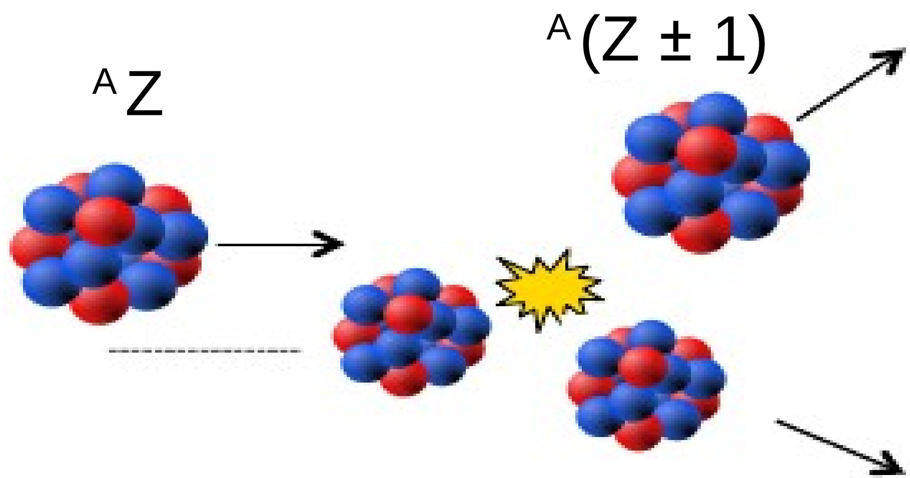
Isobaric charge-exchange reactions: a tool to study the excitation of baryonic resonances in exotic nuclear matter

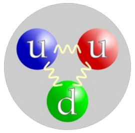


Jose Luis Rodríguez-Sánchez
University of Santiago de Compostela, Spain

Baryonic resonances

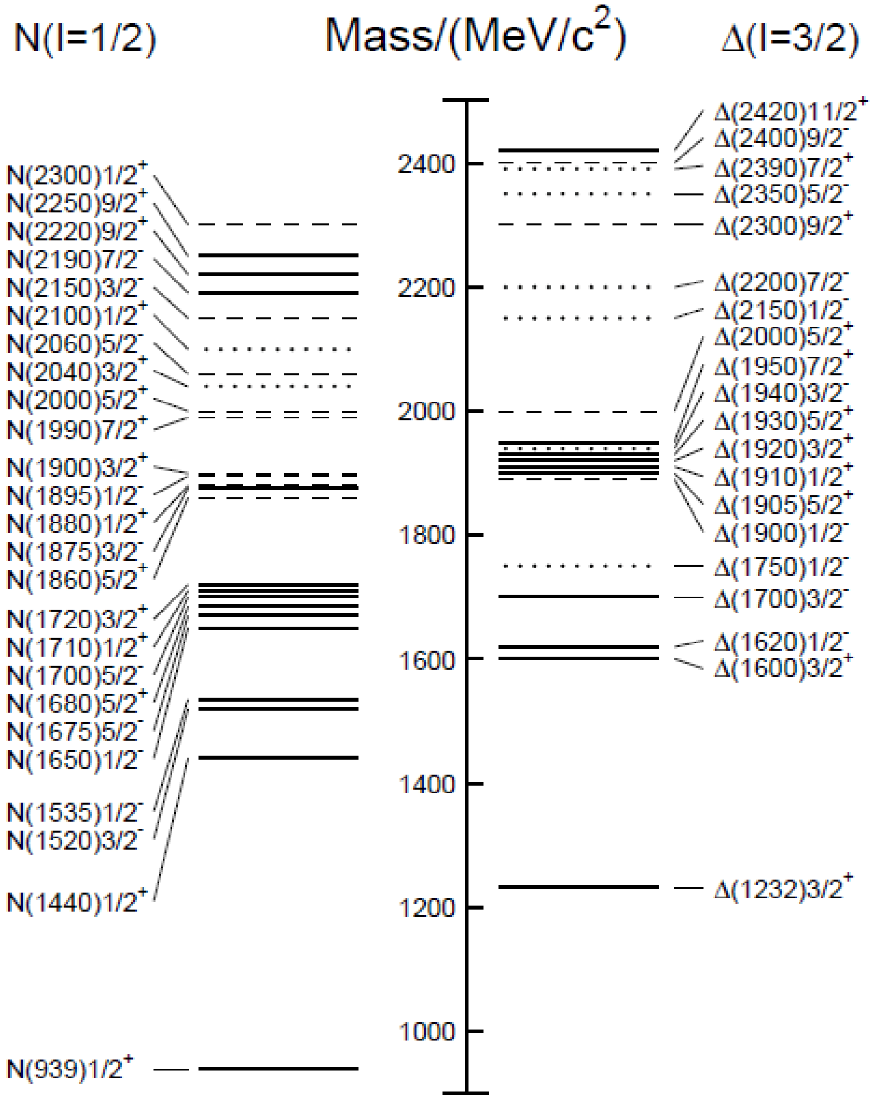
Baryonic resonances are excited states of nucleons and are also made of 3 quarks

- There are experimental measurements for around 45 resonances



- The study of their excitation spectrum provides information about the confining mechanism of quarks into a hadron and thus helps to improve our understanding of Quantum Chromodynamics (QCD)

- Their masses, widths and decay modes are used as a testing ground for several models



Excited states: resonances

Nucleon as the ground state

Baryonic resonances

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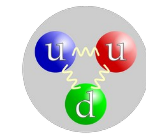
- There are experimental measurements for around 45 resonances



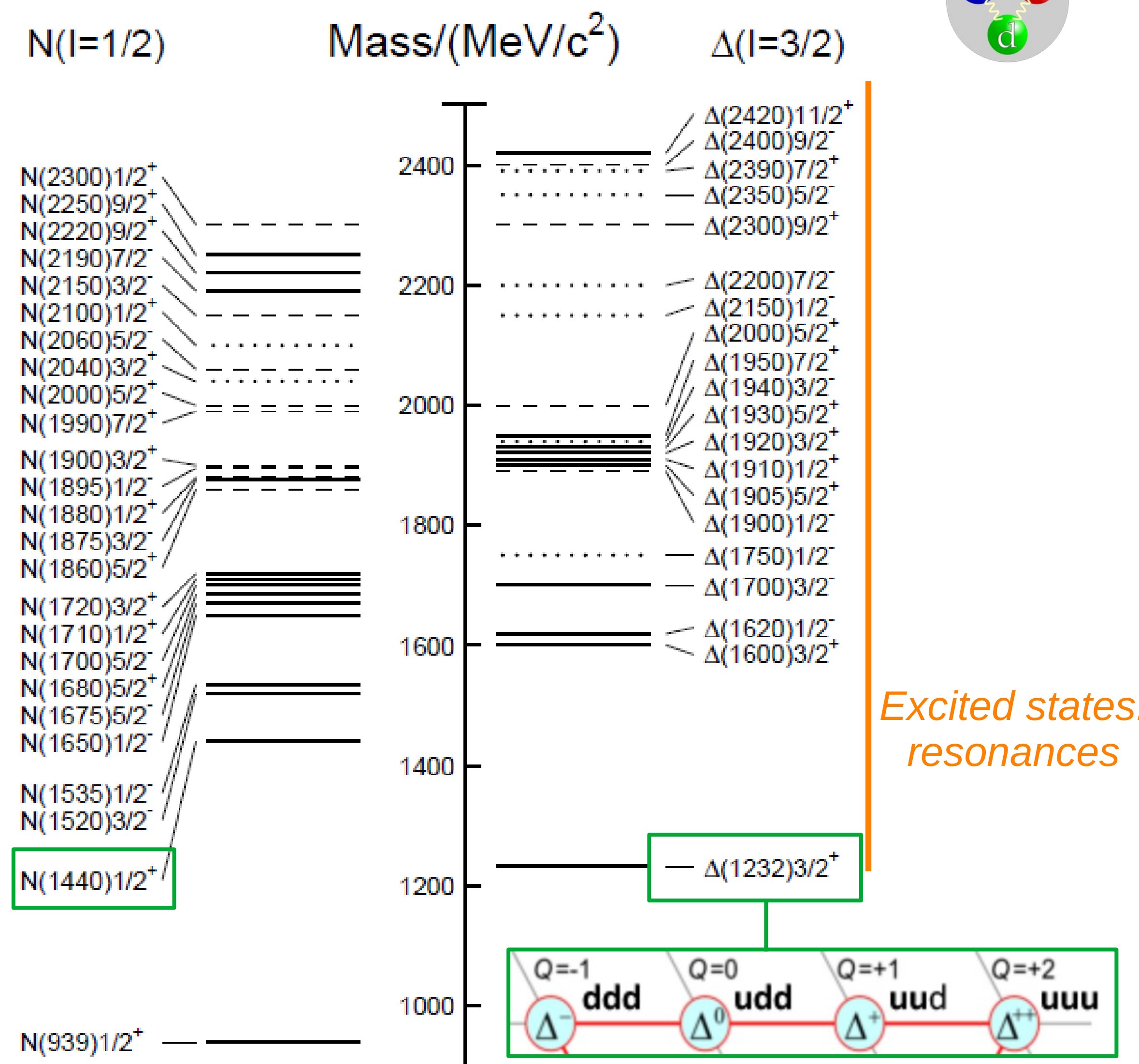
- The study of their excitation spectrum provides information about the confining mechanism of quarks into a hadron and thus helps to improve our understanding of Quantum Chromodynamics (QCD)

- Their masses, widths and decay modes are used as a testing ground for several models

- The low-lying baryon resonances are the Δ(1232) and Roper(1440) resonances

- Δ(1232) is divided into 4 isobars with a charge ranging from -1 to +2

- The study of this excitation spectrum in the nuclear medium also represents a natural extension of nuclear physics



