# Nucleon resonances in asymmetric nuclear matter:
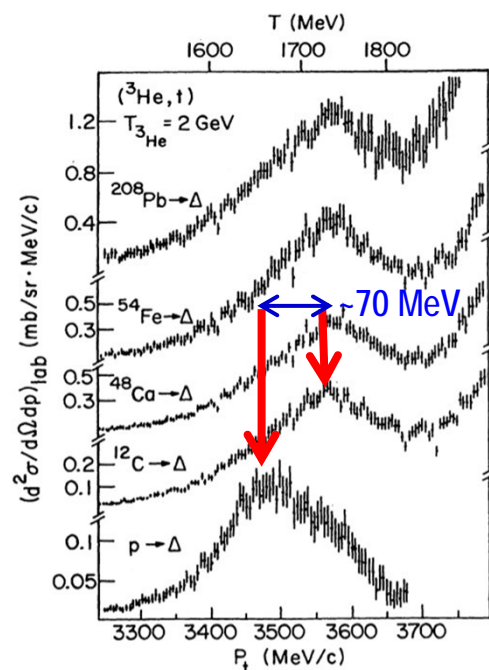
J. Benlliure

University of Santiago de Compostela, Spain

# In-medium nucleon-resonance interaction

**Motivation.**

Nucleon-resonance interactions ($\Delta N$, $N^*N$. ...) are required for a complete understanding of the nuclear many-body system and nuclear matter:

- Three-body forces

- Quenching of the Gamow-Teller strength

- EoS for neutron stars

**Present knowledge.**

✓ Modifications of the mass and width of the $\Delta$ resonance has been observed in HIC (EOS-Bevalac, FOPI Hades-GSI) and in isobaric charge-exchange reactions

✓ Those modifications were partially explained by kinematics, Fermi motion or pion absorption, while in-medium effects are still under discussion.

✓ Little information about the Roper resonance.

✓ No information on the nucleon-resonance interaction in asymmetric nuclear matter.

T (MeV)
1600   1700   1800

($^3$He, t)
$T_{^3He}$ = 2 GeV

$^{208}$Pb → $\Delta$

~70 MeV

$^{54}$Fe → $\Delta$

$^{48}$Ca → $\Delta$

$^{12}$C → $\Delta$

p → $\Delta$

$(d^2\sigma/d\Omega dp)_{lab}$ (mb/sr·MeV/c)

1.2
0.8
0.4
0.5
0.3
0.5
0.3
0.2
0.1
0.1
0.05

3300   3400   3500   3600   3700
$P_t$ (MeV/c)

# In-medium excitation of nucleon resonances

Isobar charge-exchange reactions induced by relativistic-radioactive beams

Access to in-medium excitation of nucleon resonances in asymmetric nuclear matter.



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

quasi-elastic          inelastic
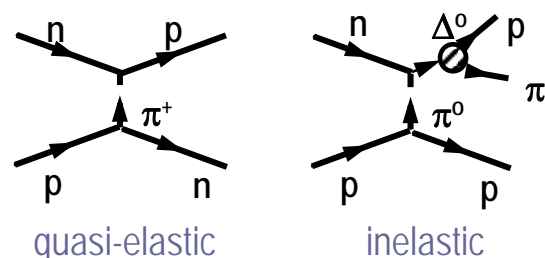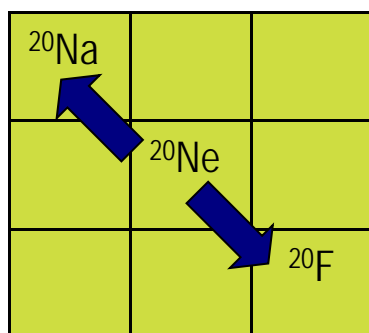
Isobar charge exchange reactions are peripheral processes.

✓ Pions scape to preserve the isobar character of the reaction.

✓ Pions have a large absorption cross section.

(n,p) and (p,n) cross sections prove the neutron and proton abundance at the nuclear surface.
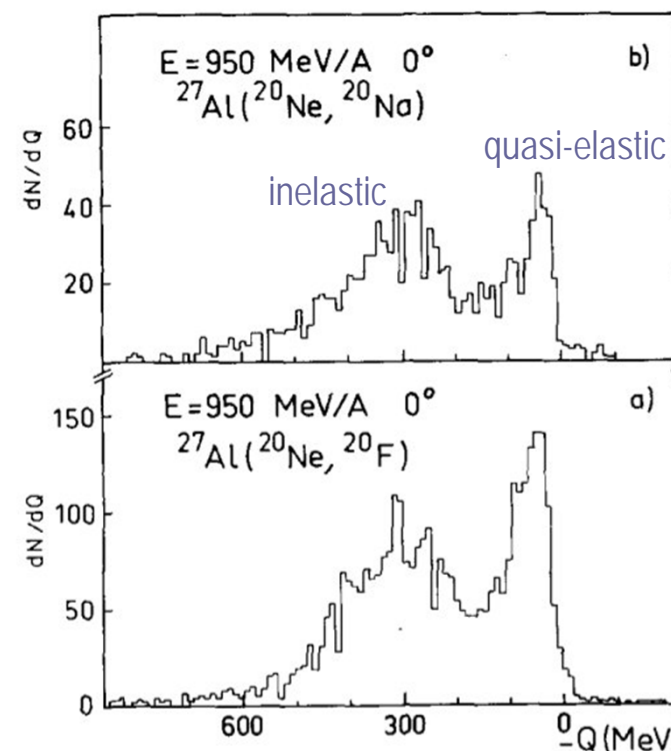
The missing energy spectra of the projectile remnants prove the excitation of the resonance.

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# Experimental requirements

Quasi-elastic and inelastic 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)
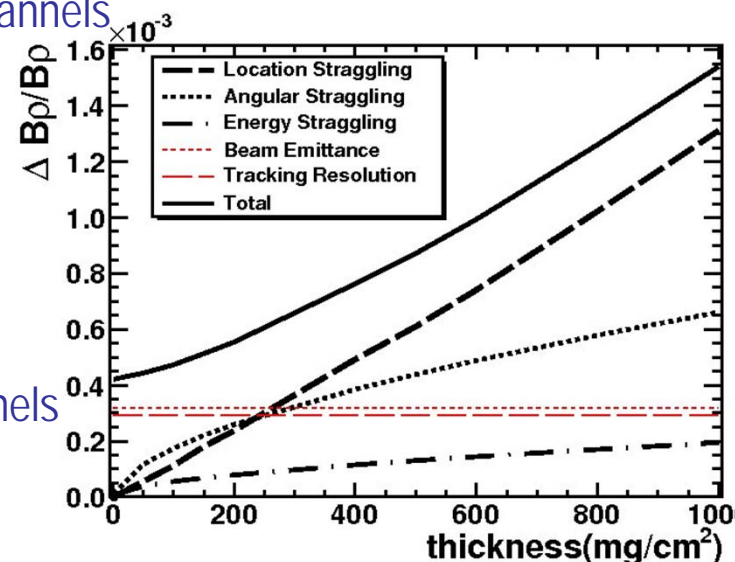
✓ isobar charge-exchange (clean reaction channel)
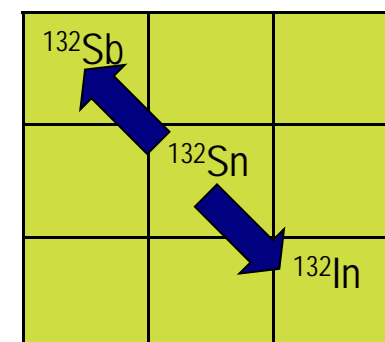
Observables:

✓ cross sections for both charge exchange reactions and channels

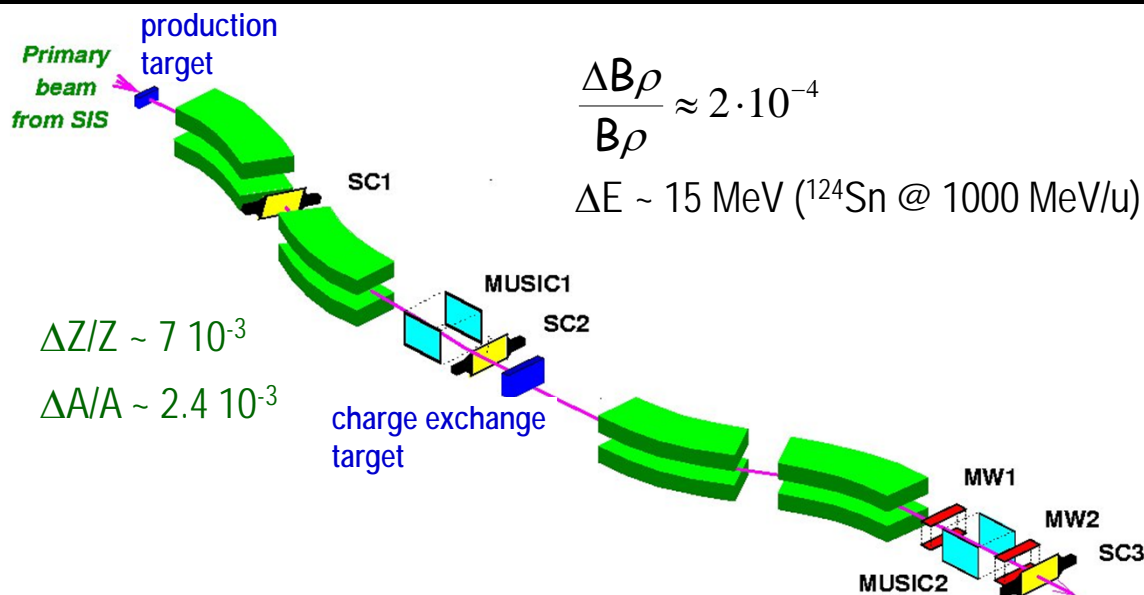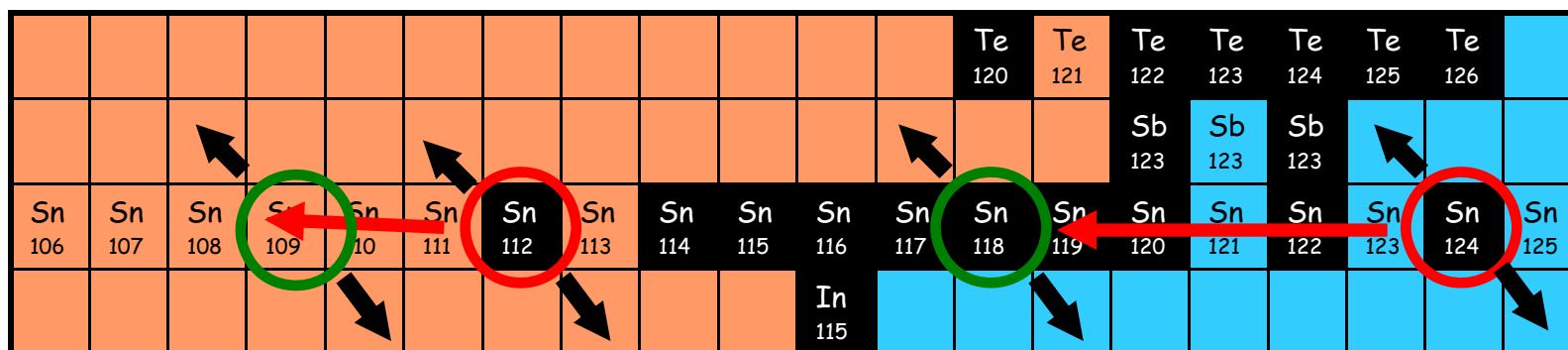✓ mean energy and width of the $\Delta$-resonance

Requirements for the setup:

✓ isotopic identification of relativistic projectile residues

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

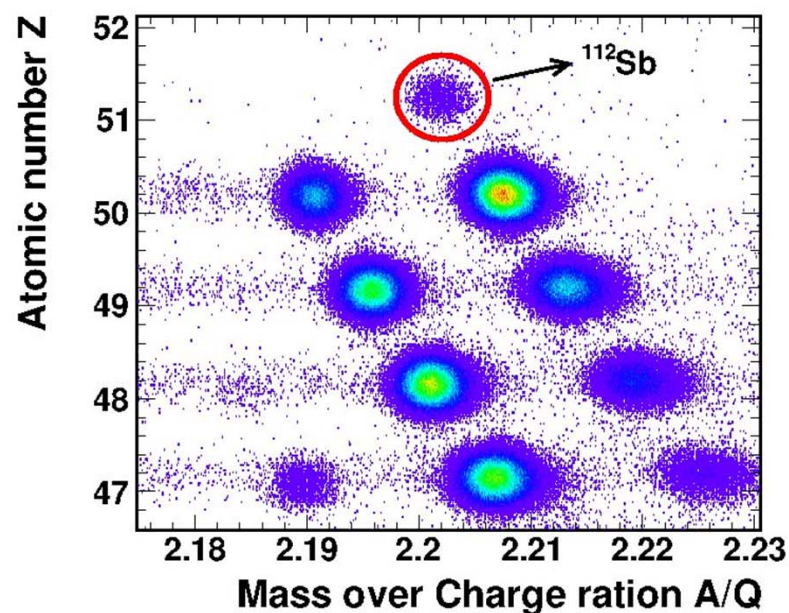Isobar charge-exchange reactions induced by relativistic-radioactive beams

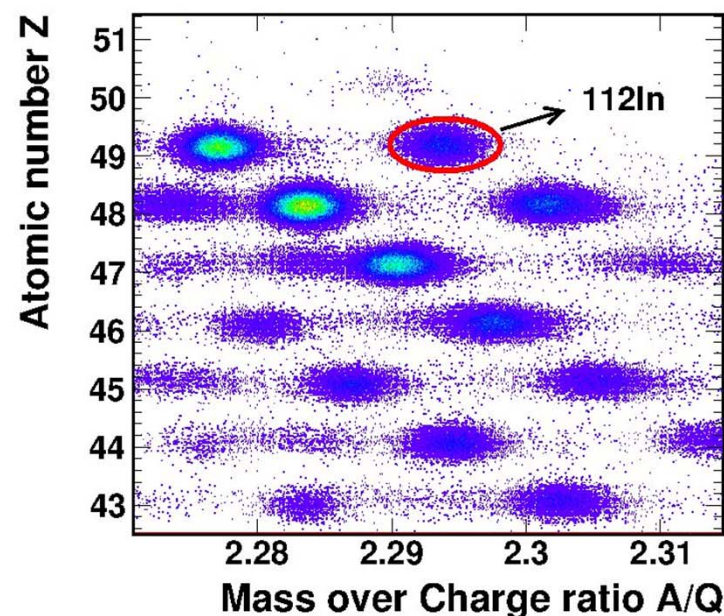Access to in-medium excitation of nucleon resonances in asymmetric nuclear matter.



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

$\Delta E \sim 15$ MeV ($^{124}$Sn @ 1000 MeV/u)

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

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

Isotopic identification of isobaric charge-exchange residues

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

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

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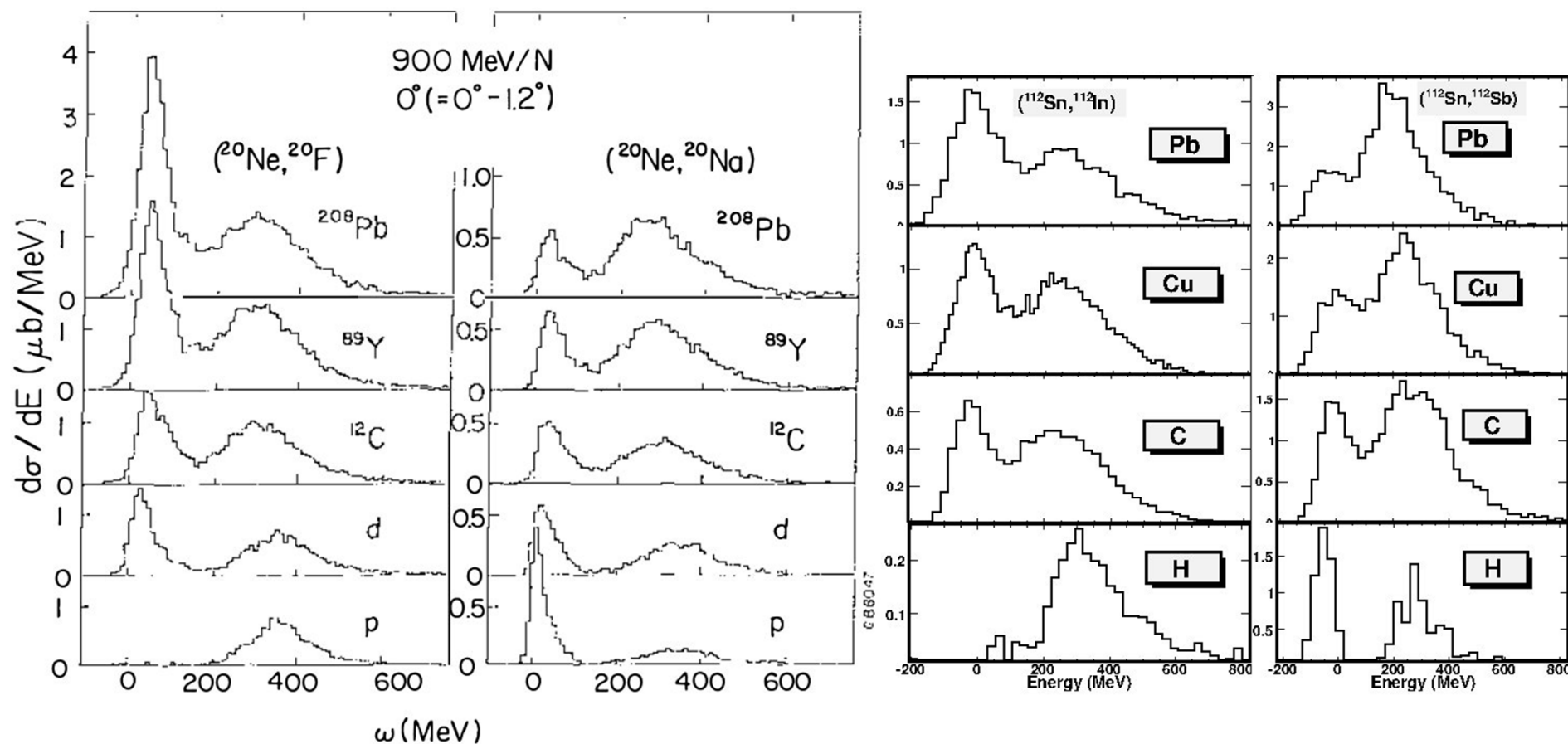
# Measurements with the FRS

