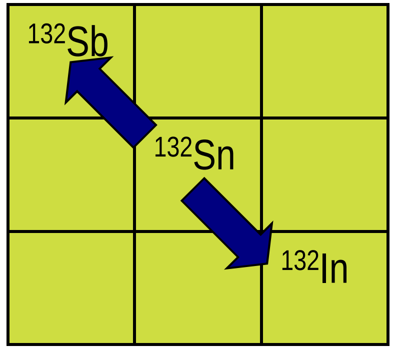
- In-medium effects manifest as a downward shift of the Δ-peak position when excited in nuclei .

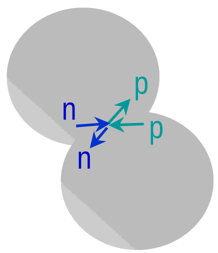
# Isobar charge-exchange reactions

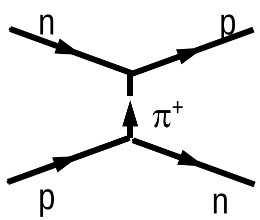
Peripheral collisions where projectile and target nuclei exchange a charge unit while leading to a cold final nucleus preserving its mass number.

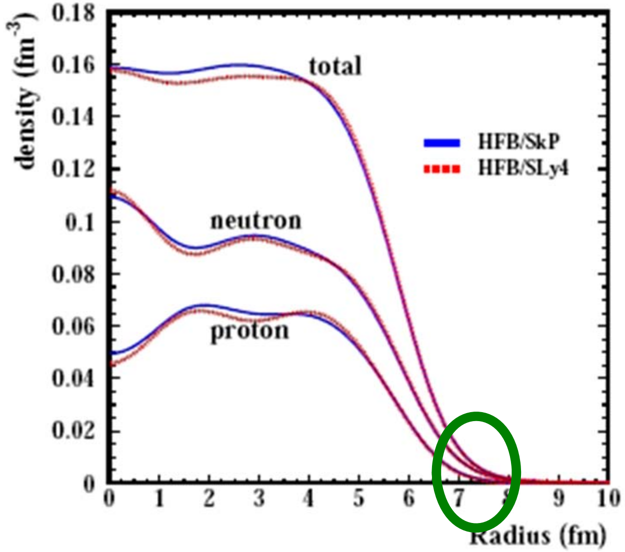
→ Quasi-elastic charge exchange (virtual pion exchange)

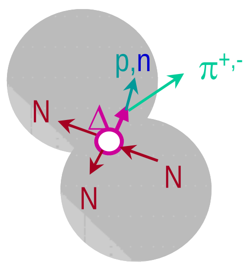
→ Baryon resonance (Δ resonance) excitation (production of a real pion scaping the nuclear medium)

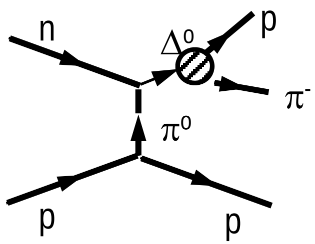


# Physics case

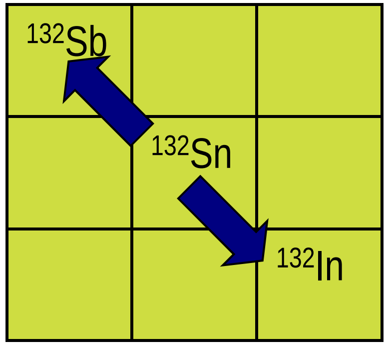
To investigate the isospin dependence of spin-isospin excitations at low and high momentum transfer for both isobar charge-exchange channels (p,n) and (n,p) using relativistic exotic projectiles.

- ✓ In-medium properties of baryon resonances in isospin asymmetric nuclear matter. (mean energy and width of the resonance)
- ✓ Gamow-Teller transition strengths
- ✓ Radial distributions of neutrons and protons.
- ✓ Nuclear matrix elements for inelastic neutrino interactions.

# Experimental requirements

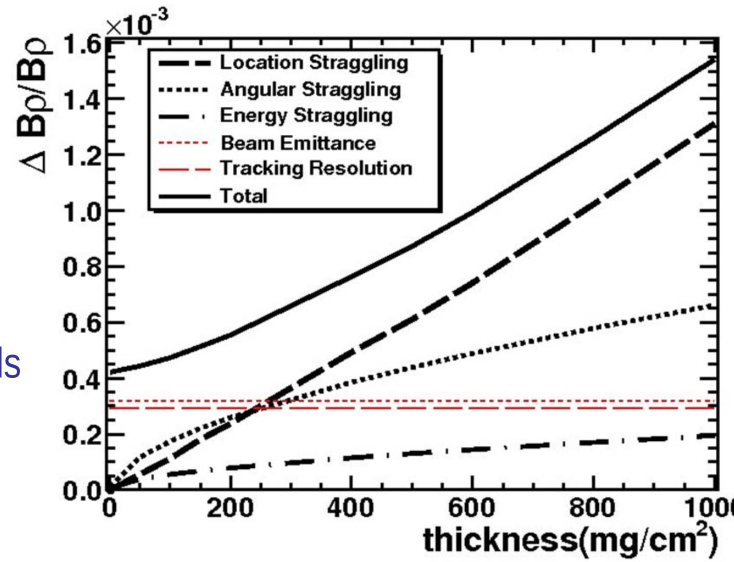
Quasi-elastic and Δ-resonant isobar charge exchange reactions, (p,n) and (n,p), in isospin asymmetric nuclear matter:

- ✓ relativistic heavy-ion collisions induced by exotic projectiles (isospin asymmetry and radial dependence)
- ✓ isobar charge-exchange (clean reaction channel)




Observables:

- ✓ cross sections for both charge exchange reactions and channels
- ✓ mean energy and width of the Δ-resonance



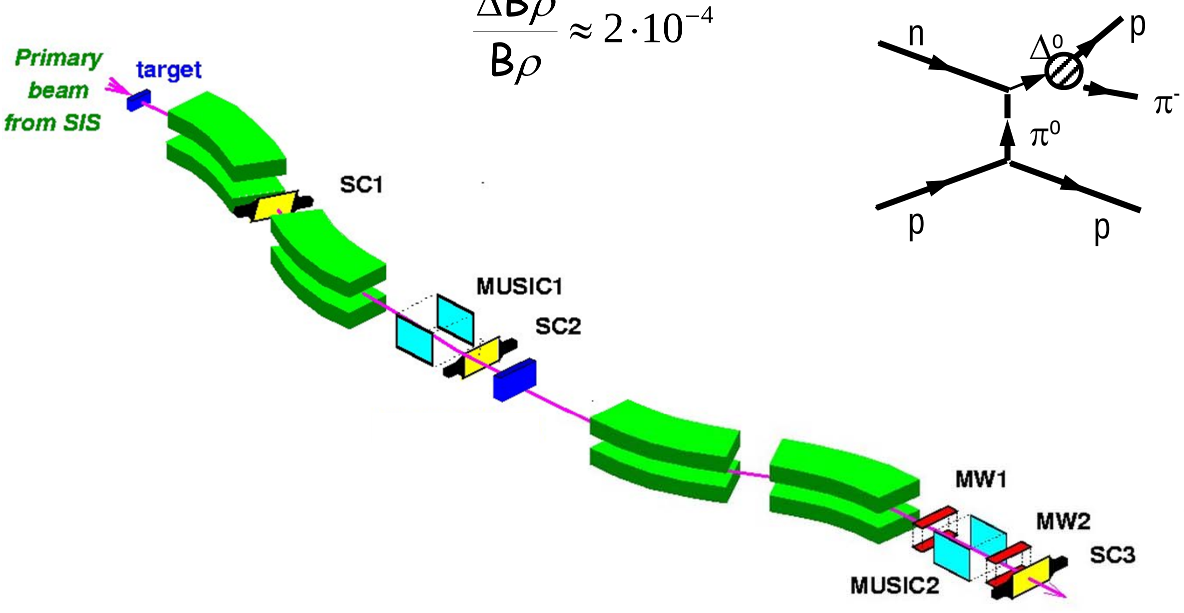

Requirements for the setup:

- ✓ isotopic identification of relativistic projectile residues
- ✓ separation of elastic and resonant charge-exchange channels
  - magnetic analysis of projectile residues

# Experiments at the FRS

$\Delta$-resonance and quasi-elastic charge-exchange reactions identified at the FRS:
(standar detection setup)

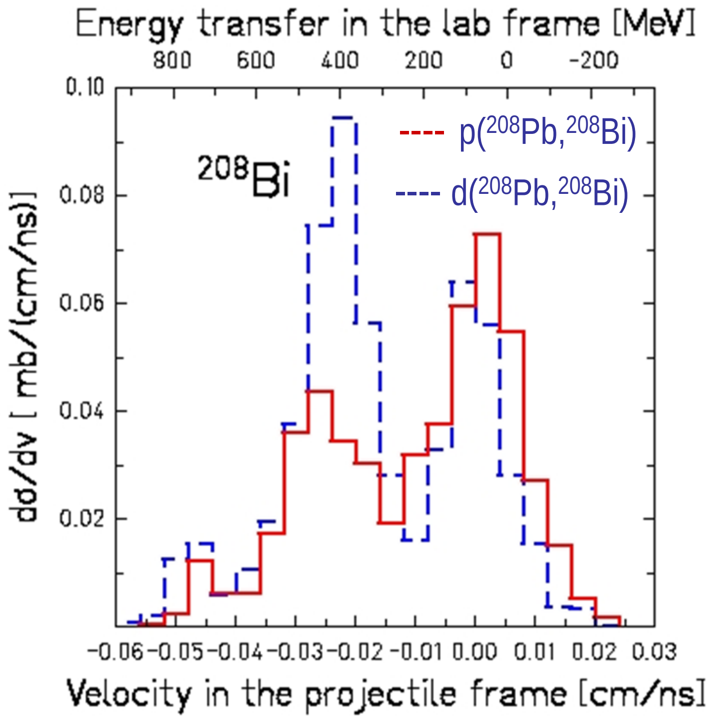
$$\frac{\Delta B\rho}{B\rho} \approx 2\cdot 10^{-4}$$




$\Delta Z/Z \sim 7\ 10^{-3}$

$\Delta A/A \sim 2.4\ 10^{-3}$

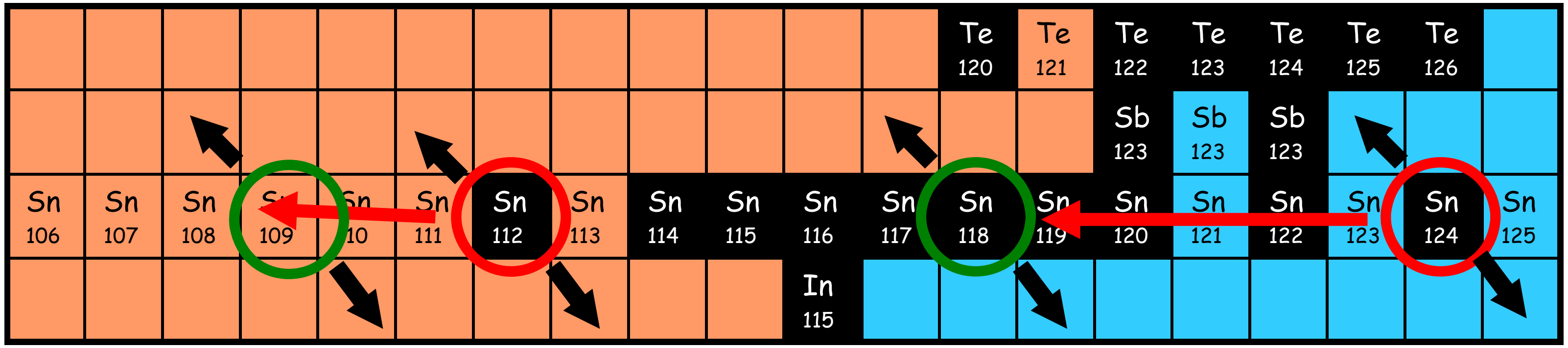
$^{208}$Pb(p,d,X)$^{208}$Bi @ 1 A GeV




A. Kelic et al., Phys. Rev. C 70 (2004) 64608

# Experiments at the FRS

## Recent high-resolution measurements




Systematic investigation of isobar charge-exchange reactions:

- ✓ $^{124}$Sn+CH$_2$,C → $^{124}$Sb,$^{124}$In @ 1000 A MeV
- ✓ $^{124}$Sn+Be → $^{118}$Sn+CH$_2$,C → $^{118}$Sb,$^{118}$In @ 1000 A MeV
- ✓ $^{112}$Sn+CH$_2$,C,Cu,Pb → $^{118}$Sb,$^{118}$In @ 400, 700, 1000 A MeV
- ✓ $^{112}$Sn+Be → $^{109}$Sn+CH$_2$,C → $^{109}$Sb,$^{109}$In @ 1000 A MeV

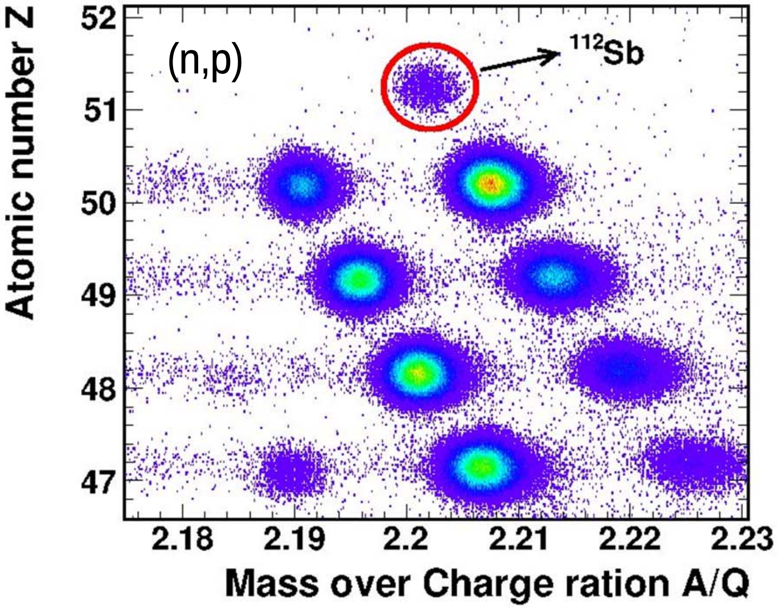
High resolution:

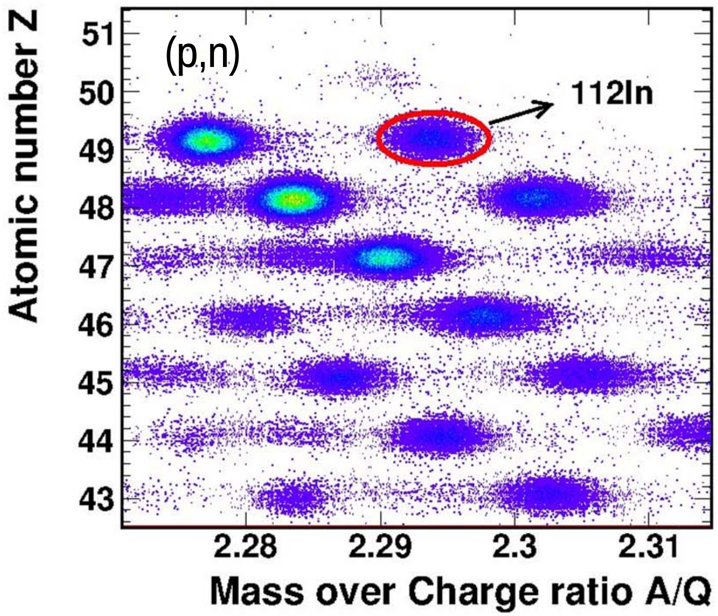
- ✓ FRS high-resolution mode
- ✓ Thin targets (~ 100 mg/cm$^2$)