Nucleon as the ground state

Baryonic resonances: πN excitation spectrum

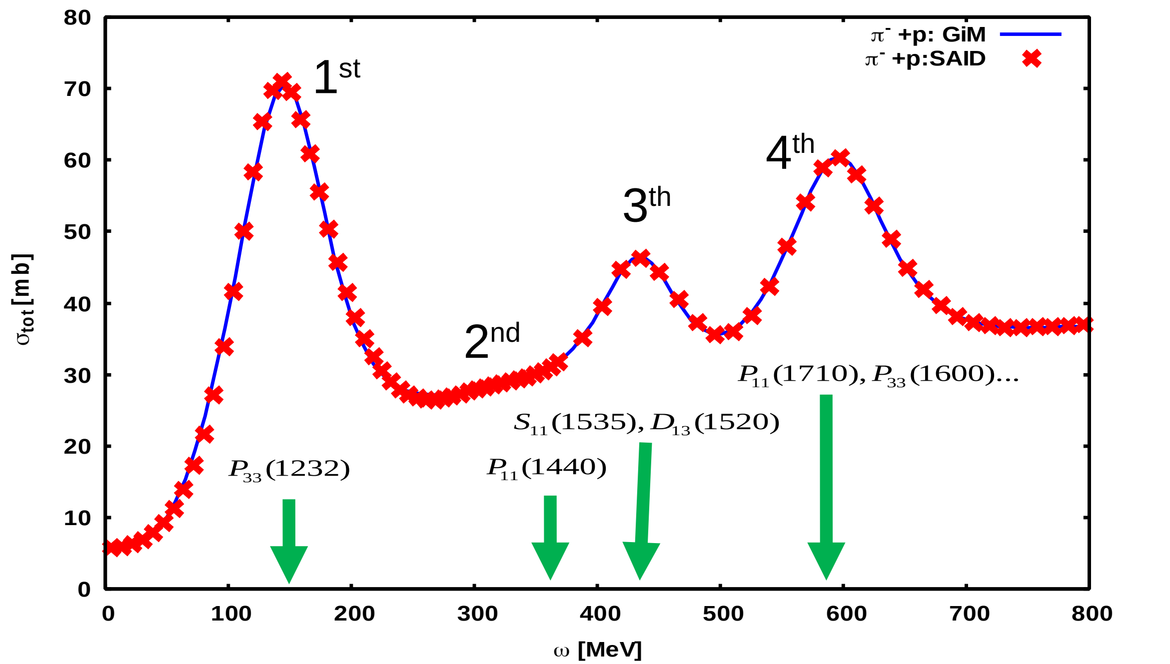
- Experimentally, looking at the excitation spectrum we observe a continum of different regions, starting in the Δ(1232) peak

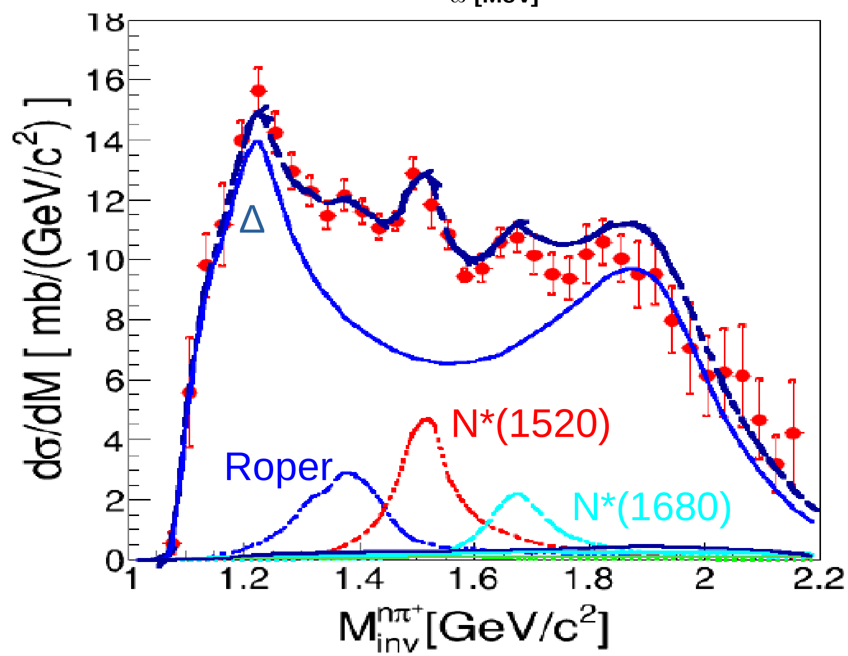
- This represents a big problem if we want to extract the properties of the baryonic resonances

- One needs to look for specific decay channels or reactions to separe each resonance

- Δ(1232) properties are well stablished in the free space, but there are still many uncertainties if we look for these in the nuclear medium. For the other resonances we do not have any information

- In particular, we do not have any information about how these properties change with the neutron-to-proton asymmetry





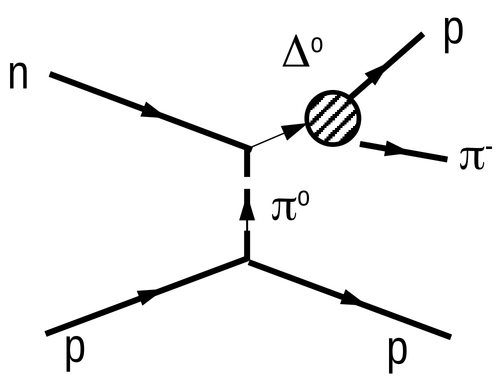
Outline

- **Motivation**
- **Isobaric charge-exchange reactions to investigate the in-medium excitation of baryonic resonances**
- **Measurements performed at the SATURNE facility**
  - Experimental setup
  - Inclusive and exclusive measurements with light ions
- **Measurements carried out at the FRagment Separator FRS @ GSI**
  - Experimental setup
  - Inclusive measurements with medium-mass ions of Sn
- **Results and comparison to sophisticated model calculations**
- **Future experiments at the FRS/Super-FRS @ GSI-FAIR**
- **Summary & Perspectives**

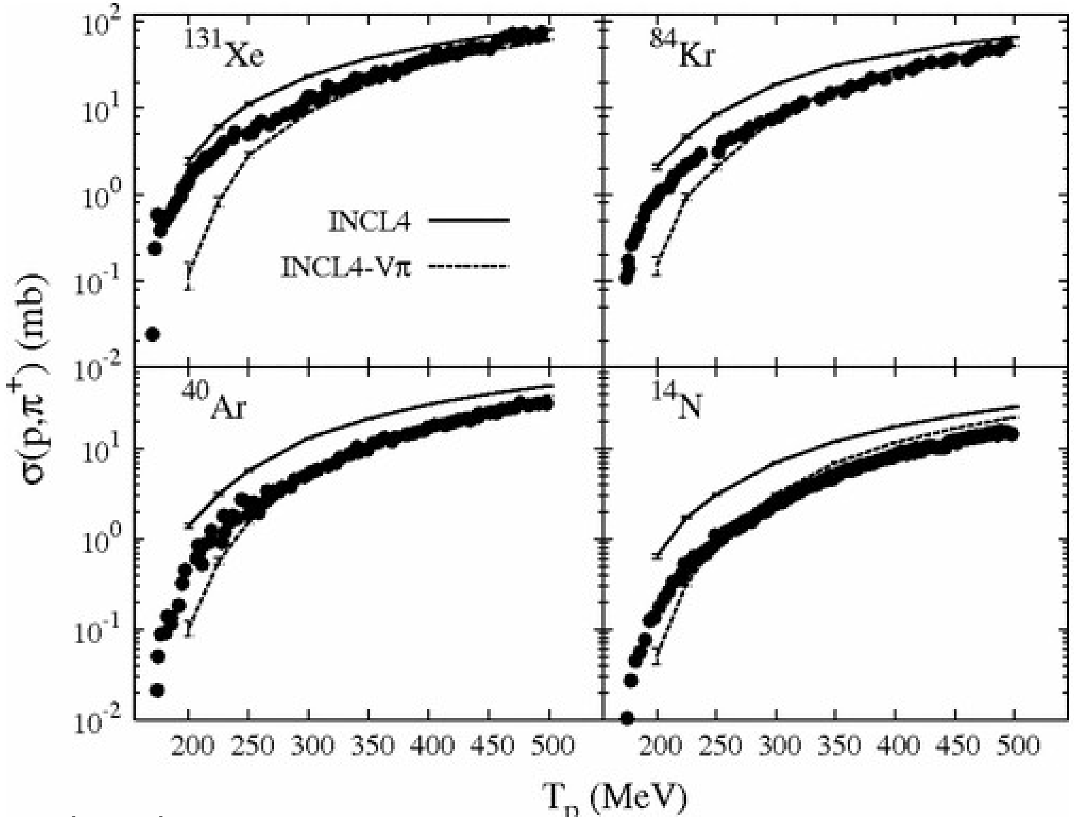
Motivation

The accurate constraint of **in-medium properties** **(isospin & density dependencies)** of baryonic resonances is still needed for a better understanding of

- Pion production in ion collisions at relativistic energies



Constraints for pion nuclear potentials

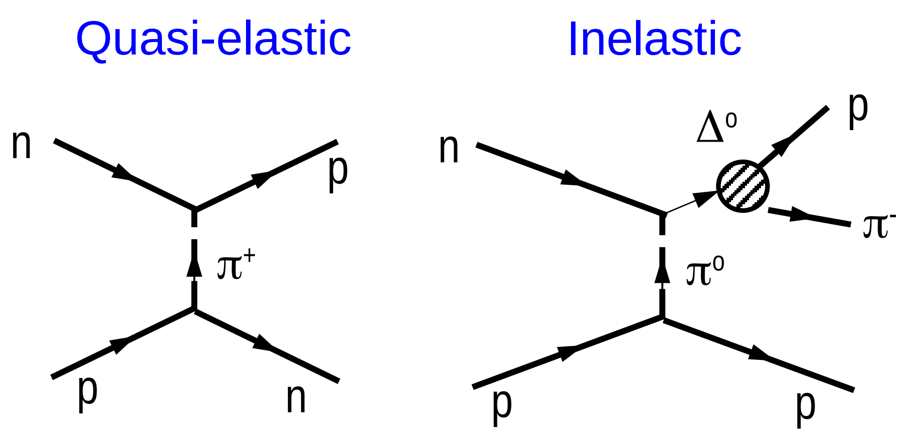


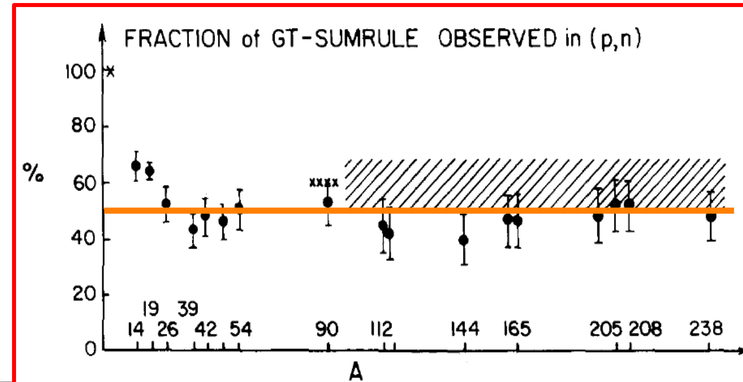
T. Aoust and J. Cugnon, Phys. Rev. C 74, 064607 (2006)