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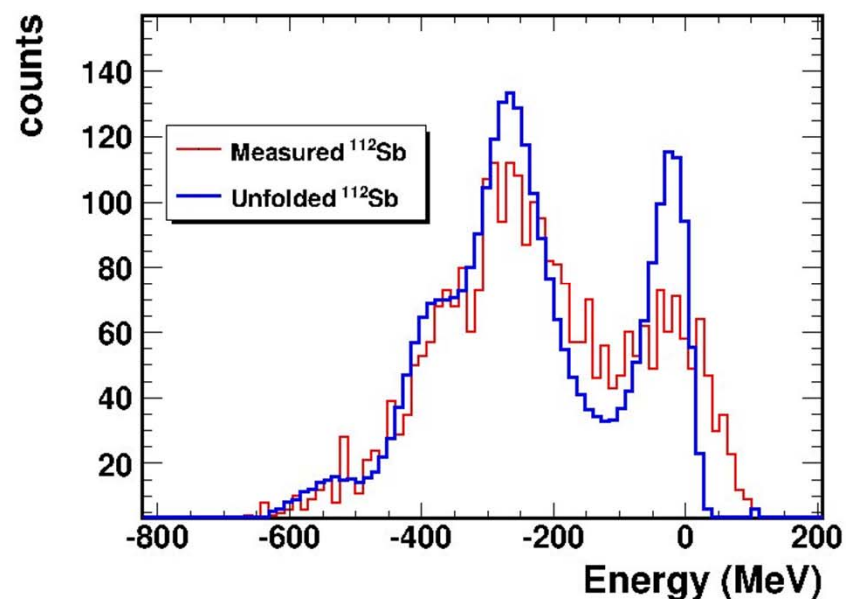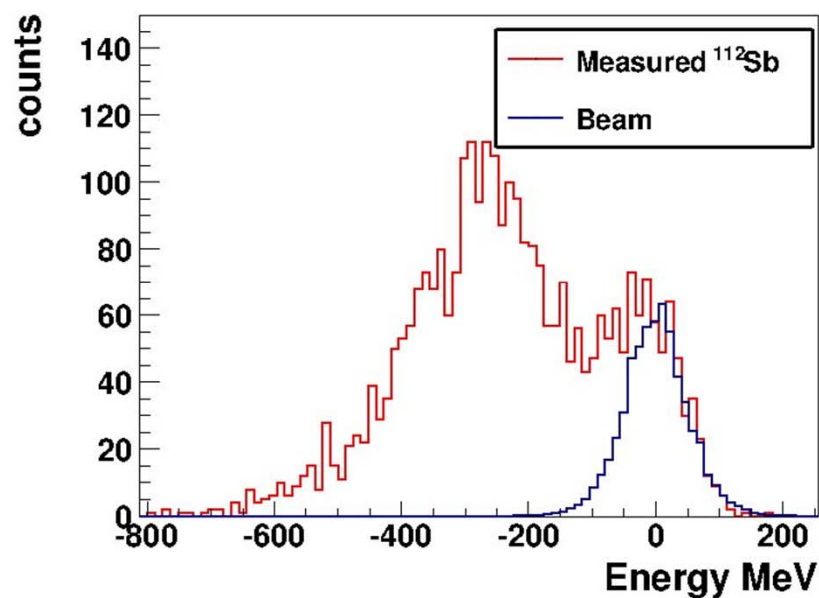


C. Bachelier et al. PLB 172 (1986) 23

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

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



Final resolution after deconvolution $\Delta E \sim 15$ MeV ($^{124}Sn$, $^{112}Sn$ @ 1000 A MeV)

# Measurements with the FRS

## Excitation of nucleon resonances


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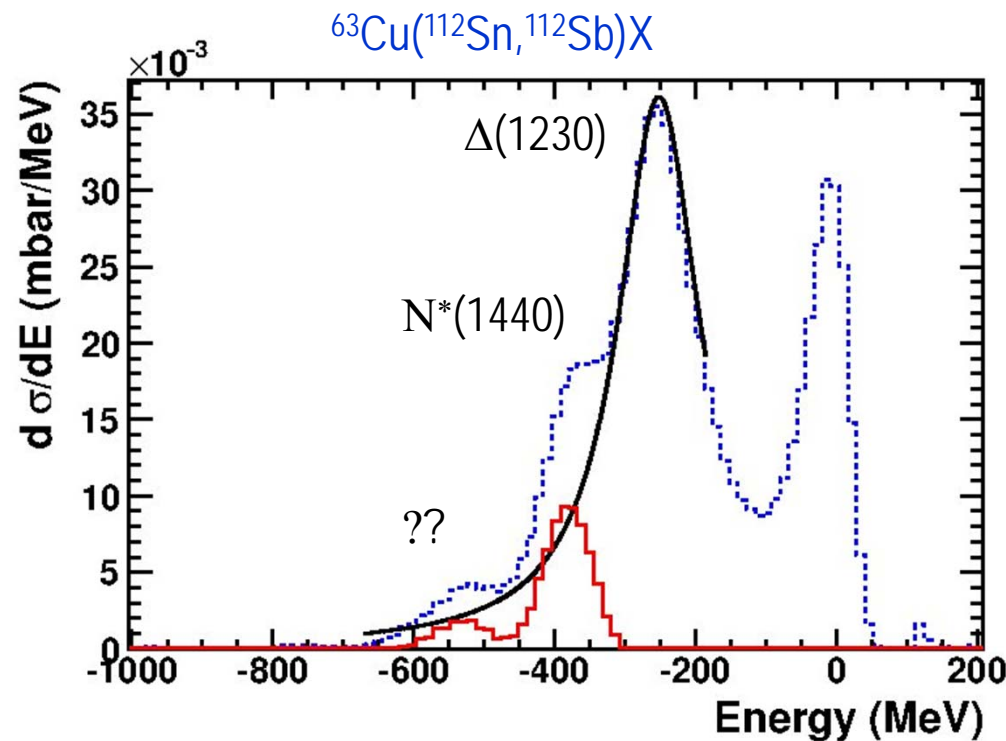

p($\alpha$, $\alpha'$)X @ 4.2 GeV
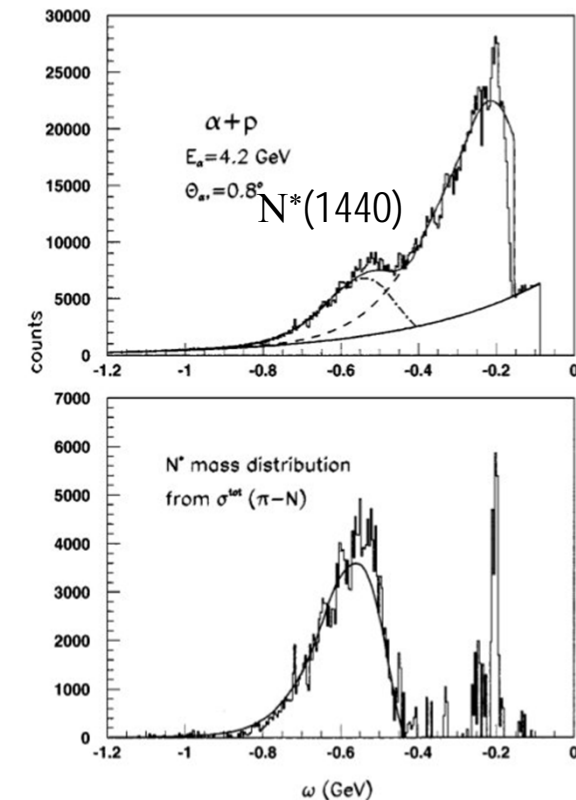
H.P. Morsch et al., PRL 69, 1336 (1992)