# Recent measurements with the FRS

## Isotopic identification of isobaric charge-exchange residues

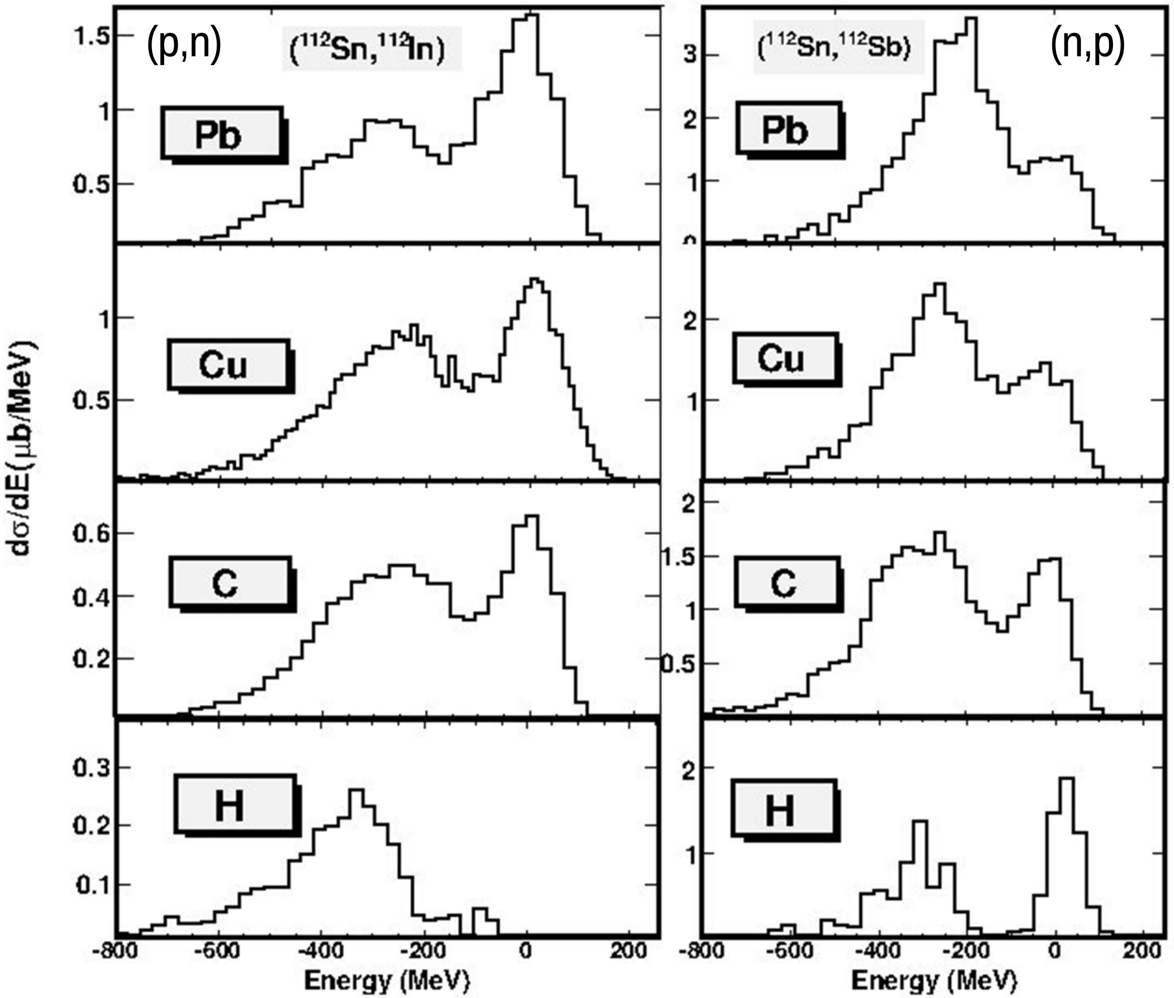
$^{112}$Sn + C @ 1000 MeV/u



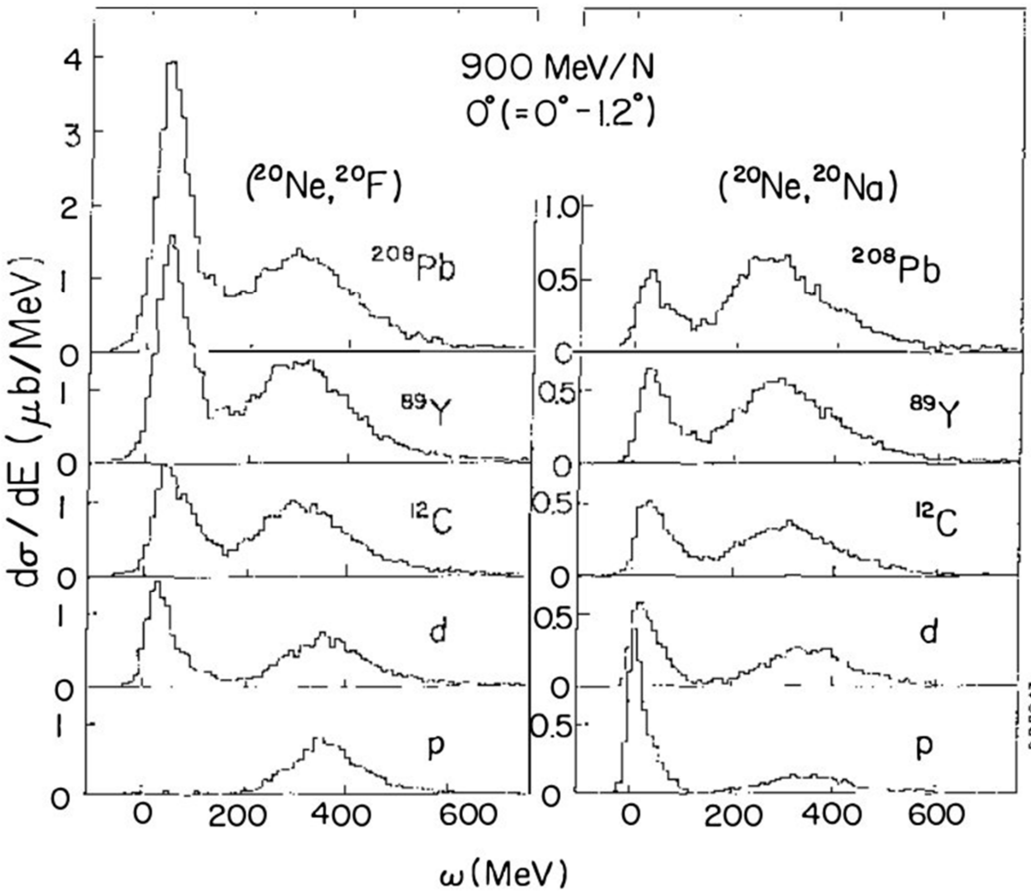
# Recent measurements with the FRS

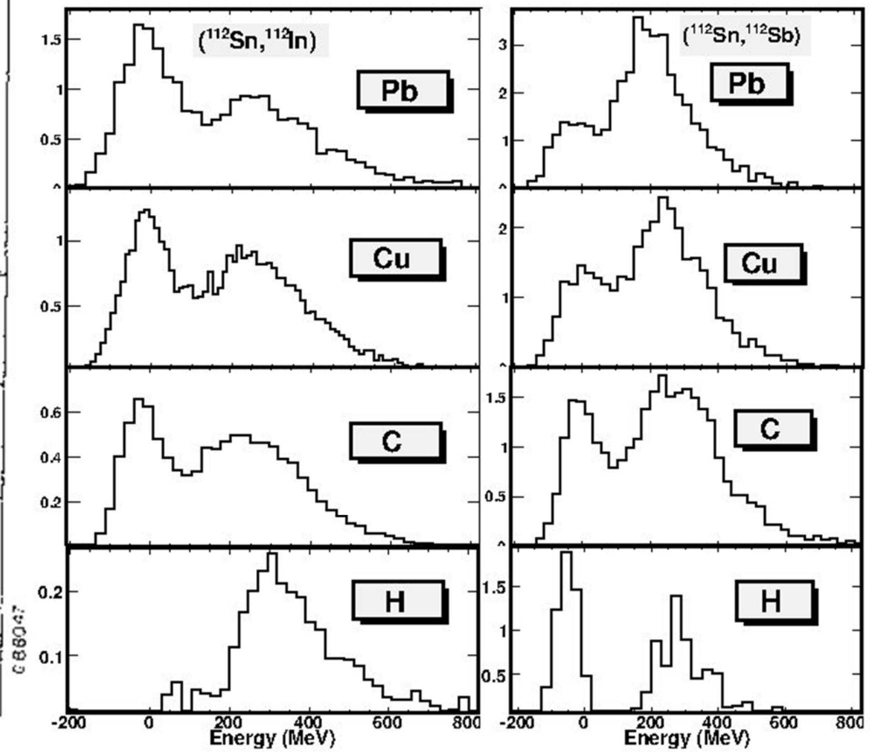
## Missing-energy spectra in isobar charge-changing reactions induced by $^{112}Sn$



# Recent measurements with the FRS

## Missing-energy spectra in isobar charge-changing reactions induced by $^{112}Sn$

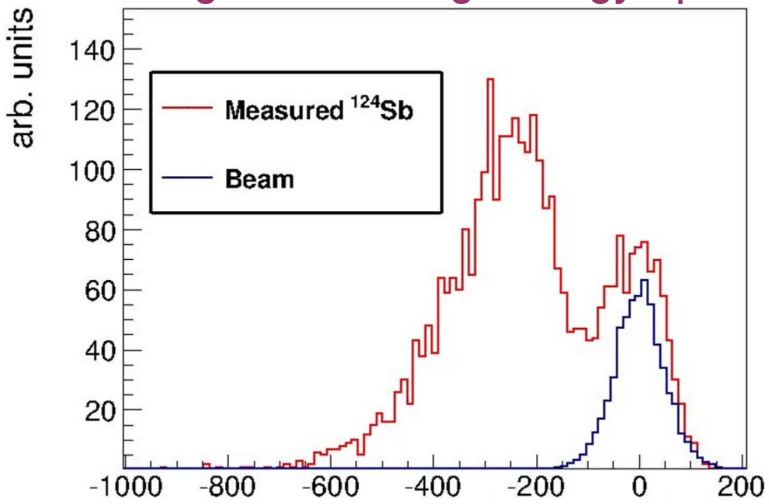