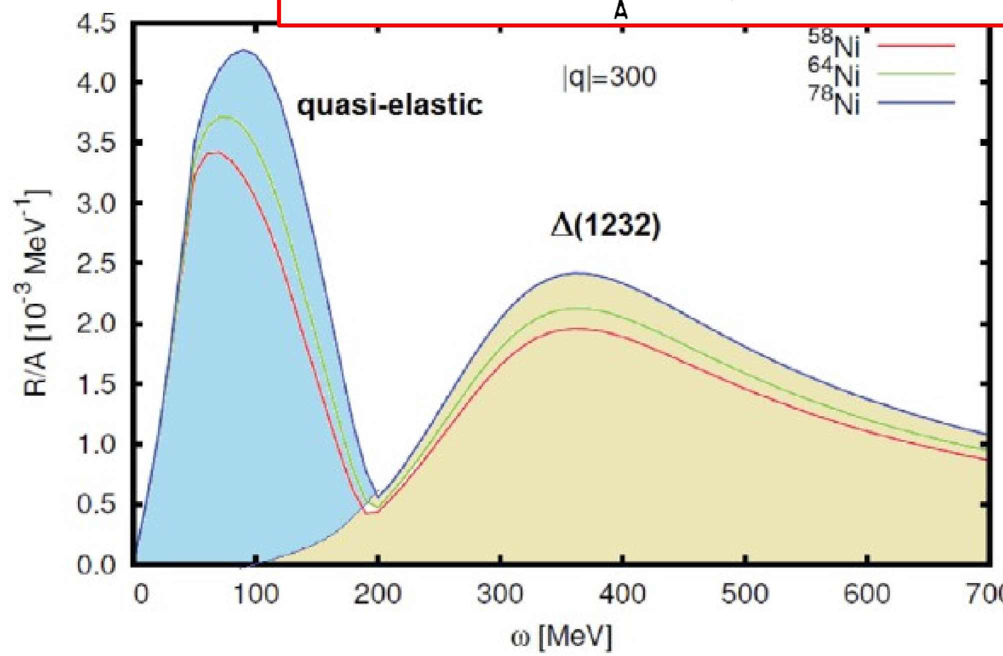
Motivation

The accurate constraint of **in-medium properties** **(isospin & density dependencies)** of baryonic resonances is still needed for a better understanding of

- Pion production in ion collisions at relativistic energies
- Quenching of the Gamow-Teller strength





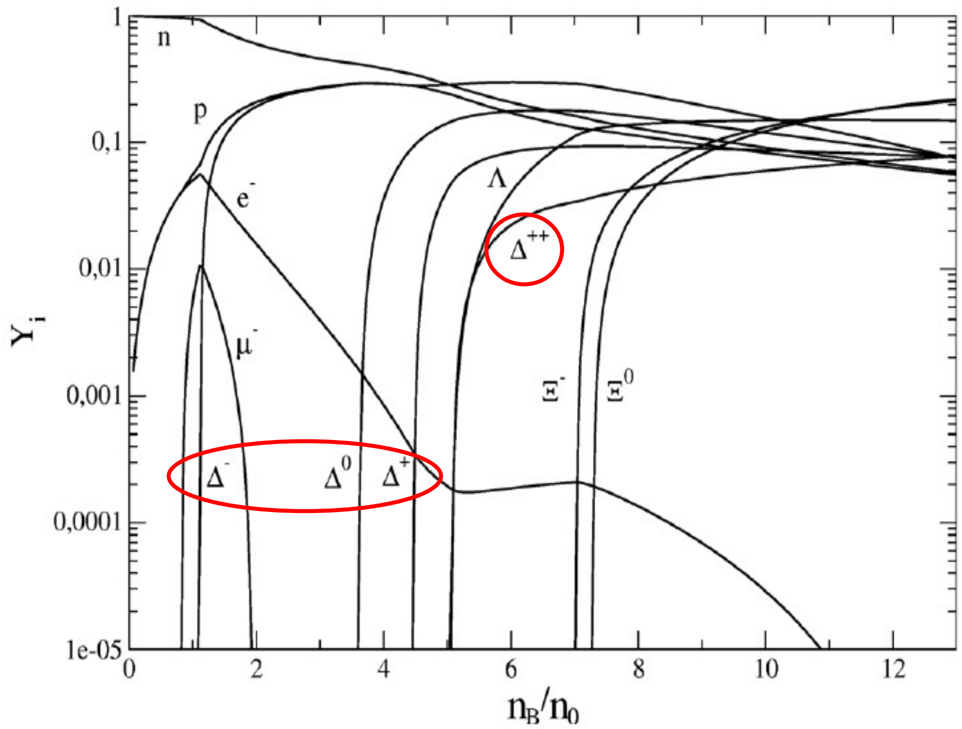


H. Lenske et al., Progress in Particle and Nuclear Physics 98, 119 (2018)

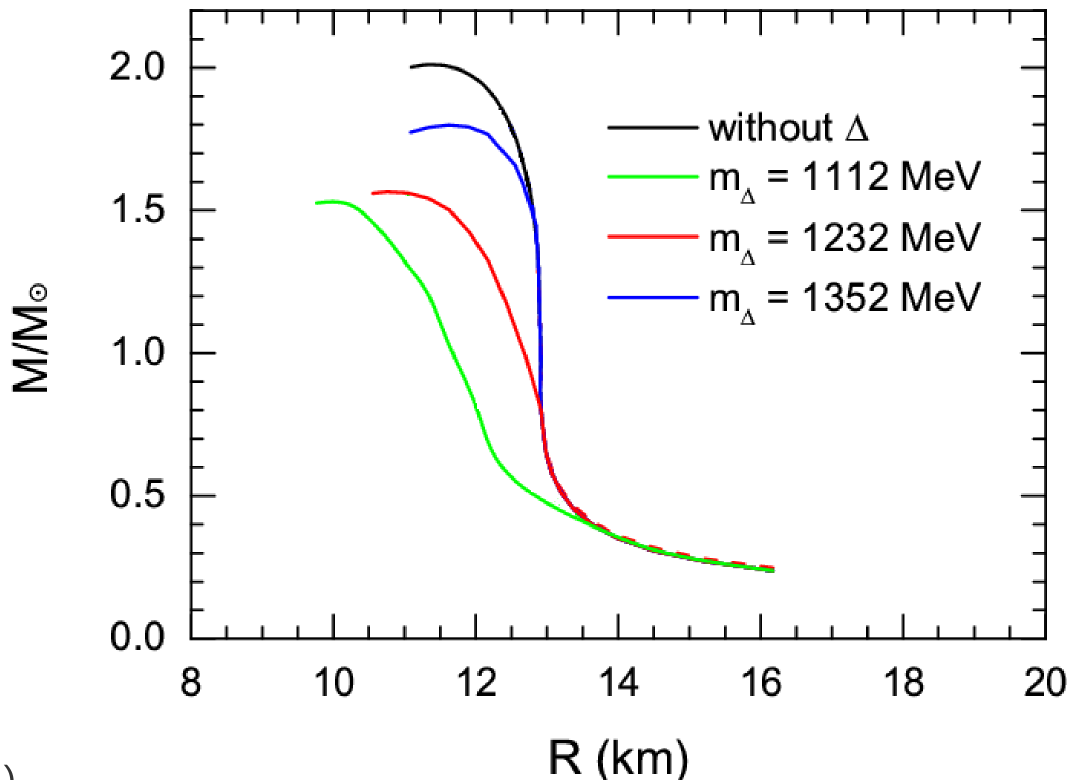
Motivation

The accurate constraint of **in-medium properties** **(isospin & density dependencies)** of baryonic resonances is still needed for a better understanding of

- Formation of Neutron Stars since it introduces specific constraints for the Equation Of State



Saturation Mass of Neutron Stars



A. Drago et al., Phys. Rev. C 90, 065809 (2014)

Motivation

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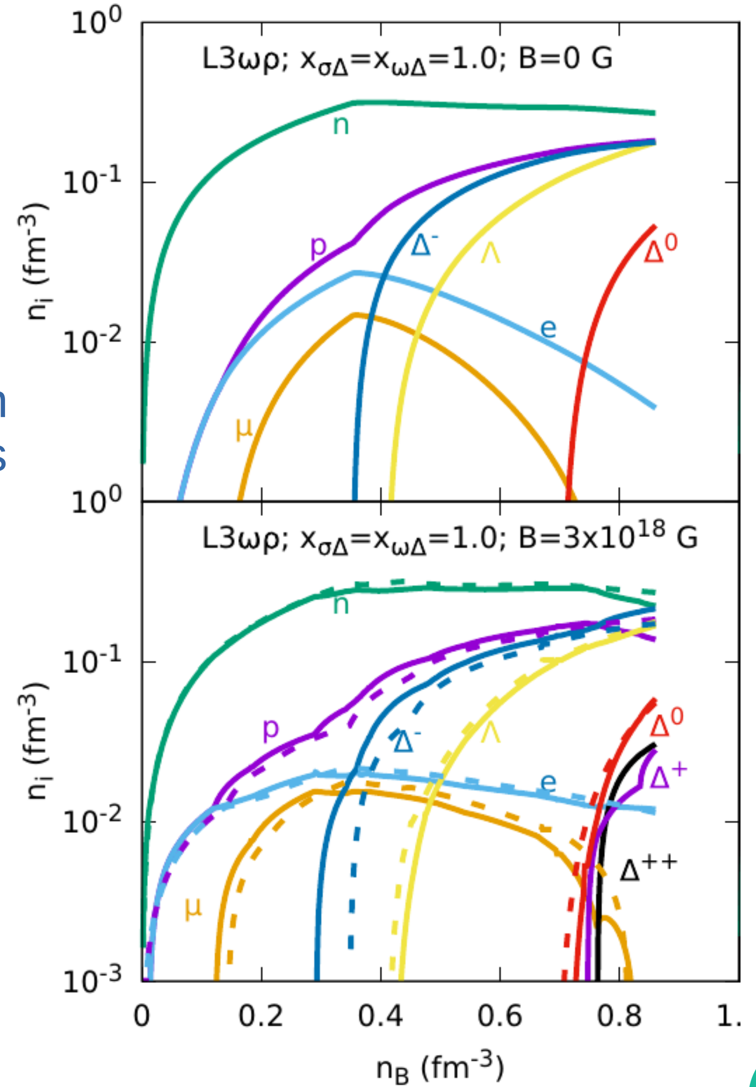
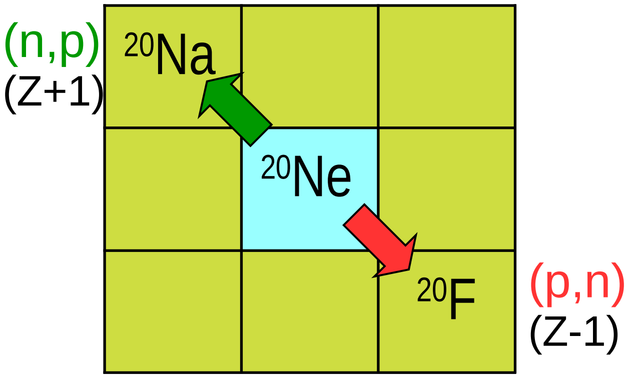
Renewed interest due to the effects of Δ baryons in magnetars, a class of compact objects that possess the largest stable magnetic fields observed in nature