✓ The unfolded data show clear structures in the inelastic component

✓ The second substructure is tentatively identified as the Roper resonance

## Energy and target dependence of the resonance excitation
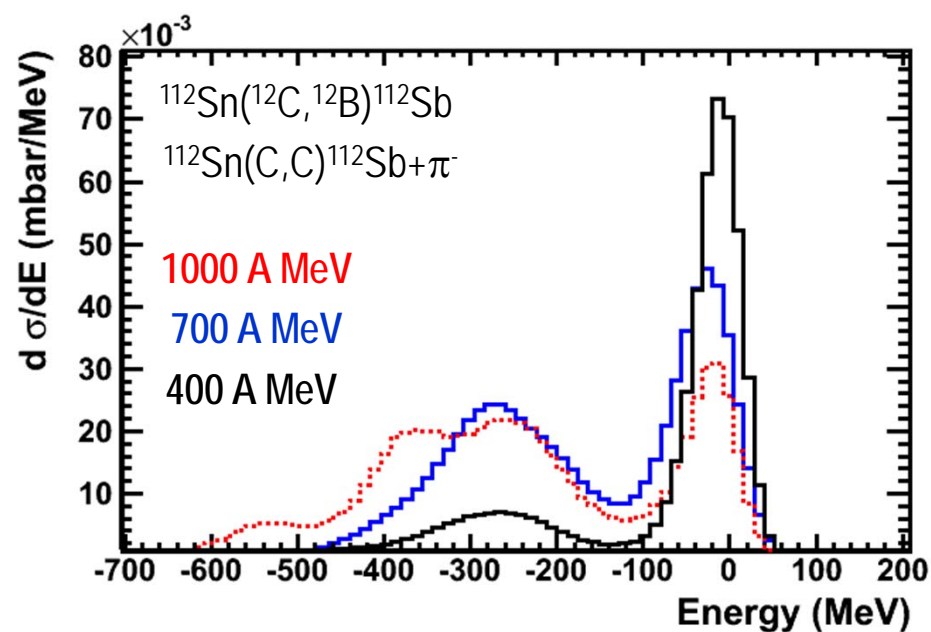


✓ Resonances excitation follows the expected
energy dependence
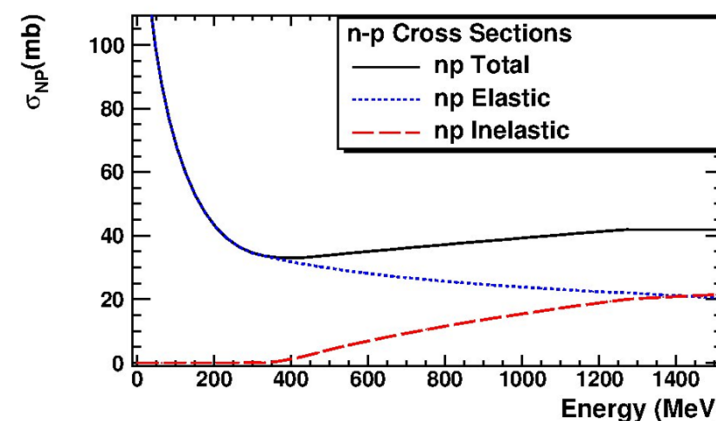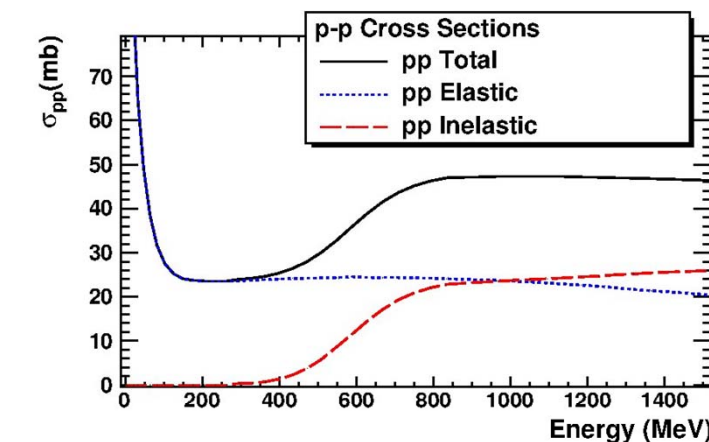
### Energy and target dependence of the resonance excitation
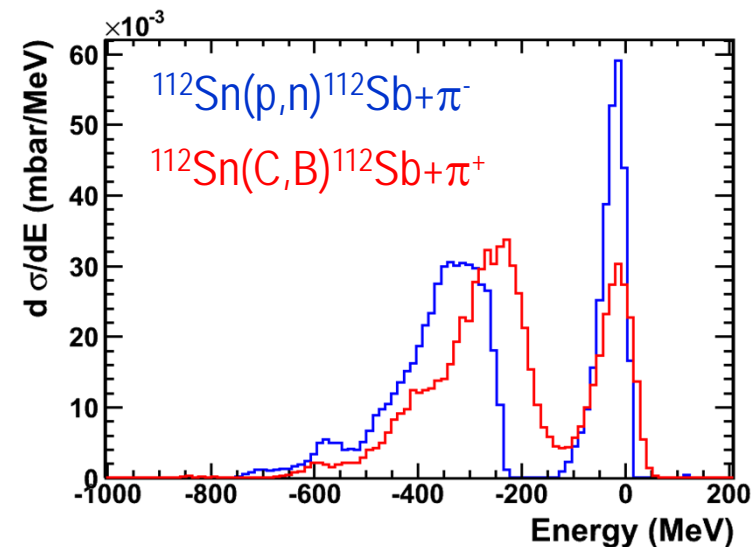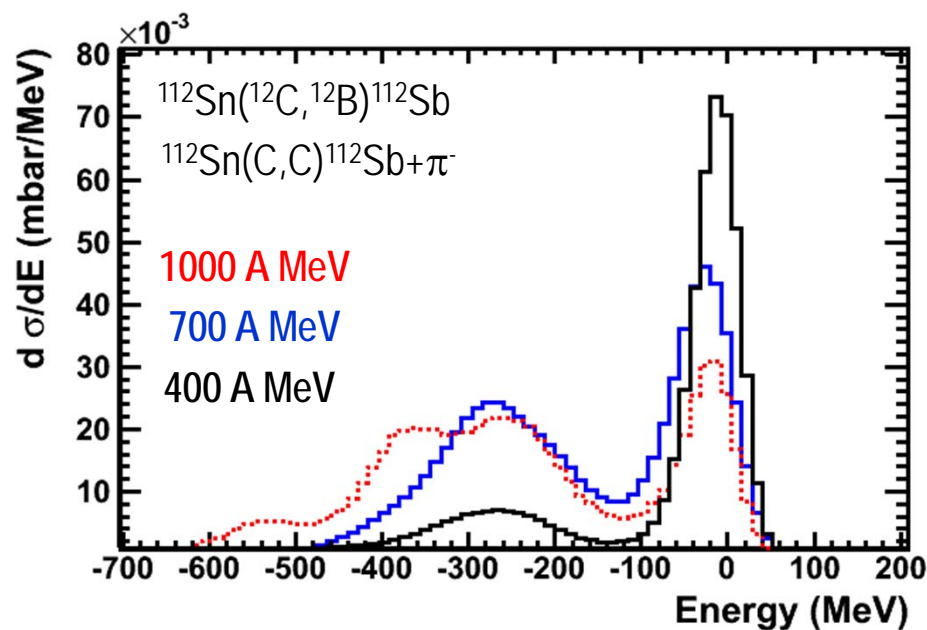


- ✓ Resonances excitation follows the expected energy dependence.