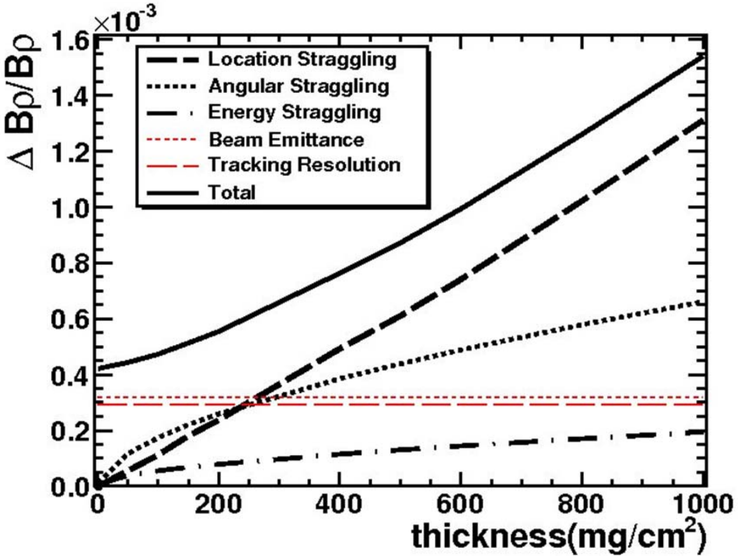




C. Bachelier et al. PLB 172 (1986) 23

# Recent measurements with the FRS

## Unfolding the missing-energy spectrum with the experimental response function




$$Y(i) = \sum_{j=1}^{n_{bin}} H(i-j) \cdot X(j)$$

Y: measured spectrum

H: experimental response function

X: observable

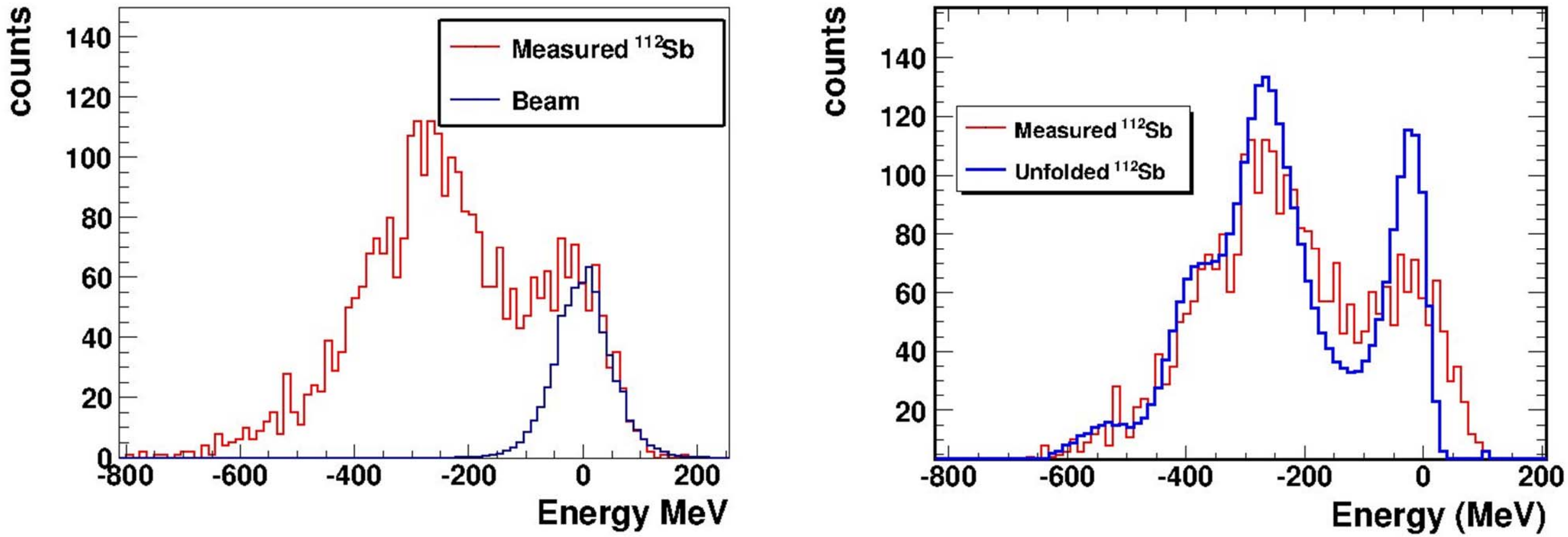
The primary beam centred through the FRS constitutes our response function H