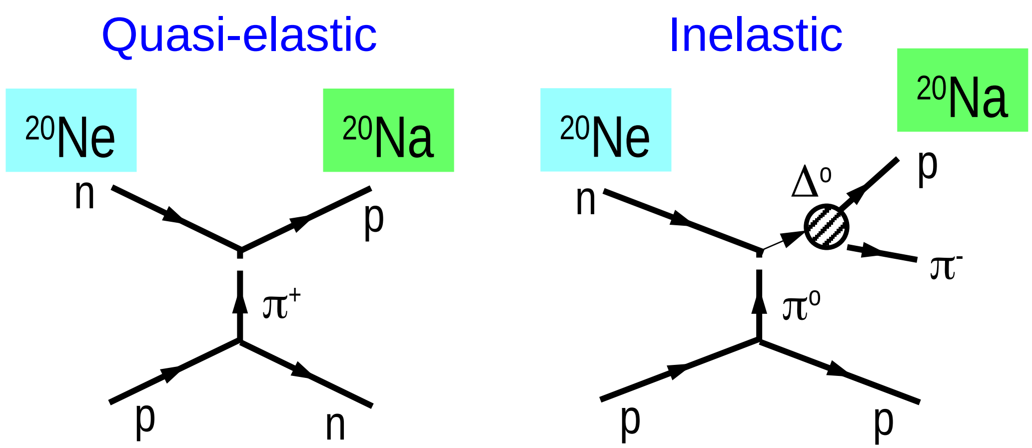


D. Marquez et al., Phys. Rev. C 106, 035801 (2022)

Isobaric charge-exchange reactions

Isobaric charge-exchange reactions allow for the direct observation of in-medium excitation of the Δ resonance for the (p,n) and (n,p) channels



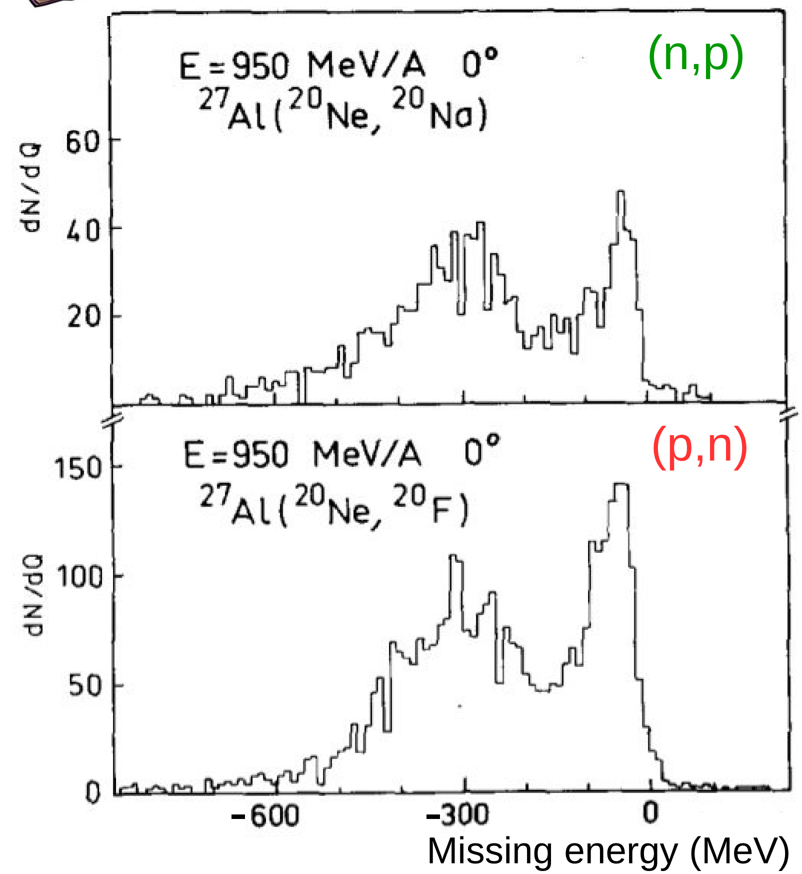


p(^{20}Ne, ^{20}Na)X

In the inelastic charge-exchange process the pion must scape in order to preserve the isobar character of the reaction

Peripheral reaction

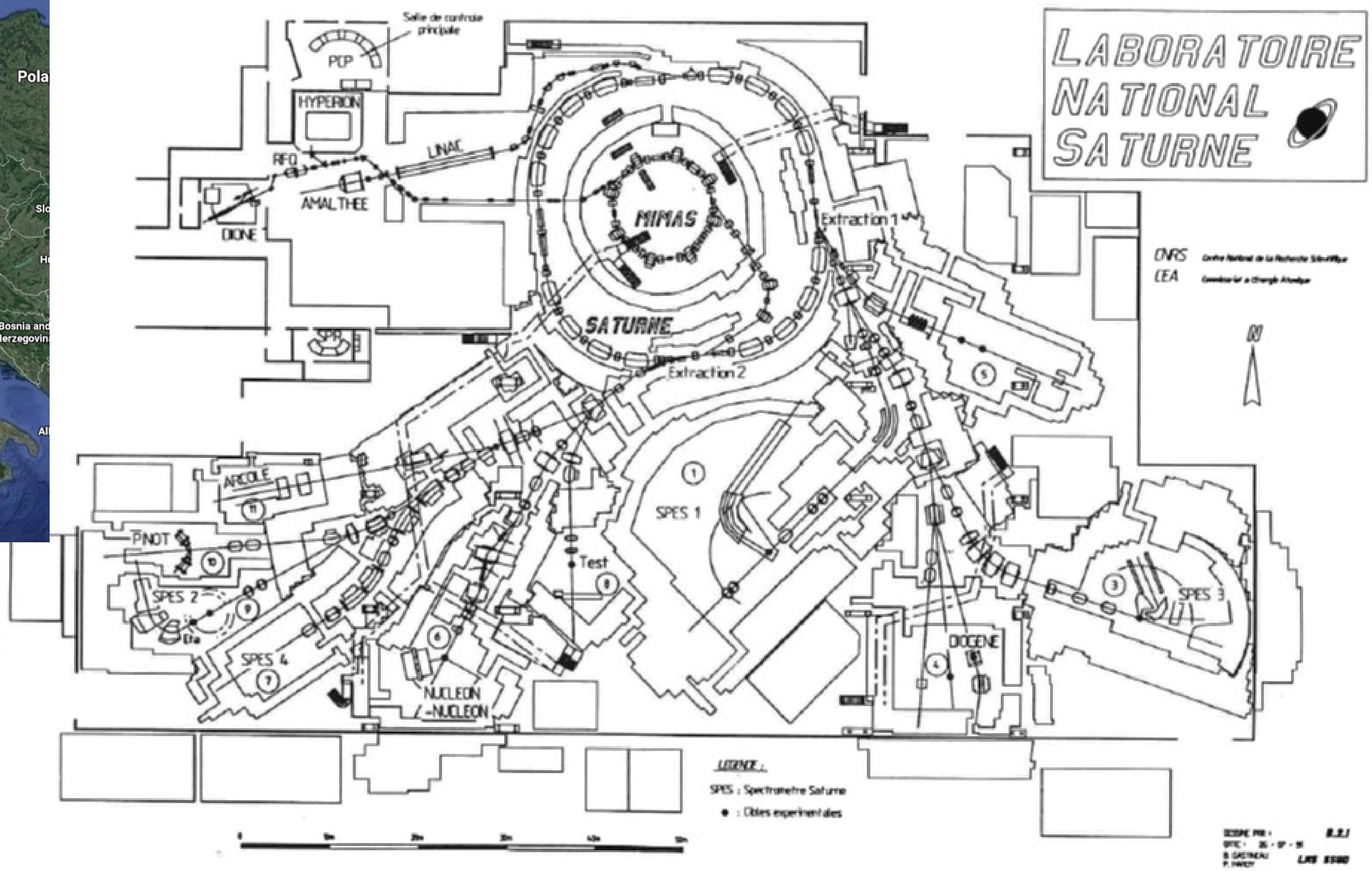
D. Bachelier et al., PLB 172, 23 (1986)