- ✓ The mass shift for light targets is also observed.

# Measurements with the FRS

## Conclusions from the pilot FRS experiment

The excitation of $\Delta$ and N* resonances was demonstrated at the FRS . The resolution could be improved up to ~ 10 MeV.

→ feasible

$^{63}Cu(^{112}Sn,^{112}Sb)X$ @ 1A GeV



$\Delta(1230)$

N*(1440)

??



$^1$H  ($^{112}Sn, ^{112}In$)

- - - Quasi-elastic
- - - Exc. in target
- - - Exc. in project.
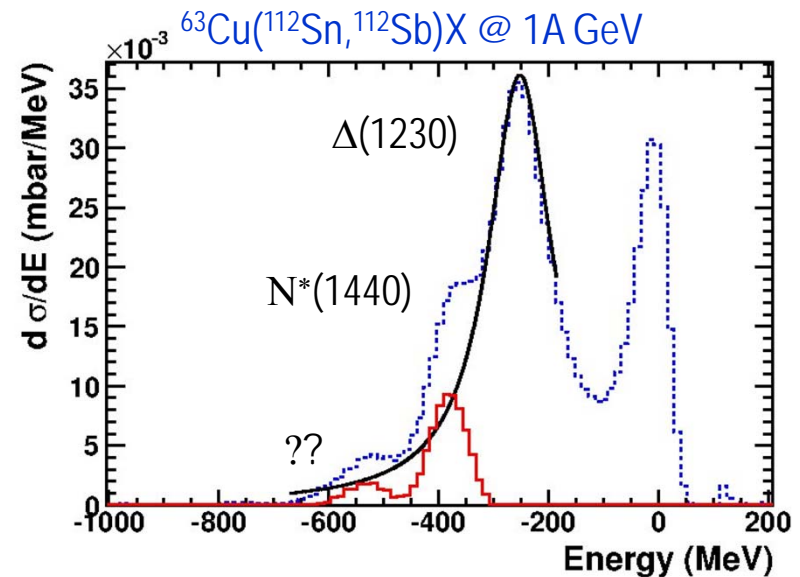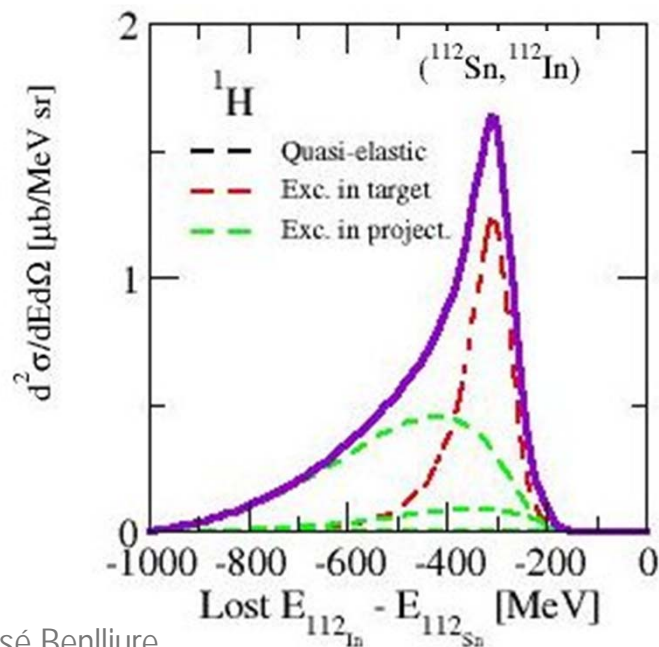
The determination of the mass and width of the resonances from the missing energy spectra requires the evaluation of:

- kinematic effects: excitations in projectile and target nuclei, and Fermi momentum.

- Medium effects: pion absorption

→ exclusive measurements required (pion detection)

→ individual resonances discrimination using a LH$_2$ target.

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# Isobar charge-exchange reactions and symmetry energy

**Isobar charge-exchange reactions induced by relativistic-radioactive beams**

Precise measurements of the neutron skin in neutron-rich nuclei.
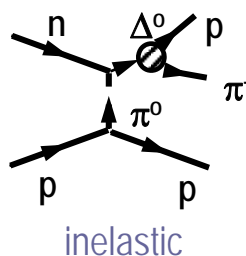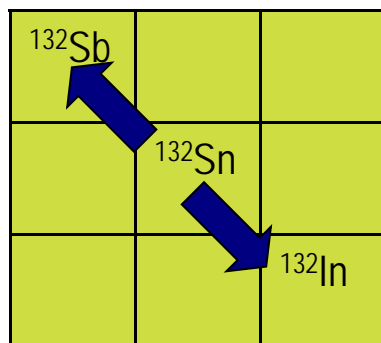


inelastic



Isobar charge exchange reactions are peripheral processes.

- ✓ Pions scape to preserve the isobar character of the reaction.
- ✓ Pions have a large absorption cross section.

(n,p) and (p,n) cross sections prove the neutron and proton abundance at the nuclear surface.

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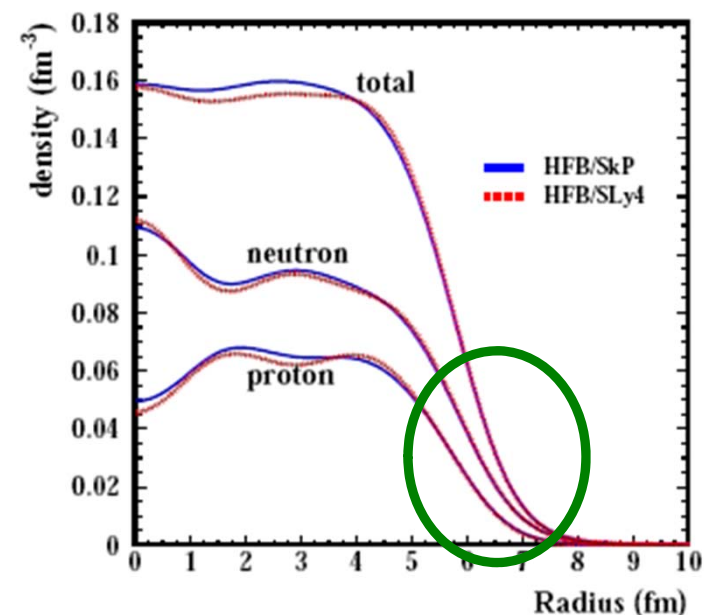
# Isobar charge-exchange reactions and symmetry energy

EoS for asymmetric nuclear matter, neutron stars

$$E(\rho,\delta) \approx E(\rho,\delta=0) + E_{sym}(\rho)\delta^2, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

Symmetry energy.

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

$$E_{sym}(\rho_0) = a_{sym} \approx 30\,A\,MeV$$

First derivative

$$L = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0} \quad \text{from 40 to 65 MeV}$$
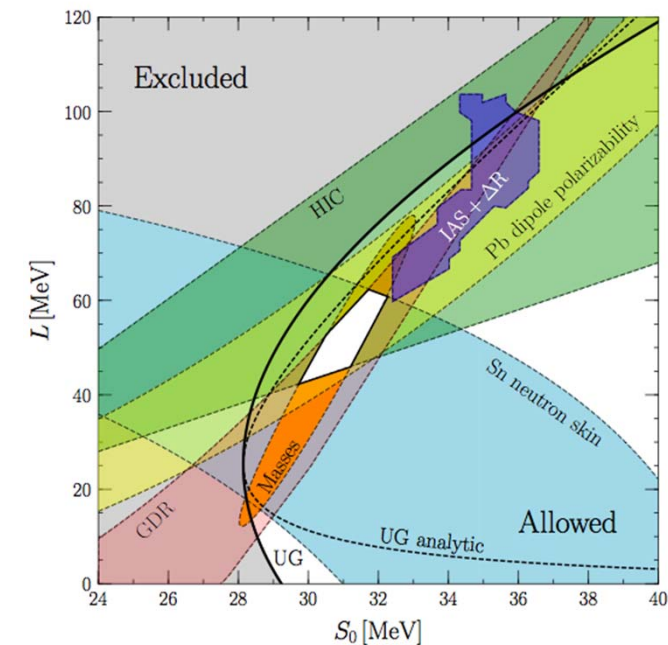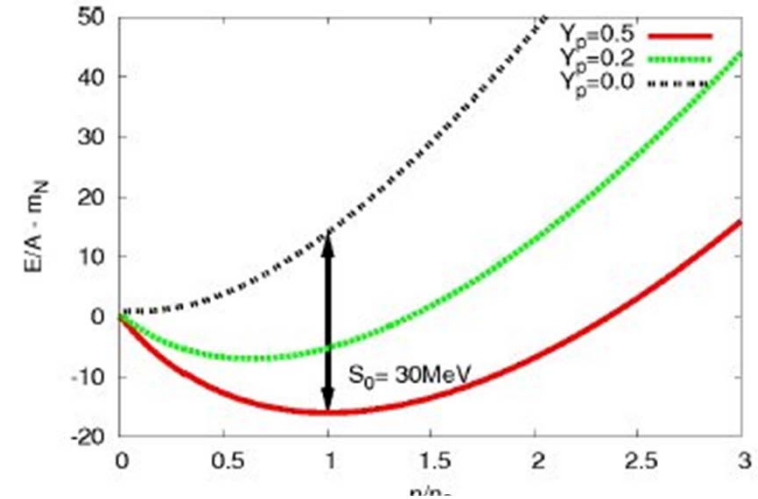
C. Tews et al. APJ 848, 105 (2017)