J. Vargas, J.B. and M. Caamaño NIMA 707 (2013) 16

# Recent measurements with the FRS

## Unfolding the missing-energy with the experimental response function

$^{112}Sn(^{63}Cu,X)^{112}Sb$



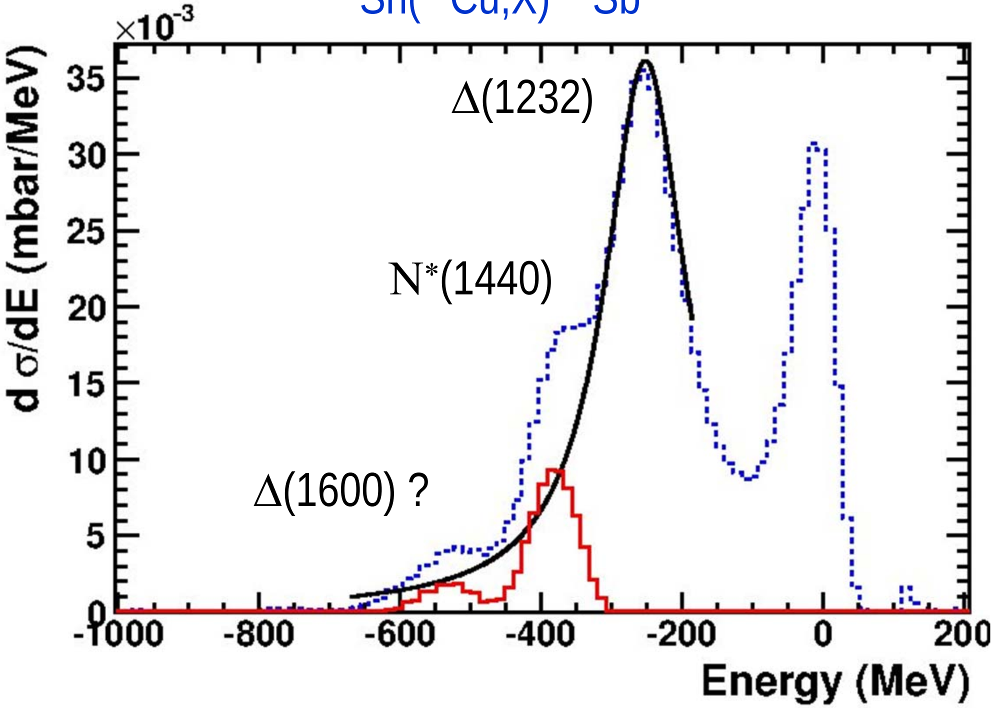

The unfolding procedure improves the resolution.

$\Delta$E ~ 15 MeV ($^{112}$Sn @ 1000 MeV/u)

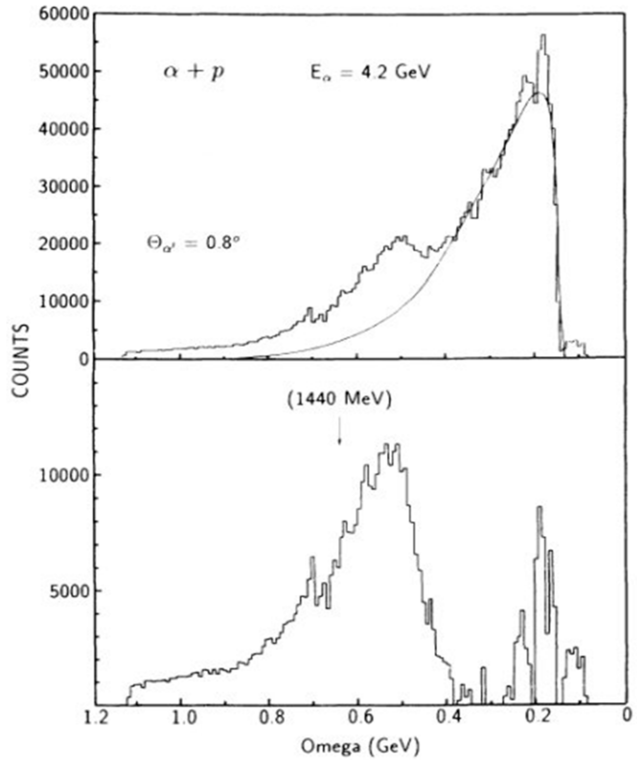
# Recent measurements with the FRS

## Excitation of several nucleon resonances

$^{112}Sn(^{63}Cu,X)^{112}Sb$




$\alpha(p,X)\alpha'$ @ 4.2 GeV

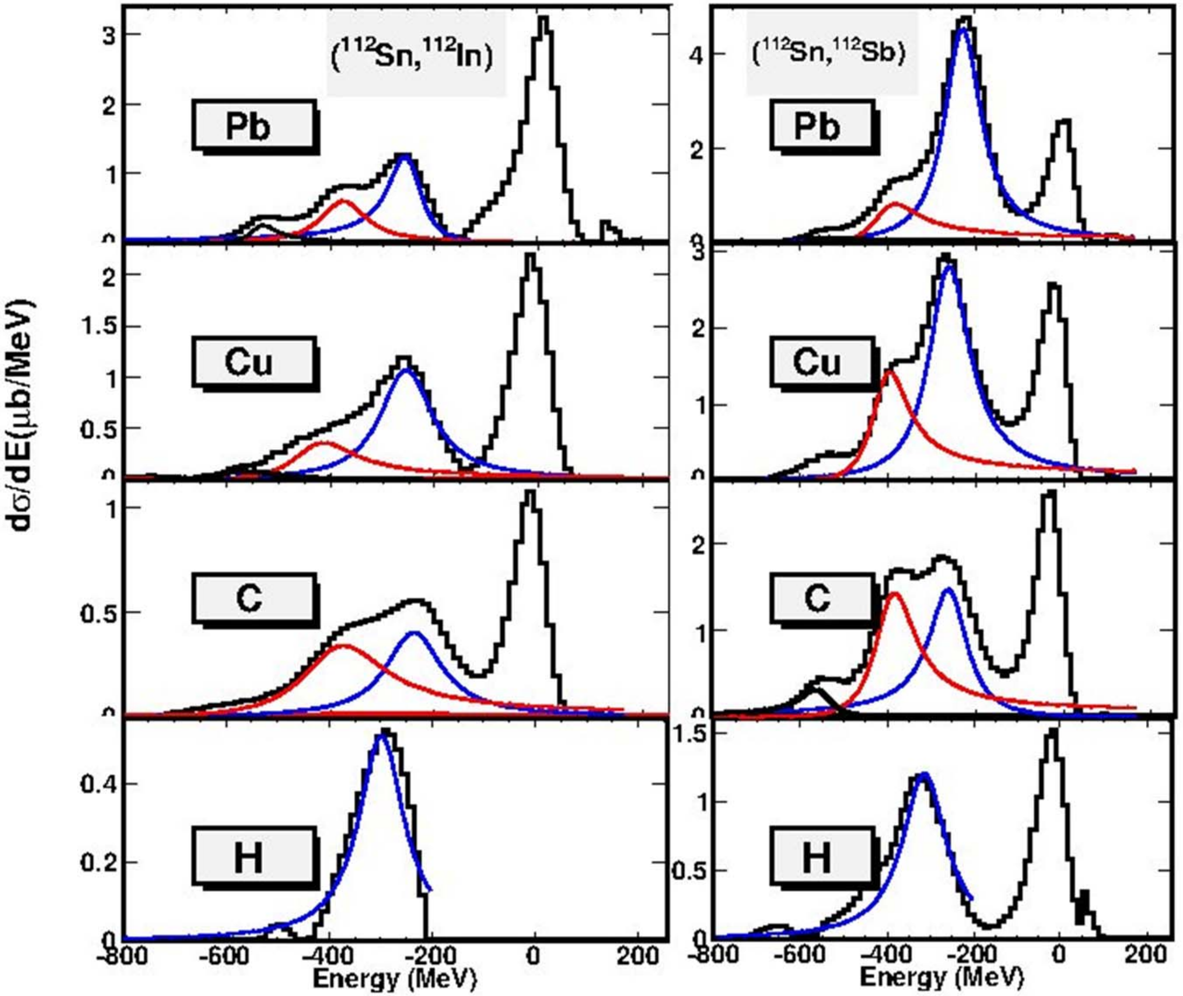



The unfolding procedure evidences new structures in the missing energy spectra associated to several nucleon resonances.