The pion emission proves the excitation of the Δ resonance

The SATURNE facility *(1977-1997)*

Saclay, France



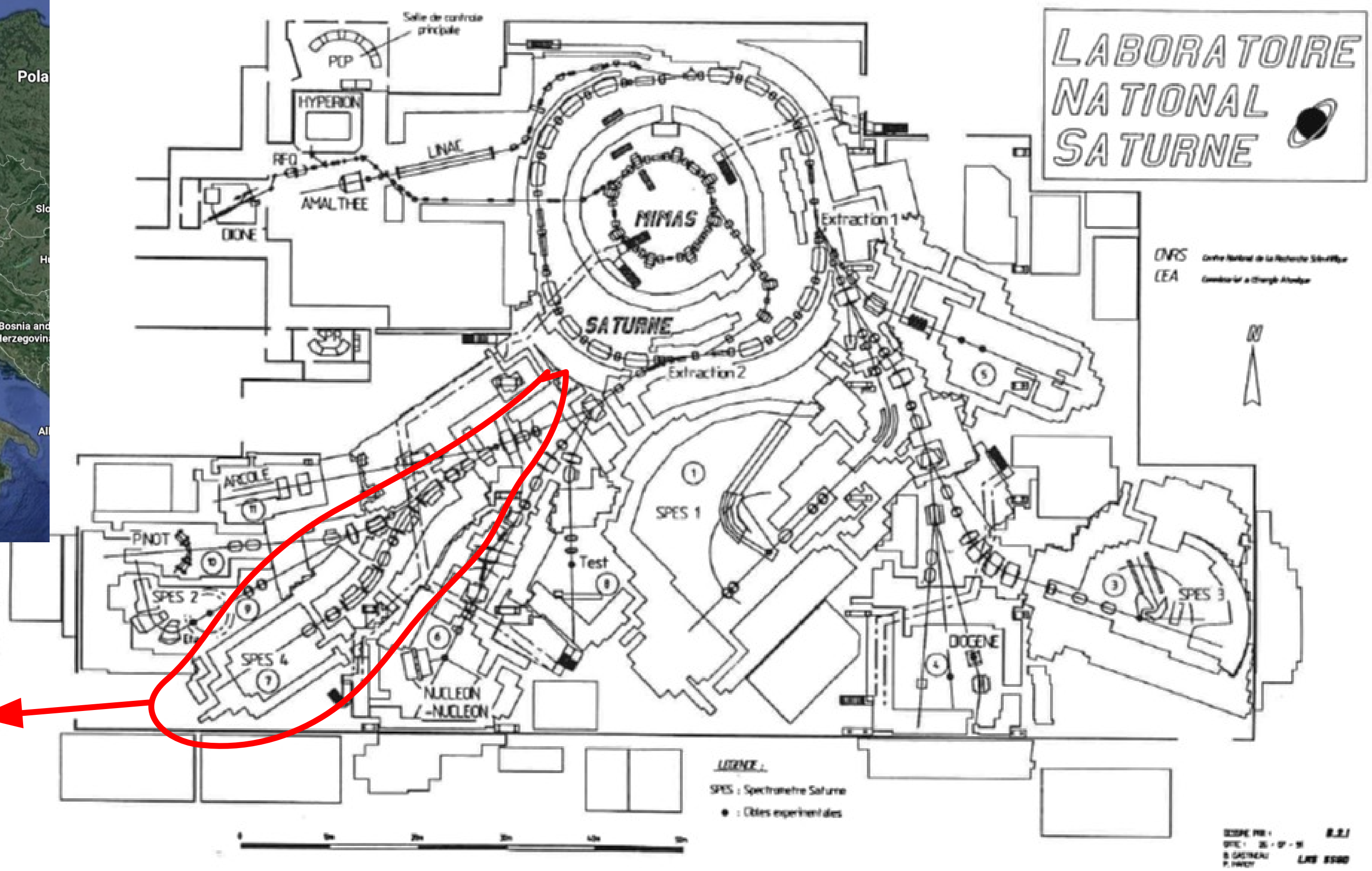
Beams *of p, n,..., ^{12}C,..., ^{84}Kr*

The 20 years of synchrotron Saturne

A. Boudard et al., World scientific (1998)

The SATURNE facility *(1977-1997)*

Saclay, France



Beams *of p, n,..., ^{12}C,..., ^{84}Kr*

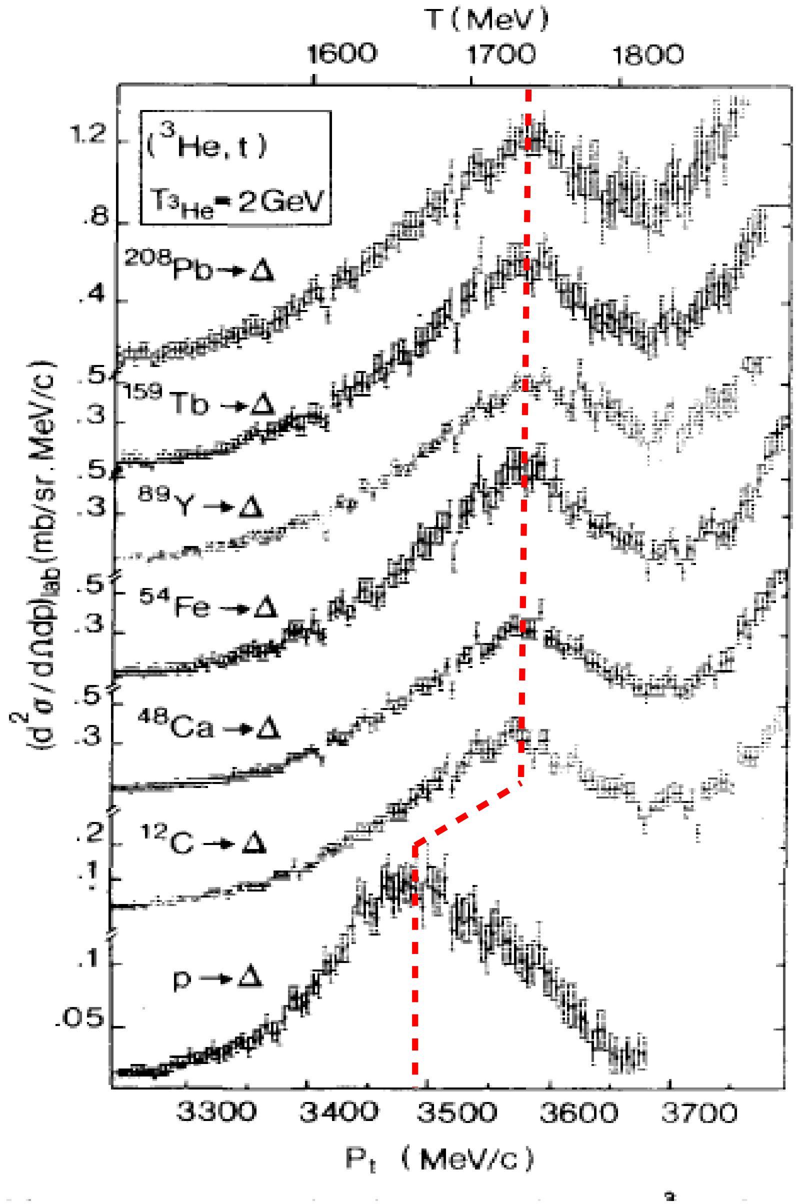
The 20 years of synchrotron Saturne
A. Boudard et al., World scientific (1998)

Isobaric charge exchange reactions for diff. nuclei

(^{3}He,t) , (d,2p)
(^{12}C,^{12}N)
(^{20}Ne,^{20}F) , (^{20}Ne,^{20}Na)
(^{14}N, ^{14}C) , (^{14}N, ^{14}O)
(^{40}Ar, ^{40}K) , (^{40}Ar, ^{40}Cl)

Inclusive (^{3}He, t) reactions

Isobaric charge-exchange reactions in different targets (from proton to ^{208}Pb)



They found that

- Prominent Δ excitation
- 70 MeV downward shift observed between proton and nuclei response

Explaining the results as

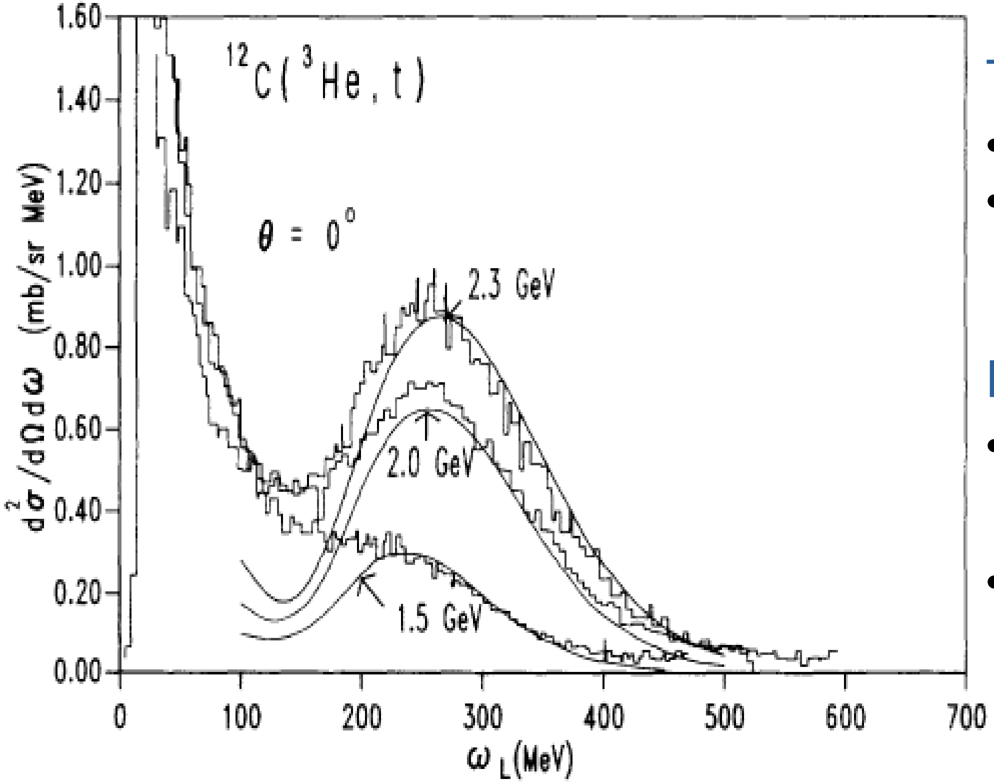
- ~30 MeV attractive Δ-hole interactions
- 40 MeV from mean-field + broadening

(Fermi momentum + ΔN–NN)

C. Ellegaard et al, Phys. Lett. B 154, 110 (1985)
D. Contardo et al, Phys. Lett. B 168, 331 (1986)

Inclusive (^{3}He, t) reactions

Isobaric charge-exchange reactions at higher energies



They found that

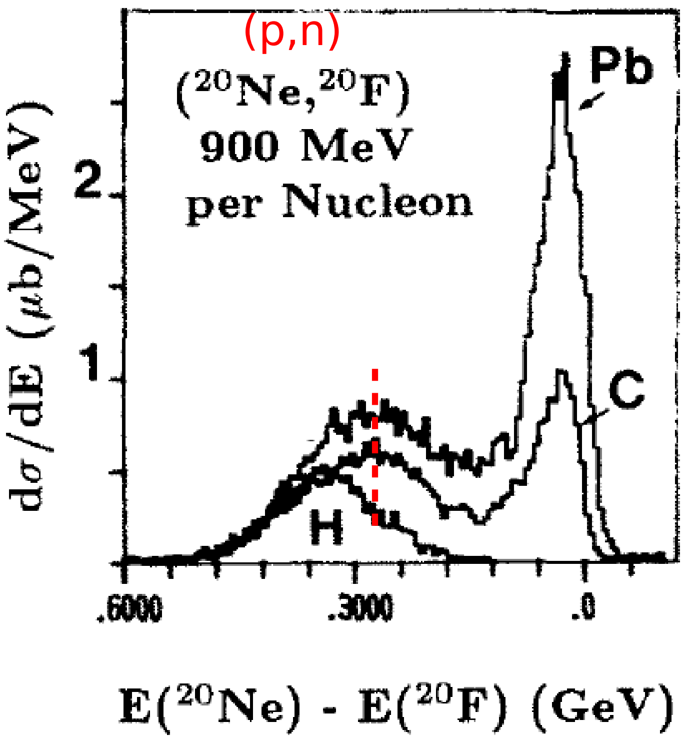
- Resonant peak increases with energy
- Its mean moves to higher missing energies