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# Isobar charge-exchange reactions and symmetry energy

Using a liquid hydrogen target the ratio of those cross sections is proportional to the neutron-skin thickness

$$\frac{\sigma(^{A}Z, ^{A}(Z+1))}{\sigma(^{A}Z, ^{A}(Z-1))} = \frac{\sigma_{np \to pp\pi^-}}{\sigma_{pp \to np\pi^+}} \frac{N_n}{N_p}$$

The ratio of those cross sections can be obtained with an accuracy better than 2% ➔ ~ 4 MeV in "L".


Calculations by I. Vidaña

Reaction at 1GeV per nucleon
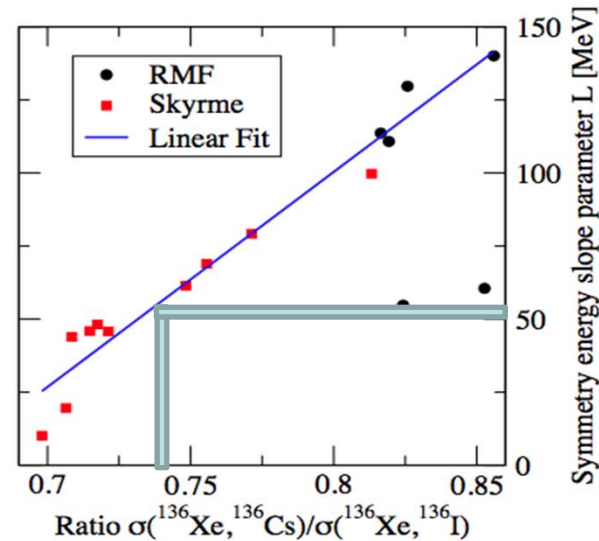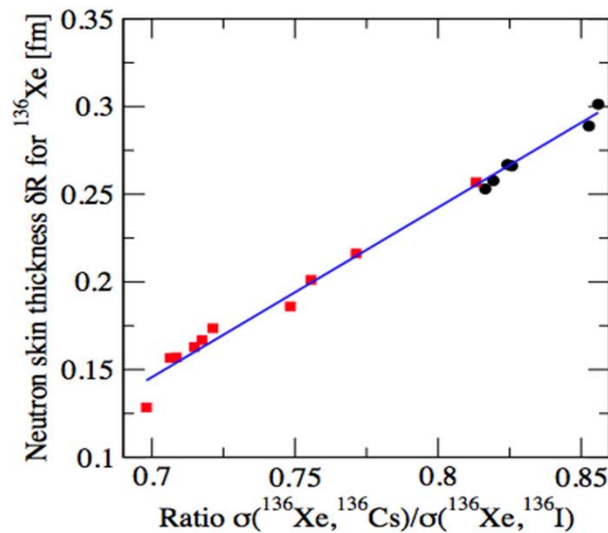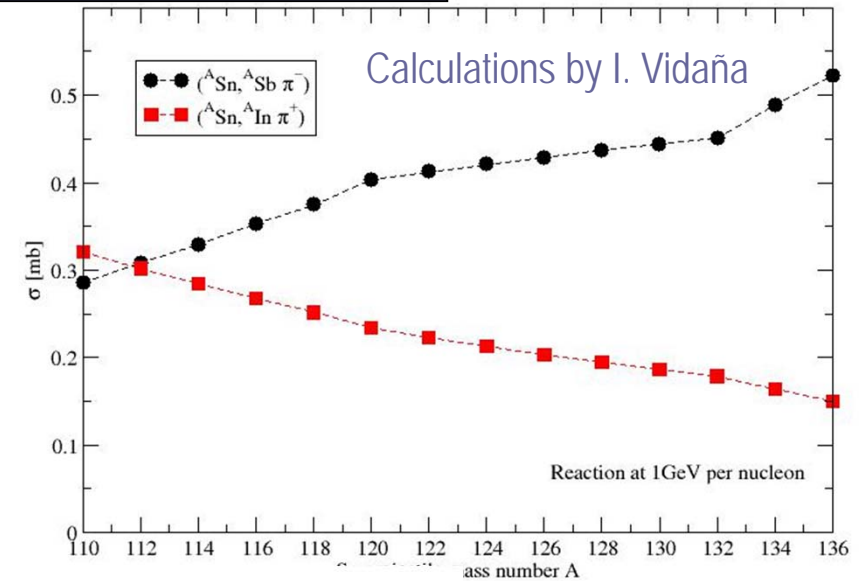
# Proposal for FAIR phase 0

## Physic cases

- ✓ To elucidate possible in-medium effects in the mass and width of the $\Delta$ resonance

- ✓ Precise characterization of the N* resonance in mass and width

- ✓ Search for heavier resonances

- ✓ To investigate the sensitivity of the isobar charge exchange cross section to the symmetry energy

## Requirements

- ✓ Beams with different neutron excess ($^{124}$Xe, $^{136}$Xe) and energies between 400A and 1200A MeV

- ✓ Isotopic identification and recoil energy of the charge-exchange products: resolution ~10 MeV

- ✓ Identification and momentum of charged pions: WASA type detector, solenoide+tracker.

- ✓ Liquid hydrogen target.

# Dedicated experiments

**Observables:**

✓ cross sections for both charge exchange channels ($\sigma(n,p)/\sigma(p,n)\sim2\%$)

✓ missing-energy spectra of the projectile remnant (~10 MeV)
  mean energy and width of the $\Delta$ and N* resonances

✓ momenta of the emitted pions ($\Delta p/p\sim10\%$)
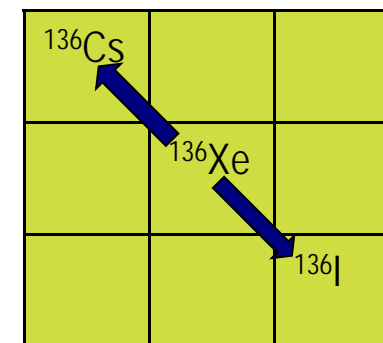


**Requirements for the setup:**

✓ isotopic identification of projectile remnants

✓ precise determination of the energy lost in the reaction
  magnetic analysis of the projectile remnants and minimum matter

✓ kinematic identification of the projectile-like pions.
  large-acceptance light-charged particle detector WASA

✓ liquid-hydrogen target to reduce the contribution of different
  resonance isobars
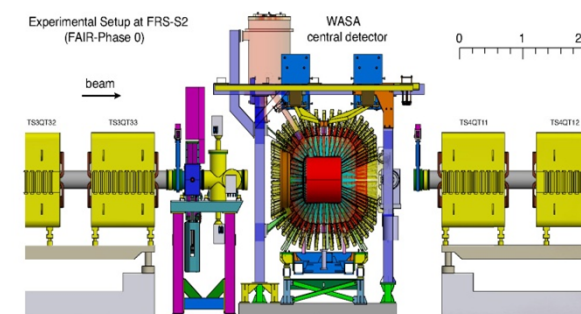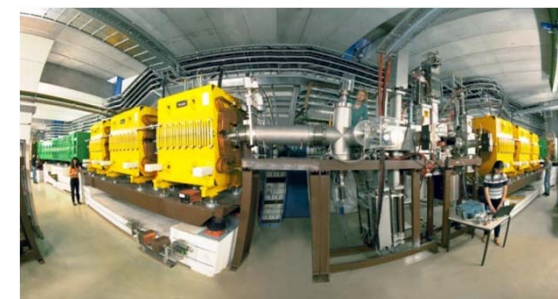
# New proposal for FAIR phase 0