H.P. Morsch et al., PRL 69, 1336 (1992)

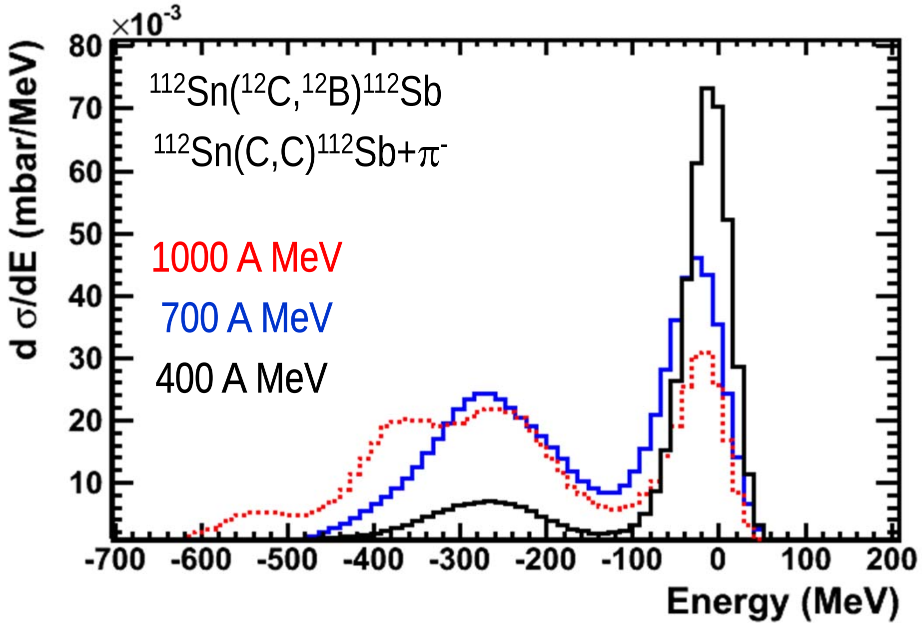
# Recent measurements with the FRS

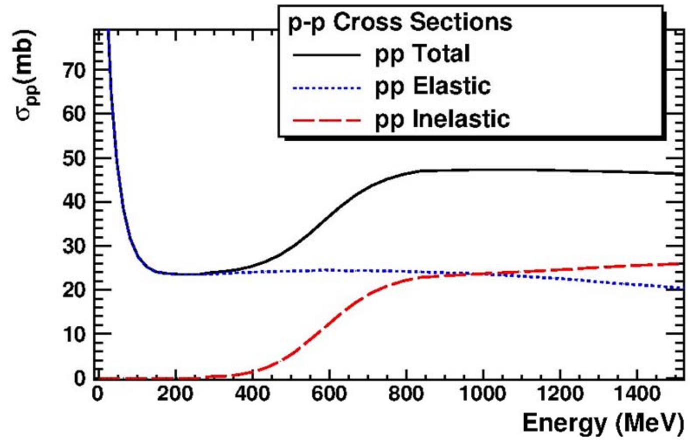
## Mean energy and width of the resonances

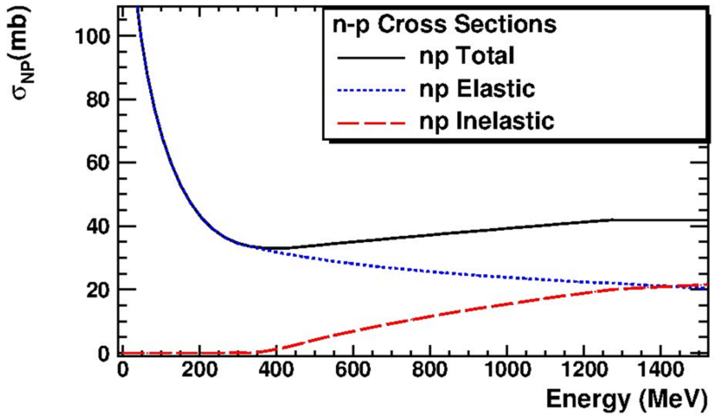


# Recent measurements with the FRS

## Energy and target dependence of the resonance excitation



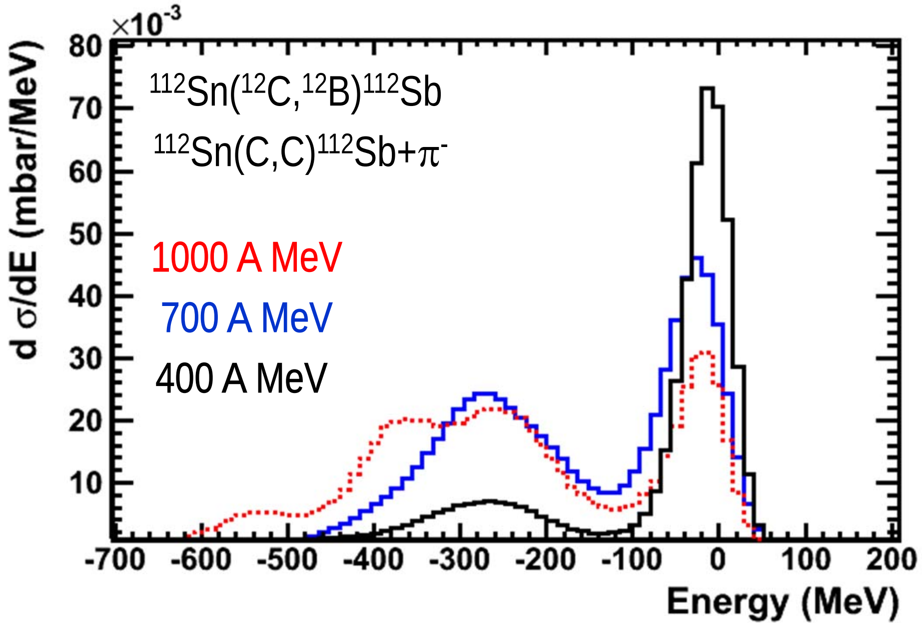



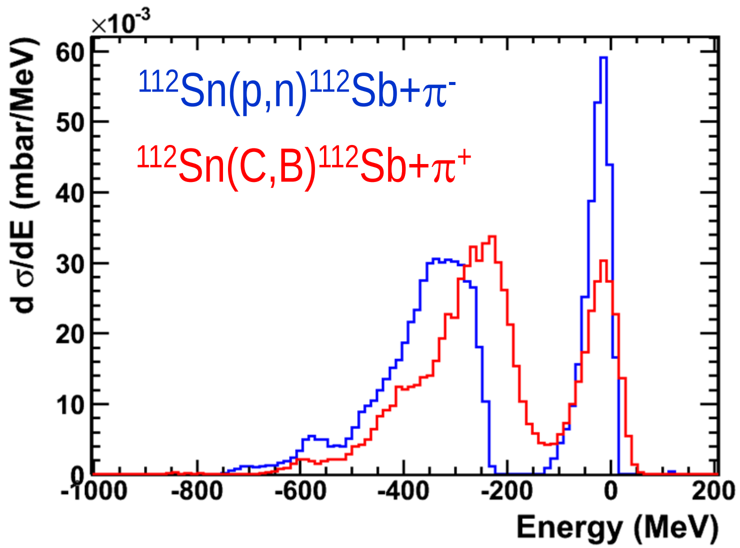

In nucleus-nucleus collisions Δ-resonance excitation may occurs below the pion production threshold:

- Fermi momentum of the nucleons

# Recent measurements with the FRS

## Energy and target dependence of the resonance excitation



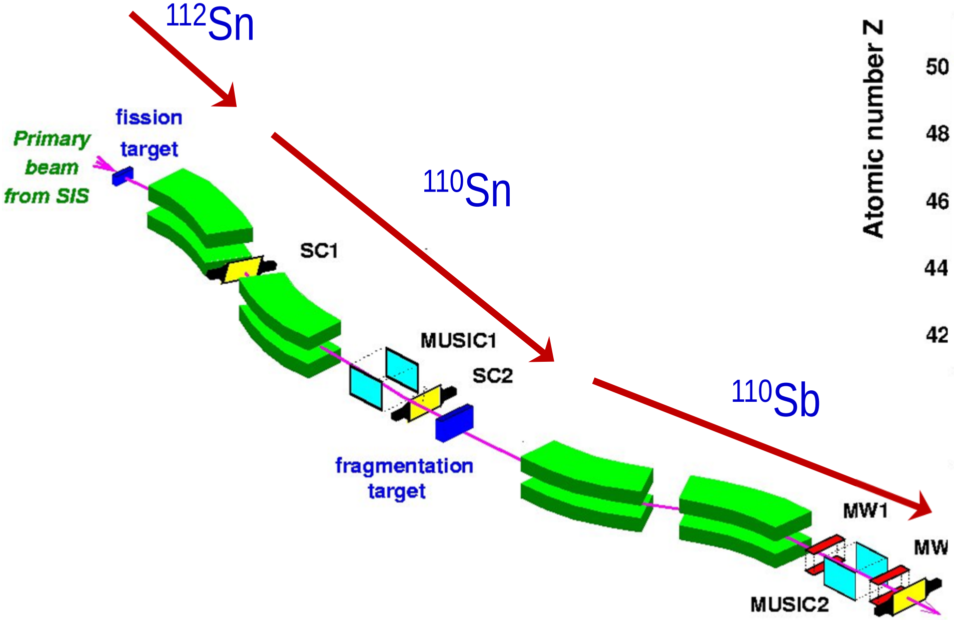



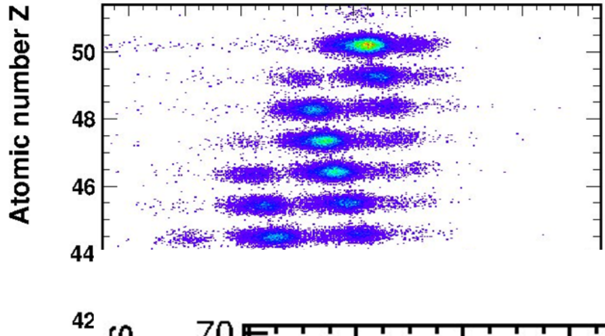

In nucleus-nucleus collisions $\Delta$-resonance excitation occurs below the pion production threshold:

- Fermi momentum of the nucleons
- Lower energy of the $\Delta$-resonance

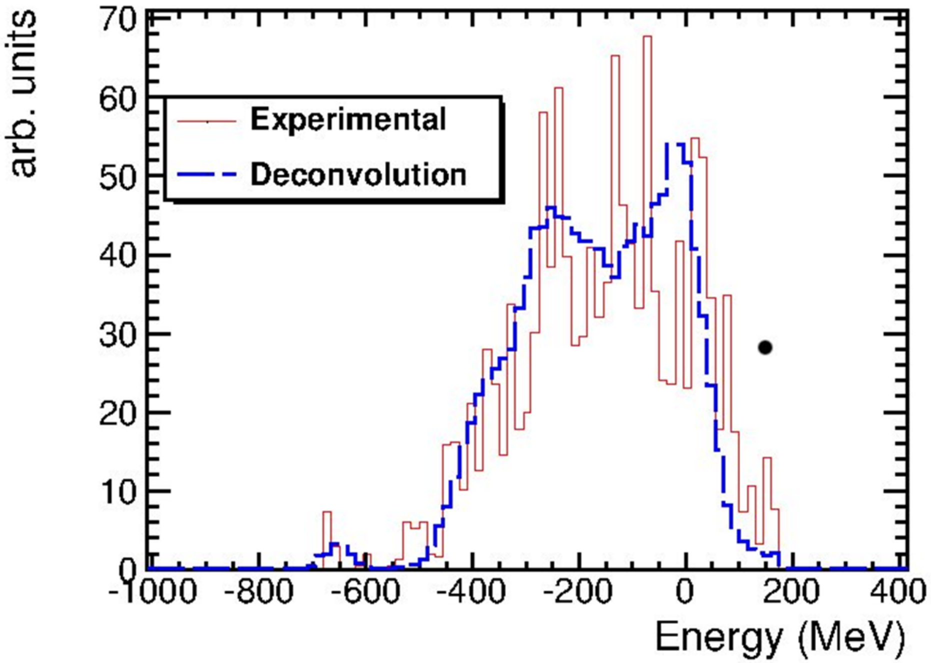
# Recent measurements with the FRS

## Missing-energy spectra with secondary beams




$^{110}$Sn(C,X)$^{110}$Sb+$\pi^-$




Main difficulties:

- Low statistics
- Thick S2 target (1 g/cm$^2$ C)
- Important background at S2

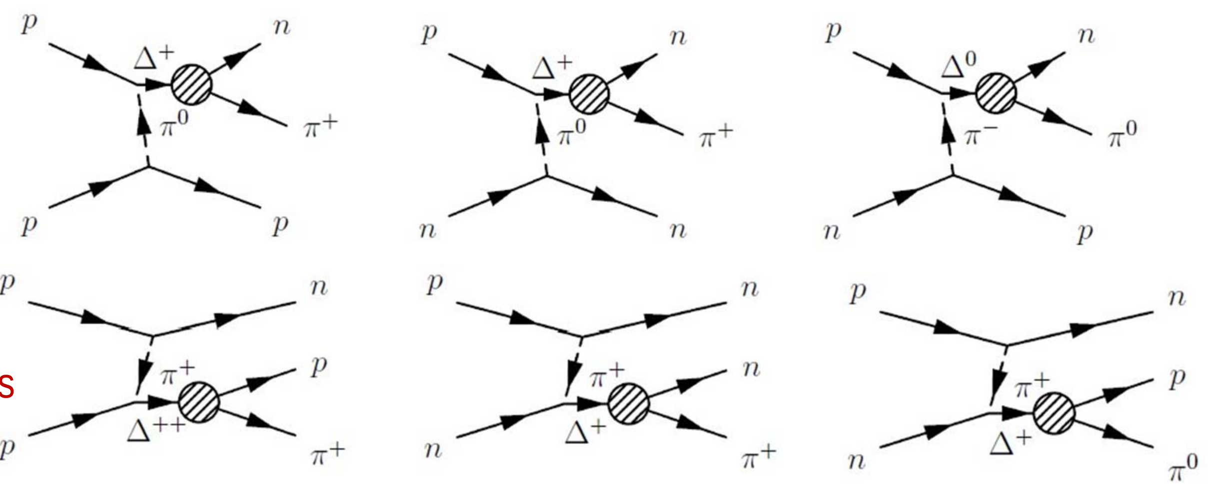
# Options for future

Exclusive measurements:

→ Pion detection

Projectile excitations

Target excitations

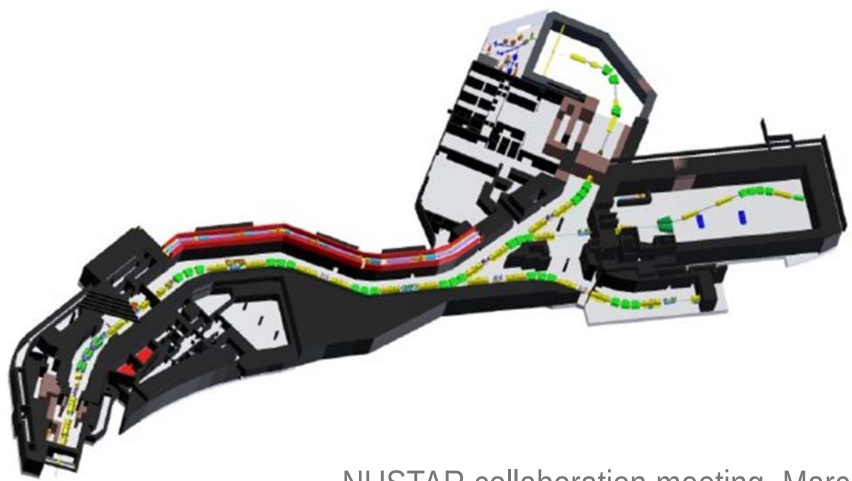



Measurements with secondary beams:

→ Larger secondary beam intensities

→ Contaminants suppresion

→ Thinner reaction targets



## Conclusions

✓ A high-resolving power magnetic spectrometer has been proven to be an excellent tool to identify nucleonic excitations in heavy-ion charge-exchange reactions:

- proton and neutron densities at the nuclear surface from (p,n), (n,p) channels
- in medium effects: energy shift in the resonance peak

✓ The Super-FRS, and later on the R3B high-resolution spectrometer, will offer unique opportunities for these investigations

- extremely asymmetric nuclear matter
- improved separation capabilities (pre-separator)
- better resolution

✓ Exclusive measurements detecting pions should also be investigated

# Collaboration

**J. Vargas**, J. Benlliure, H. Alvarez, Y. Ayyad, S. Beceiro, M. Caamaño, E. Casarejos, D. Cortina, P. Díaz, M. Mostazo, C. Paradela

Universidad de Santiago de Compostela

T. Aumann, J. Atkinson, K. Boretzky, A. Estrade, H. Geissel, A. Kelic, Y. Litvinov, S. Pietri, A. Prochazka, M. Takechi, H. Weick, J. Winfield

GSI

A. Chatillon, J. Taieb

DAM/CEA

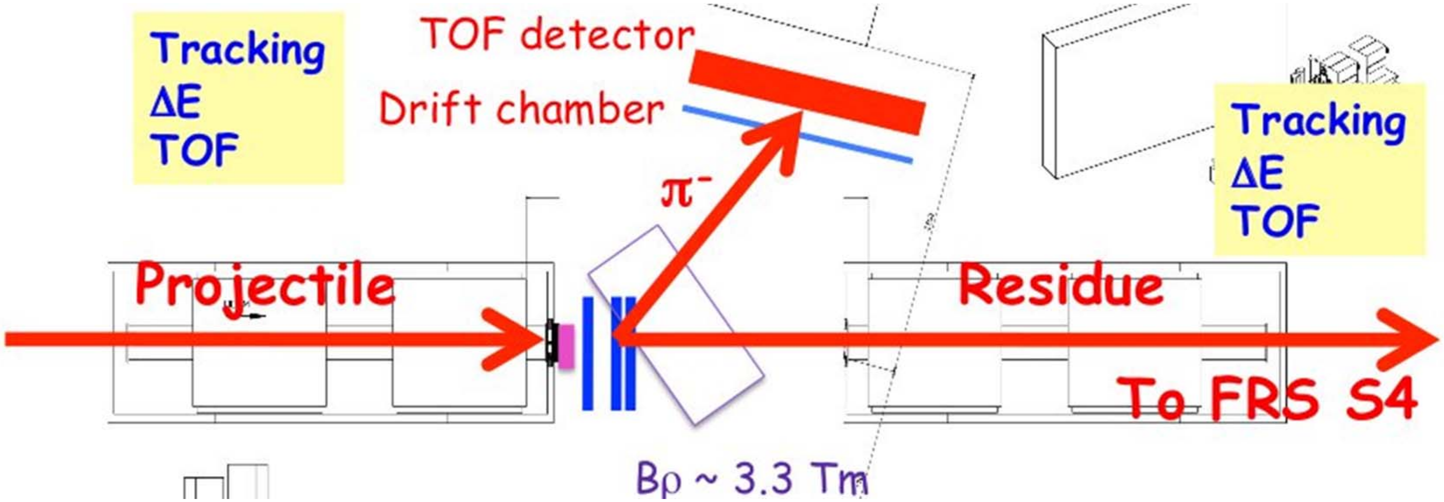
H. Lenske

U. Giessen

# Options for future

## Exclusive measurements

Identification of projectile and target excitations by detecting pions

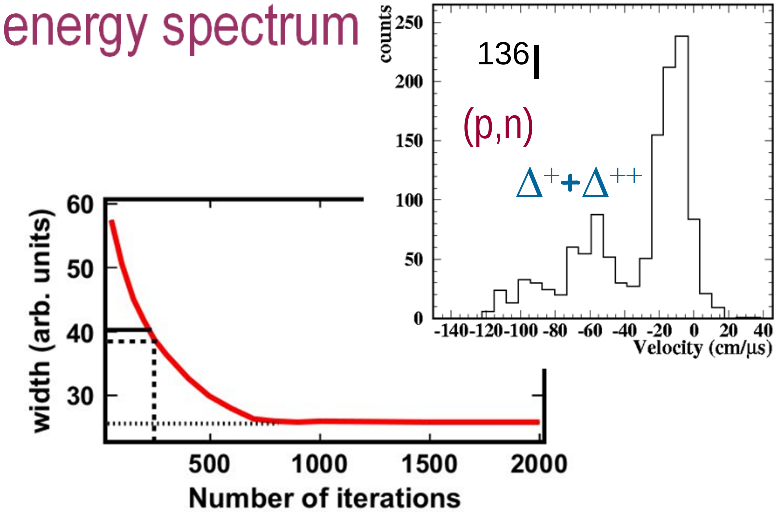



From T. Saito, SuperFRS meeting 2012

## Unfolding and regularization of the missing-energy spectrum

The most reliable unfolding techniques are based on iterative procedures (Richardson-Lucy)

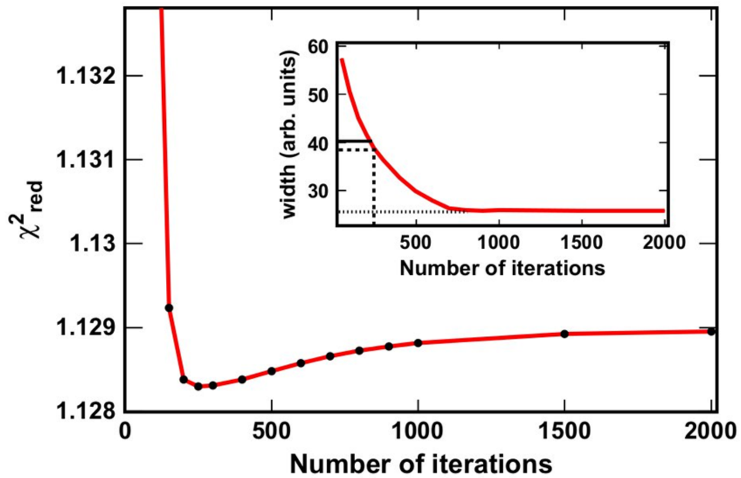
$$X^{(m)}(i) = X^{(m-1)}(i)\sum_{j=1}^{n_{bins}} H(j-i)\,\frac{Y(j)}{\sum_{k=1}^{n_{bin}} H(j-k)X^{(m-1)}(k)}$$




Regularization methods are needed to determine the optimum number of iterations

$$Y^{Conv}(i) = \sum_{j=1}^{n_{bins}} H(i-j)\cdot X^{Calc}(j)$$

$$\chi^2_{red} = \frac{1}{(n'-1)}\sum_{i=1}^{n_{bins}}\left(\frac{Y(i)-Y^{Conv}(i)}{\varepsilon(i)}\right)^2$$




J. Vargas, J.B. and M. Caamaño NIMA 707 (2013) 16