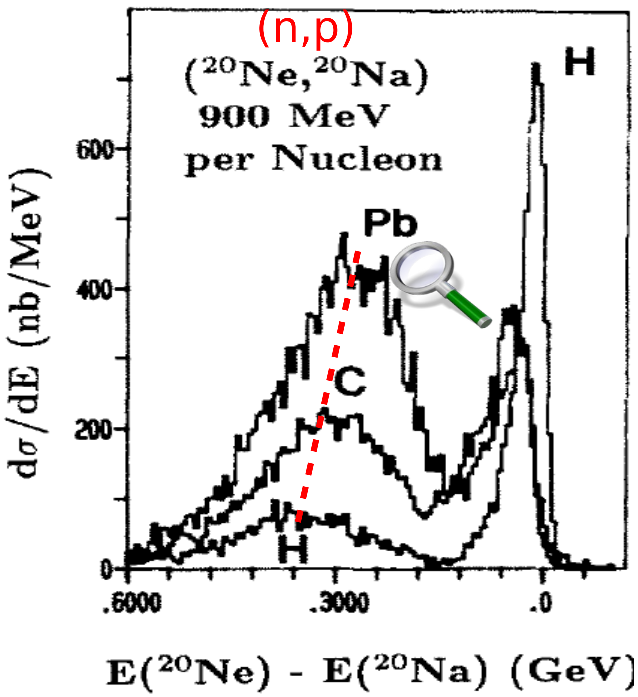
Explaining the results as

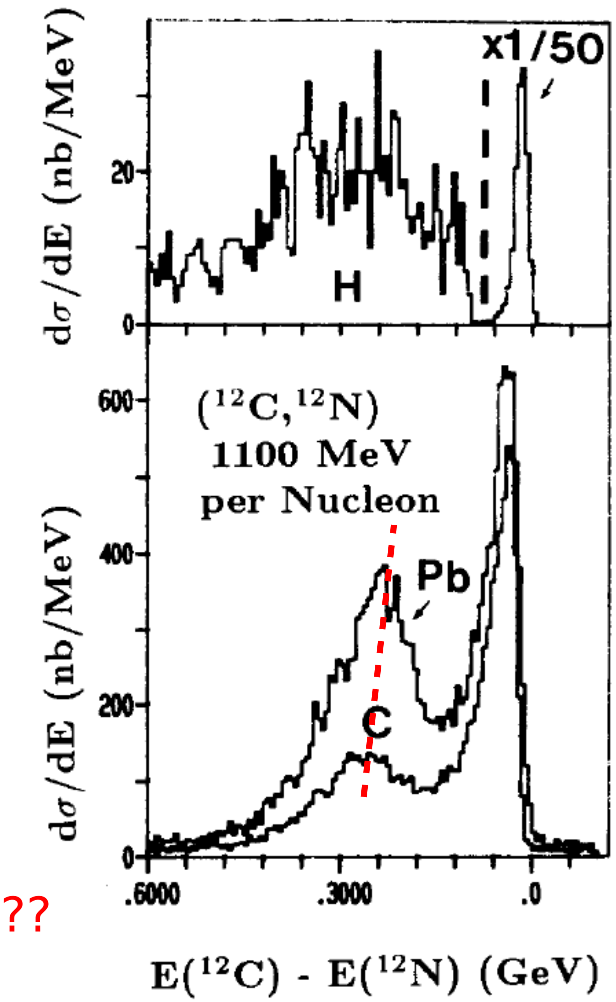
- Higher energies increase the probability of populating the Δ phase space
- Increase of the probability of producing other resonances like Roper

T. Udagawa et al, Phys. Rev. C 49, 3162 (1994)

Inclusive reactions with ^{20}Ne and ^{12}C projectiles





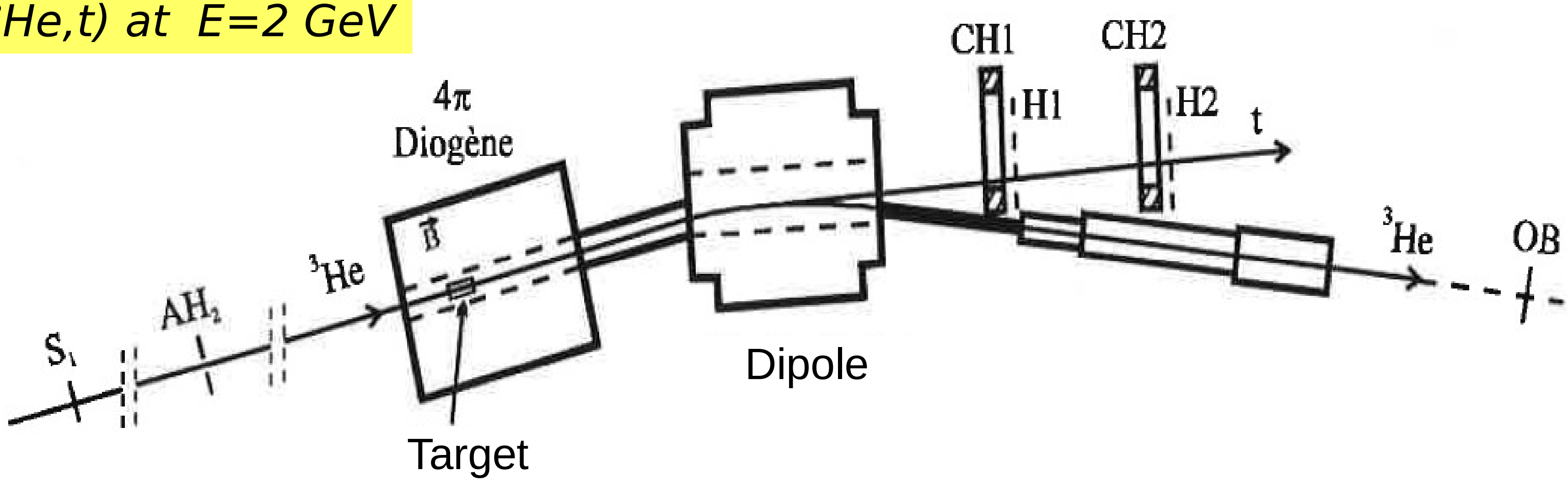


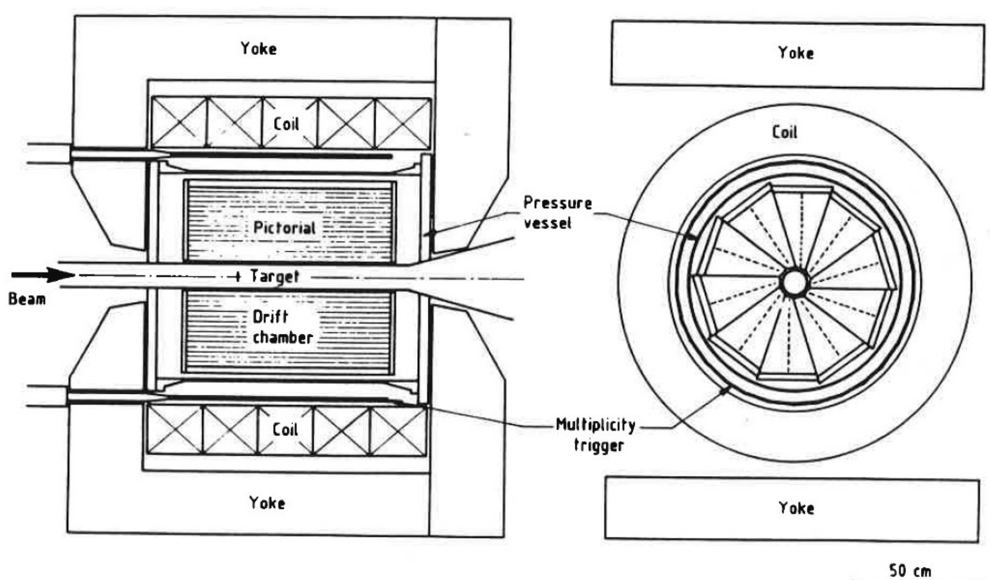
- Shift also observed for the missing energy
- Dependence on target mass in (p,n)-type transitions??