## Kinematical identification of projectile/target pions
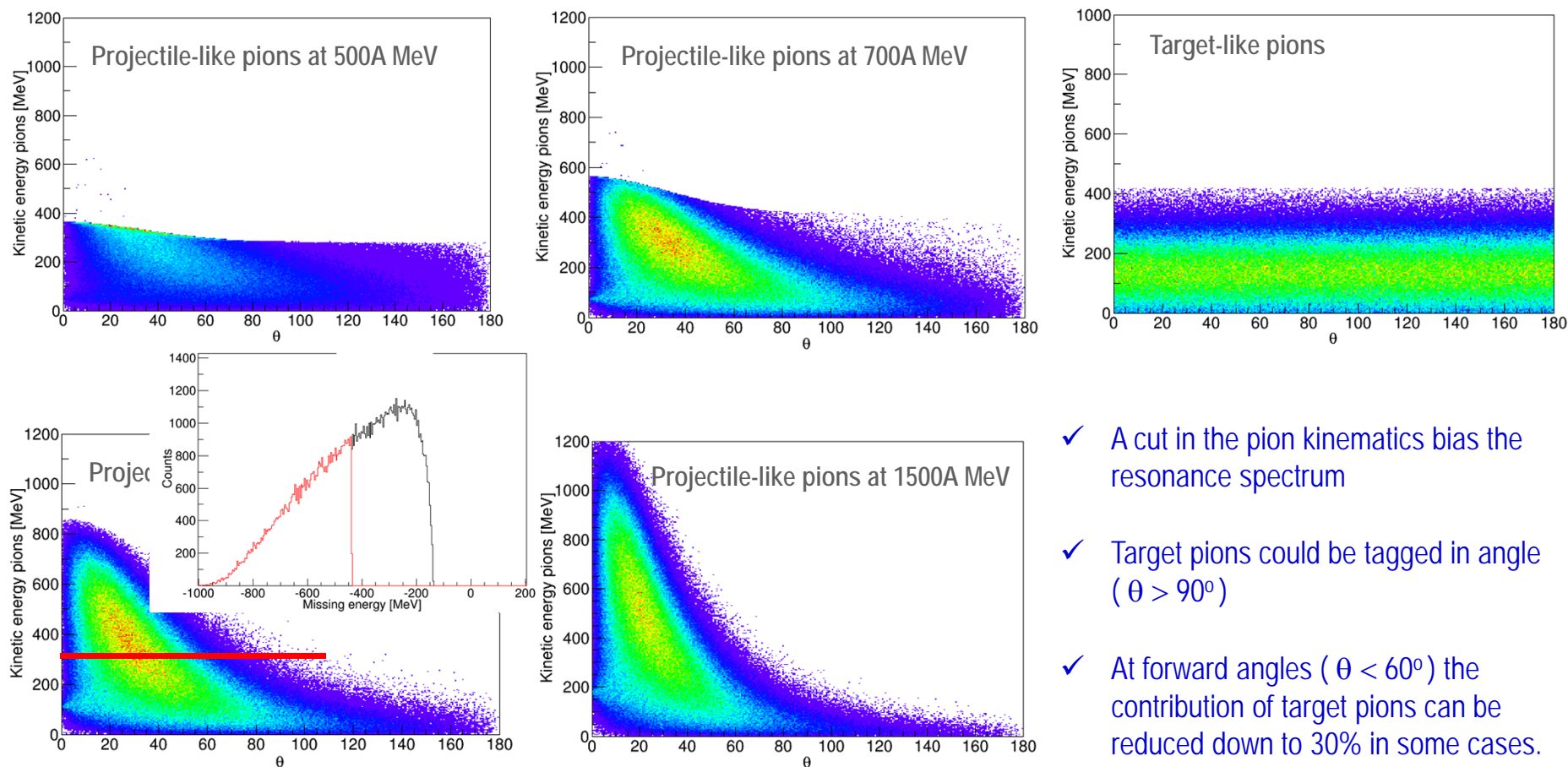


✓ A cut in the pion kinematics bias the resonance spectrum

✓ Target pions could be tagged in angle ( $\theta > 90^o$ )

✓ At forward angles ( $\theta < 60^o$ ) the contribution of target pions can be reduced down to 30% in some cases.

Δ-resonance identification

(p,n)

(n,p)

**Δ(1232) excitation** (p,n)

| excitation the target | | excitation in the projectile | |
|---|---|---|---|
| $p(p,n)\Delta^{++} = p(p,n)p\pi^{+}$ | $[\sqrt{2}]$ | $p(p,\Delta^{+})p = p(p,n\pi^{+})p$ | $[-\sqrt{2}/3]$ |
| $n(p,n)\Delta^{+} = n(p,n)n\pi^{+}$ | $[\sqrt{2}/3]$ | $n(p,\Delta^{+})n = n(p,n\pi^{+})n$ | $[\sqrt{2}/3]$ |
| $n(p,n)\Delta^{+} = n(p,n)p\pi^{0}$ | $[-2/3]$ | $n(p,\Delta^{0})p = n(p,n\pi^{0})p$ | $[2/3]$ |

**Δ(1232) excitation** (n,p)

| excitation in the target | | excitation in the projectile | |
|---|---|---|---|
| $p(n,p)\Delta^{0} = p(n,p)n\pi^{0}$ | $[2/3]$ | $p(n,\Delta^{0})p = p(n,p\pi^{-})p$ | $[-\sqrt{2}/3]$ |
| $p(n,p)\Delta^{0} = p(n,p)p\pi^{-}$ | $[-\sqrt{2}/3]$ | $p(n,\Delta^{+})n = p(n,p\pi^{0})n$ | $[-2/3]$ |
| $n(n,p)\Delta^{-} = n(n,p)n\pi^{-}$ | $[-\sqrt{2}]$ | $n(n,\Delta^{0})n = n(n,p\pi^{-})n$ | $[\sqrt{2}/3]$ |

**$N^{*}(1440)$ excitation** (p,n)

| excitation in the target | | excitation in the projectile | |
|---|---|---|---|
| $n(p,n)P_{11}^{+} = n(p,n)n\pi^{+}$ | $[-2\sqrt{2}]$ | $p(p,P_{11}^{+})p = p(p,n\pi^{+})p$ | $[-\sqrt{2}]$ |
| $n(p,n)P_{11}^{+} = n(p,n)p\pi^{0}$ | $[2]$ | $n(p,P_{11}^{+})n = n(p,n\pi^{+})n$ | $[\sqrt{2}]$ |
| | | $n(p,P_{11}^{0})p = n(p,n\pi^{0})p$ | $[-2]$ |

**$N^{*}(1440)$ excitation** (n,p)

| excitation in the target | | excitation in the projectile | |
|---|---|---|---|
| $p(n,p)P_{11}^{0} = p(n,p)n\pi^{0}$ | $[-2]$ | $p(n,P_{11}^{0})p = p(n,p\pi^{-})p$ | $[-\sqrt{2}]$ |
| $p(n,p)P_{11}^{0} = p(n,p)p\pi^{-}$ | $[2\sqrt{2}]$ | $p(n,P_{11}^{+})n = p(n,p\pi^{0})n$ | $[2]$ |
| | | $n(n,P_{11}^{0})n = n(n,p\pi^{-})n$ | $[\sqrt{2}]$ |

✓ Hydrogen target + 400A MeV (only Δ excitation)

(n,p) + π⁻ detection → Δ⁰ in projectile and target with similar probability (θ<60°) more projectile than target)

(p,n) + π⁺ detection → Δ⁺⁺ in target more probable than Δ⁺ in projectile (θ>90° mostly target)

In both cases the background from quasi-elastic charge-exchange reactions is removed

# New proposal for FAIR phase 0

## P$_{11}$-resonance identification

### (p,n)

| $\Delta(1232)$ excitation | | | |
|---|---|---|---|
| **excitation the target** | | **excitation in the projectile** | |
| $p(p,n)\Delta^{++} = p(p,n)p\pi^{+}$ | $[\sqrt{2}]$ | $p(p,\Delta^{+})p = p(p,n\pi^{+})p$ | $[-\sqrt{2}/3]$ |
| $n(p,n)\Delta^{+} = n(p,n)n\pi^{+}$ | $[\sqrt{2}/3]$ | $n(p,\Delta^{+})n = n(p,n\pi^{+})n$ | $[\sqrt{2}/3]$ |
| $n(p,n)\Delta^{+} = n(p,n)p\pi^{0}$ | $[-2/3]$ | $n(p,\Delta^{0})p = n(p,n\pi^{0})p$ | $[2/3]$ |
| $N^{*}(1440)$ excitation | | | |
| **excitation in the target** | | **excitation in the projectile** | |
| $n(p,n)P_{11}^{+} = n(p,n)n\pi^{+}$ | $[-2\sqrt{2}]$ | $p(p,P_{11}^{+})p = p(p,n\pi^{+})p$ | $[-\sqrt{2}]$ |
| $n(p,n)P_{11}^{+} = n(p,n)p\pi^{0}$ | $[2]$ | $n(p,P_{11}^{+})n = n(p,n\pi^{+})n$ | $[\sqrt{2}]$ |
| | | $n(p,P_{11}^{0})p = n(p,n\pi^{0})p$ | $[-2]$ |

### (n,p)

| $\Delta(1232)$ excitation | | | |
|---|---|---|---|
| **excitation in the target** | | **excitation in the projectile** | |
| $p(n,p)\Delta^{0} = p(n,p)n\pi^{0}$ | $[2/3]$ | $p(n,\Delta^{0})p = p(n,p\pi^{-})p$ | $[-\sqrt{2}/3]$ |
| $p(n,p)\Delta^{0} = p(n,p)p\pi^{-}$ | $[-\sqrt{2}/3]$ | $p(n,\Delta^{+})n = p(n,p\pi^{0})n$ | $[-2/3]$ |
| $n(n,p)\Delta^{-} = n(n,p)n\pi^{-}$ | $[-\sqrt{2}]$ | $n(n,\Delta^{0})n = n(n,p\pi^{-})n$ | $[\sqrt{2}/3]$ |
| $N^{*}(1440)$ excitation | | | |
| **excitation in the target** | | **excitation in the projectile** | |
| $p(n,p)P_{11}^{0} = p(n,p)n\pi^{0}$ | $[-2]$ | $p(n,P_{11}^{0})p = p(n,p\pi^{-})p$ | $[-\sqrt{2}]$ |
| $p(n,p)P_{11}^{0} = p(n,p)p\pi^{-}$ | $[2\sqrt{2}]$ | $p(n,P_{11}^{+})n = p(n,p\pi^{0})n$ | $[2]$ |
| | | $n(n,P_{11}^{0})n = n(n,p\pi^{-})n$ | $[\sqrt{2}]$ |

✓ Hydrogen target + (p,n) channel + 1000A MeV ( $\Delta$ and P$_{11}$ excitation)

P$^{+}$ decay into n+$\pi^{+}\pi^{0}$ rejects any $\Delta$ excitation

$N(1440) \rightarrow N\pi \quad 55 - 75\%$

$N(1440) \rightarrow N\pi\pi \quad 30 - 40\%$
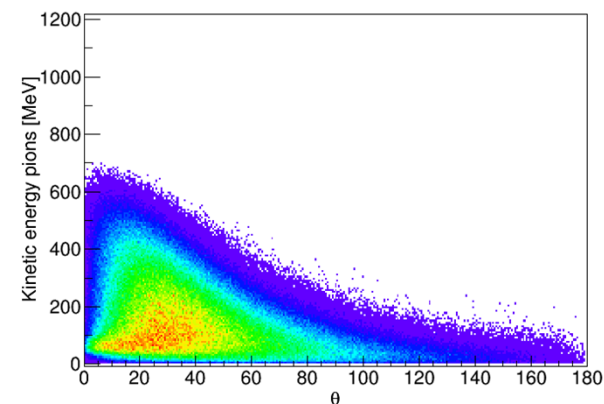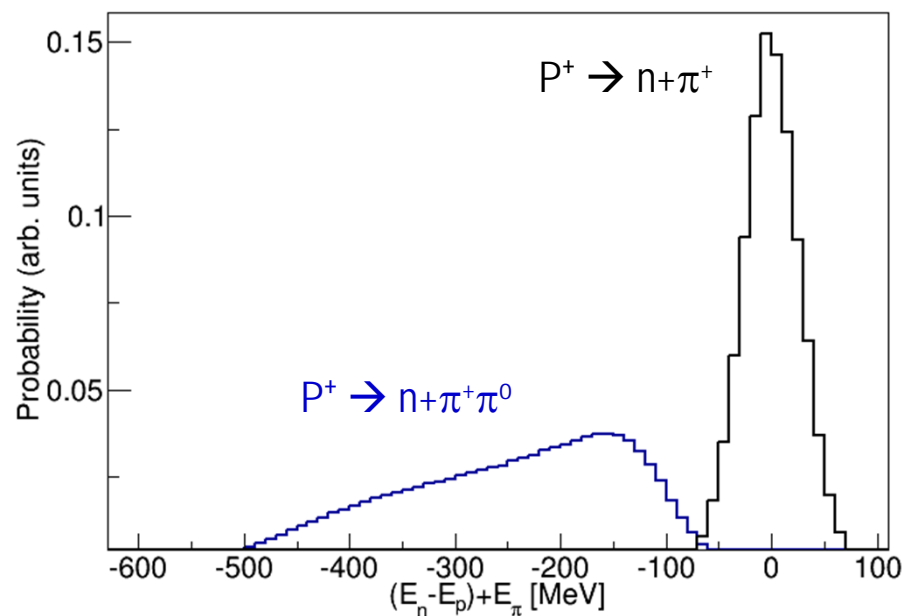
$P_{11}^{+} \rightarrow n\,\pi^{+}\pi^{0}$

- $\pi^{0}$ decay into photons $\pi^{0} \rightarrow \gamma\gamma$

- Measurement of the charged pion momentum $\rightarrow$ shift in the total energy spectrum due to the $\pi^{0}$.

# New proposal for FAIR phase 0

$P_{11}$-resonance identification from missing energy spectra in $P^+ \rightarrow n+\pi^++\pi^0$

$\pi^+$ momentum measurement



✓ The estimated resolution for the pion momentum measurement ~ 10%.

✓ Lowest possible threshold and relatively large angular range for pion detection.

✓ Detailed simulations with a specific pion detection setup to be done.

# Summary

✓ **Physic cases:**

Precise characterization of the in-medium properties of the Delta and Roper resonances

Search for heavier resonances

Sensitivity of the charge-exchange cross sections to the symmetry energy

✓ **Beams:**

Stable $^{124}$Xe and $^{136}$Xe and secondary $^{118}$Xe
Energies between 400A and 1200A MeV and intensities ~$10^8$ – $10^9$ ions/s
Two shifts per stable beam and energy, and three shifts per energy for unstable beams

Technical requirements:

➤ Liquid hydrogen target

➤ Reaction residues identification and recoil energy measured with a resolution around 10 MeV

➤ Charged pion detection: $\pi$-, $\pi$+ discrimination and energy determination with 10% resolution

   Pion detector common to hypernuclei and mesic-atom proposals



$^{12}C(4.2\ GeV/c)+^{12}C \rightarrow X+p+\pi^++\pi^-$

EPJA 20, 351 (2004)

N(1440)

N(1520)
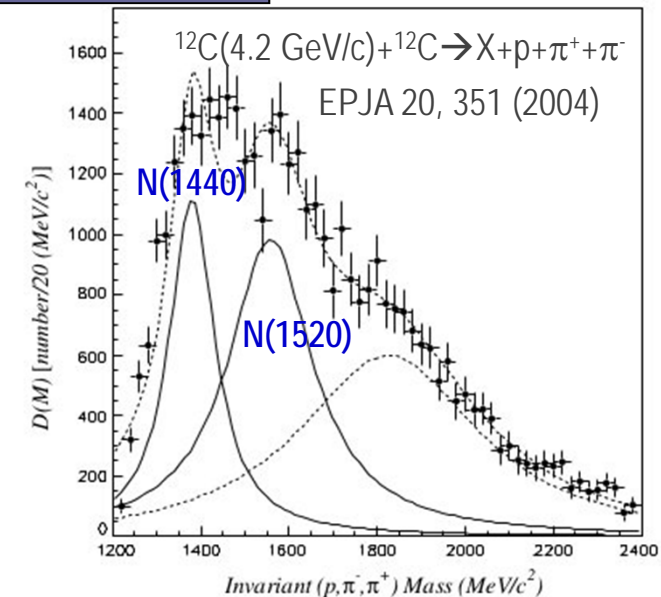
# Collaborators

**U. Santiago de Compostela**: J.Benlliure, D. Cortina, J. Díaz, J.L. Rodríguez

**GSI:** H. Geissel, C. Scheidenberger, H. Weick, J. Winfield

**U. Coimbra**: I. Vidaña

**U. Giessen**: H. Lenske

**U. Beihang, RCNP :** I. Tanihata


**+ Hypernucli subcoll. + Mesic atoms subcoll. + SuperFRS coll.**