M. Roy-Stephan et al, Nucl. Phys. A 488, 178 (1988)

Exclusive (^{3}He, t) measurements at Saturne

(^{3}He,t) at E=2 GeV





DIOGENE for π and p detection

10 drift chambers

$20° < \Theta_{lab} < 132°$

$\Delta\Theta \sim$ 2-3°

$15 < E_\pi < 300$ MeV

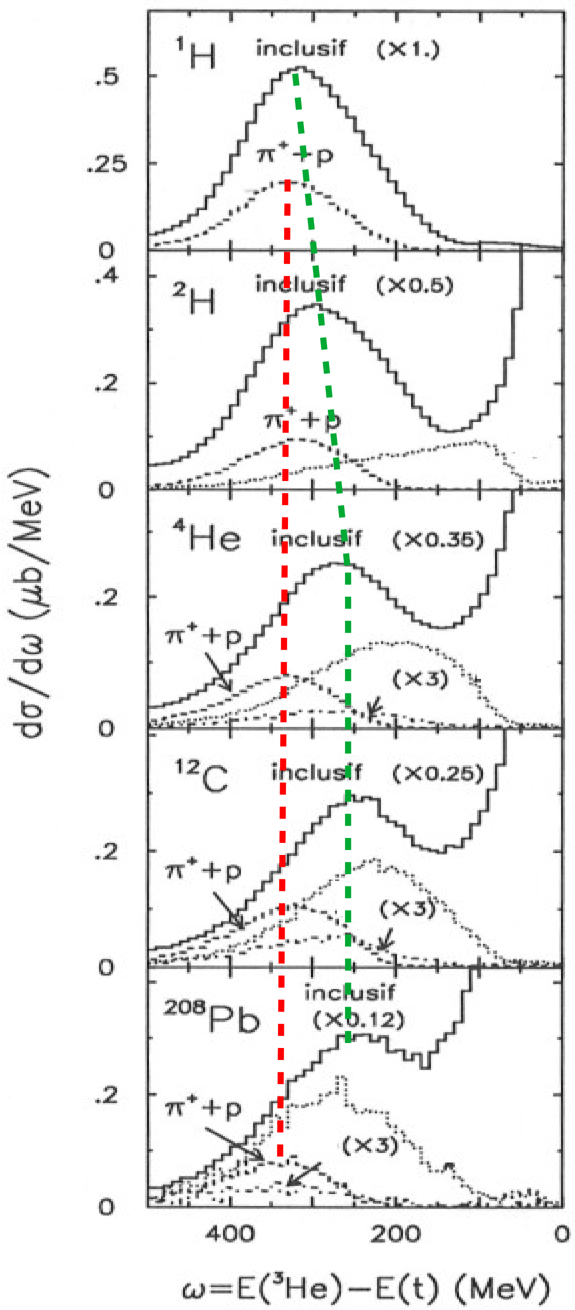
$30 < E_p < 450$ MeV

$\Delta p/p \sim 10\%$ for pions

$\Delta p/p \sim 18\%$ for protons

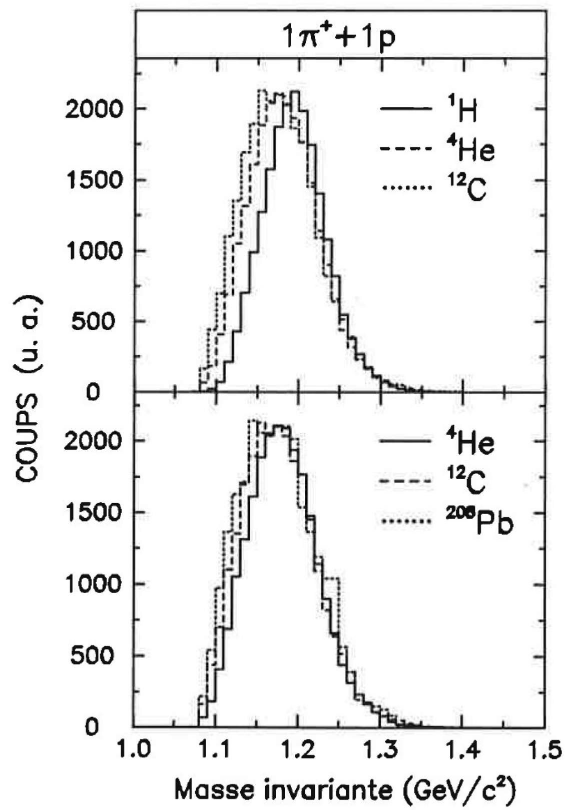
T. Hennino et al, Phys. Lett. B 283, 42 (1992)

Exclusive (^{3}He, t) reactions: Δ decay measurements



They found that

- 70 MeV downward shift observed between nucleon and nuclei response for the missing energy distributions
- No shift in the missing energy from πp correlations



Correlations with pions showed

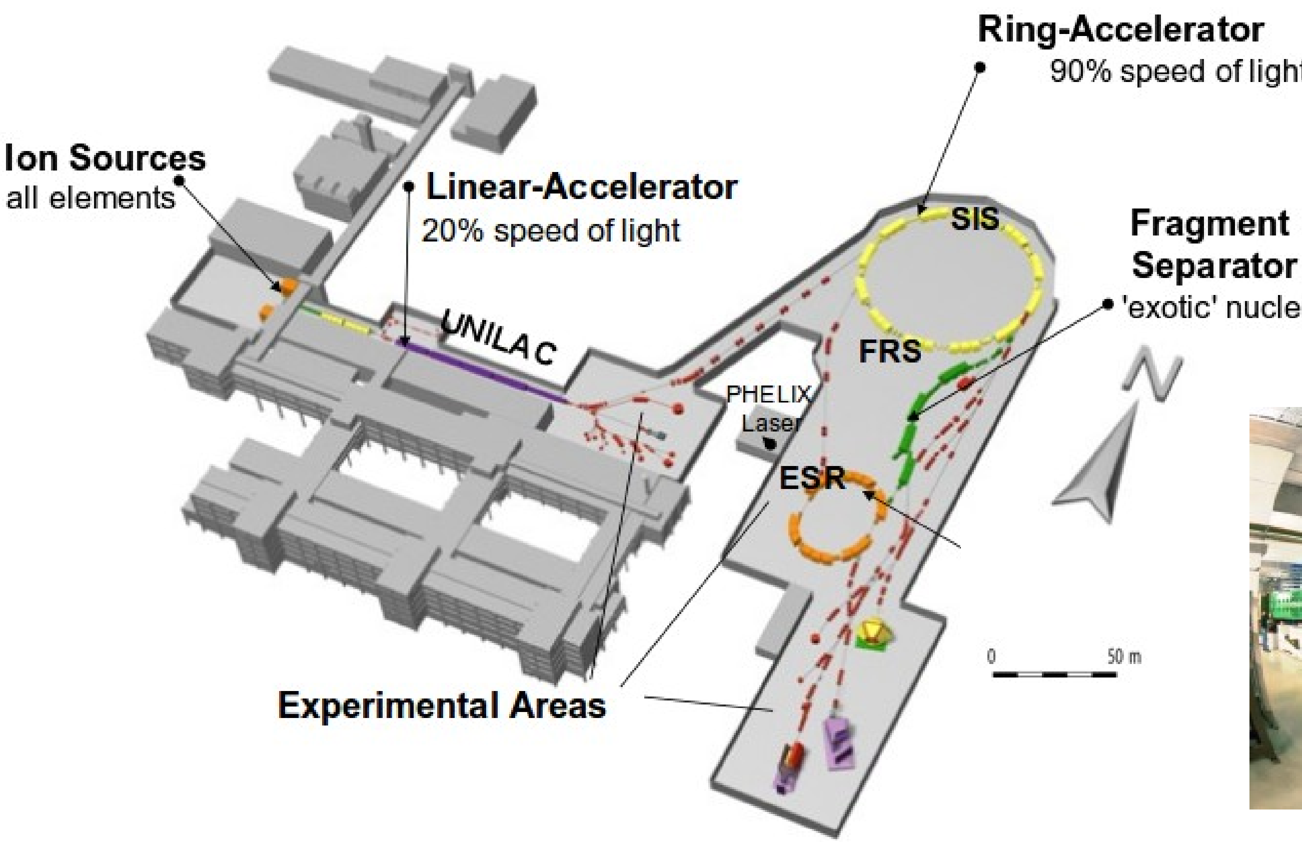
- Shift of the invariant mass between light and heavy targets
- Change of the Δ mass with the nuclear medium ~ 40 MeV

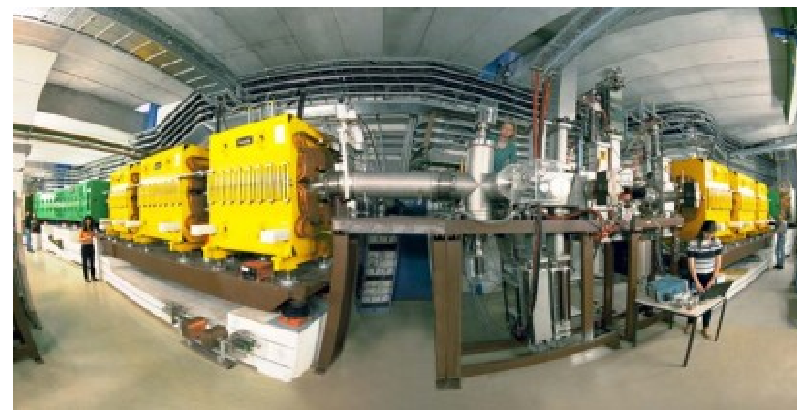
Input for
Neutron Star calculations

T. Hennino et al, Phys. Lett. B 283, 42 (1992)
K. Sneppen et al, Phys. Rev. C 50, 338 (1994)

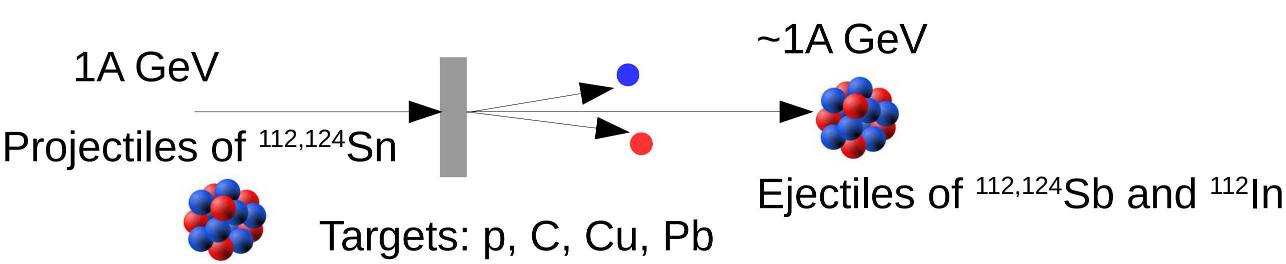
FRagment Separator FRS @ GSI (2011)

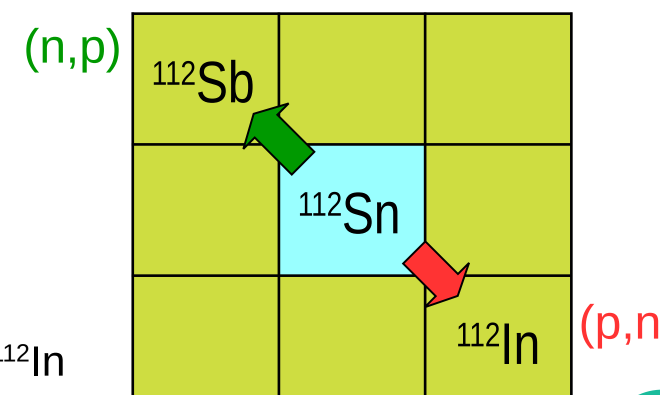
See **C. Scheidenberger**’*s talk*



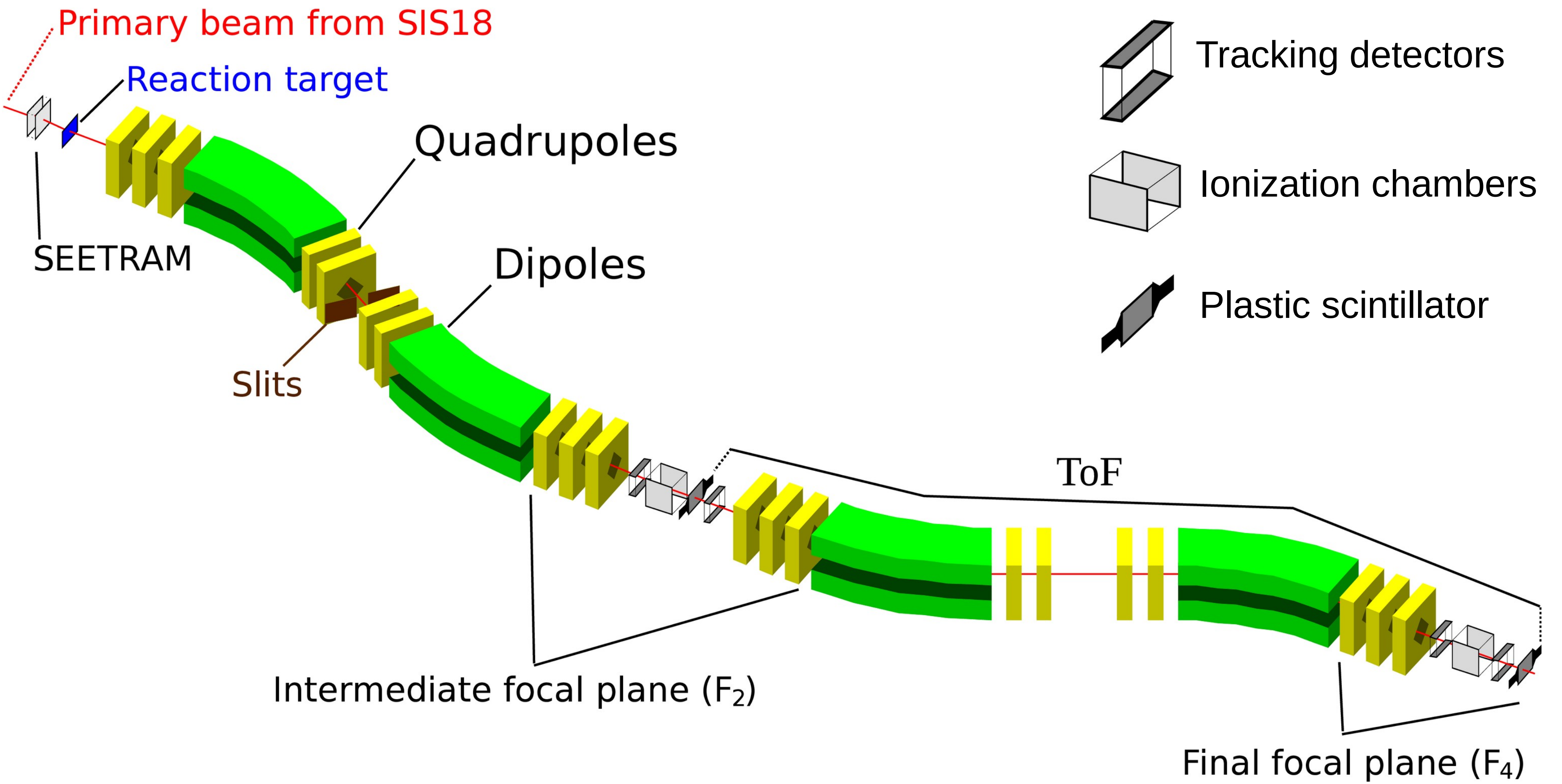


- Medium-mass projectiles at high kinetic energies
- Inverse kinematics





FRagment Separator FRS @ GSI (2011)

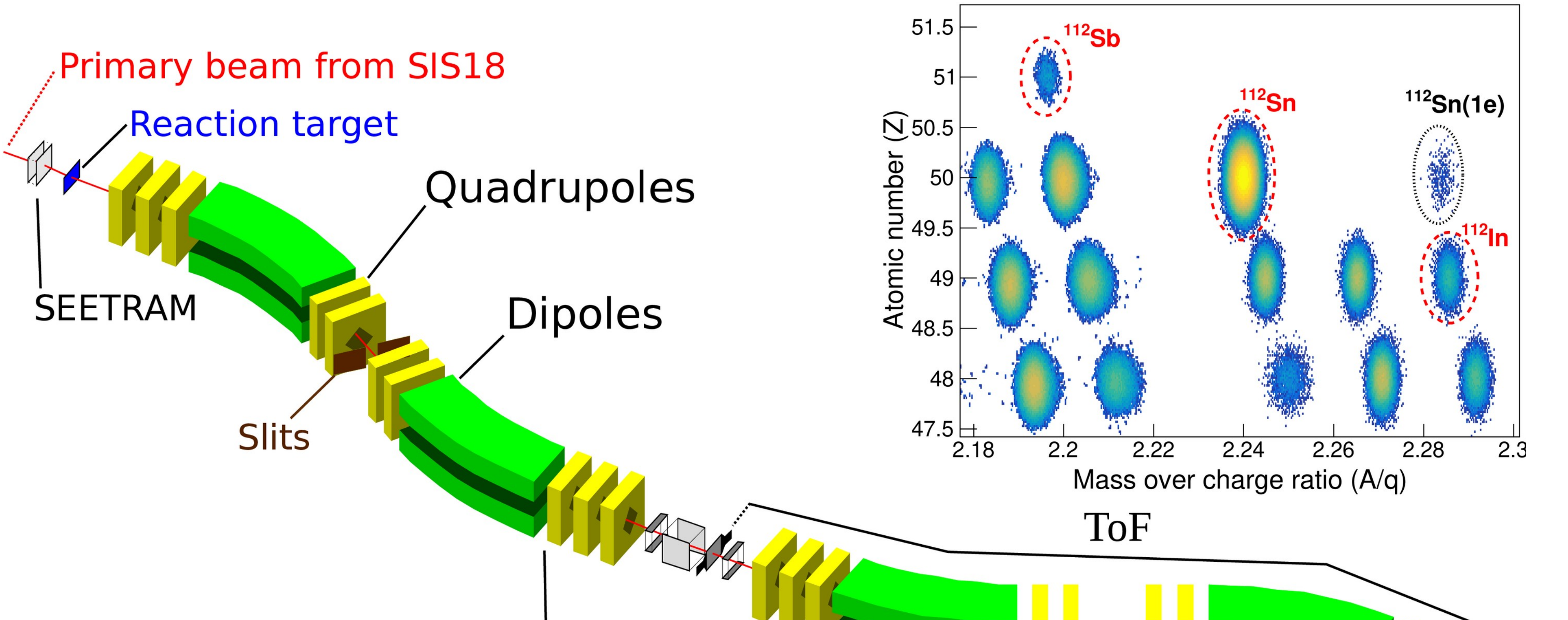


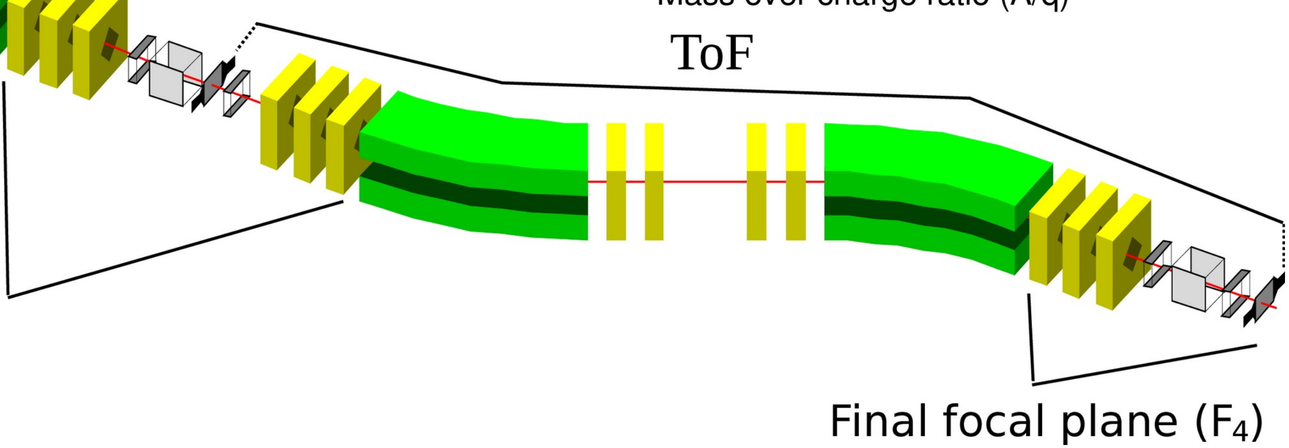
$$\frac{A}{Z} = \frac{e}{u} \frac{B\rho}{\gamma \beta c}$$

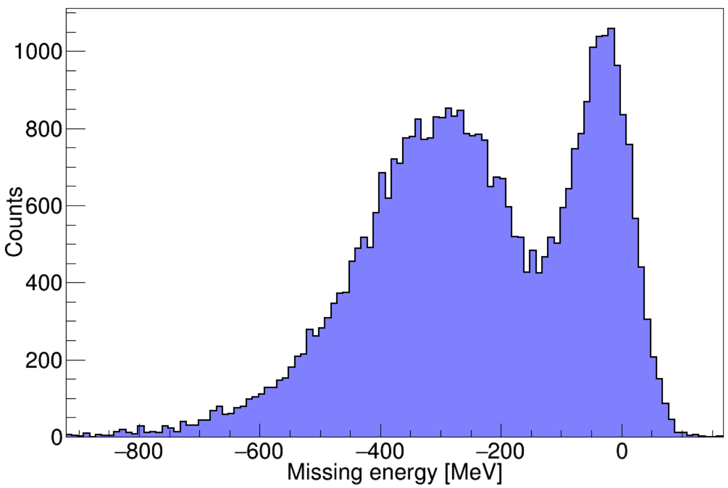
Z ~ √ΔE from ionization chambers
Bρ from tracking detectors
β from ToF measurements

H. Geissel et al., NIMB 70, 286 (1992)

FRagment Separator FRS @ GSI (2011)



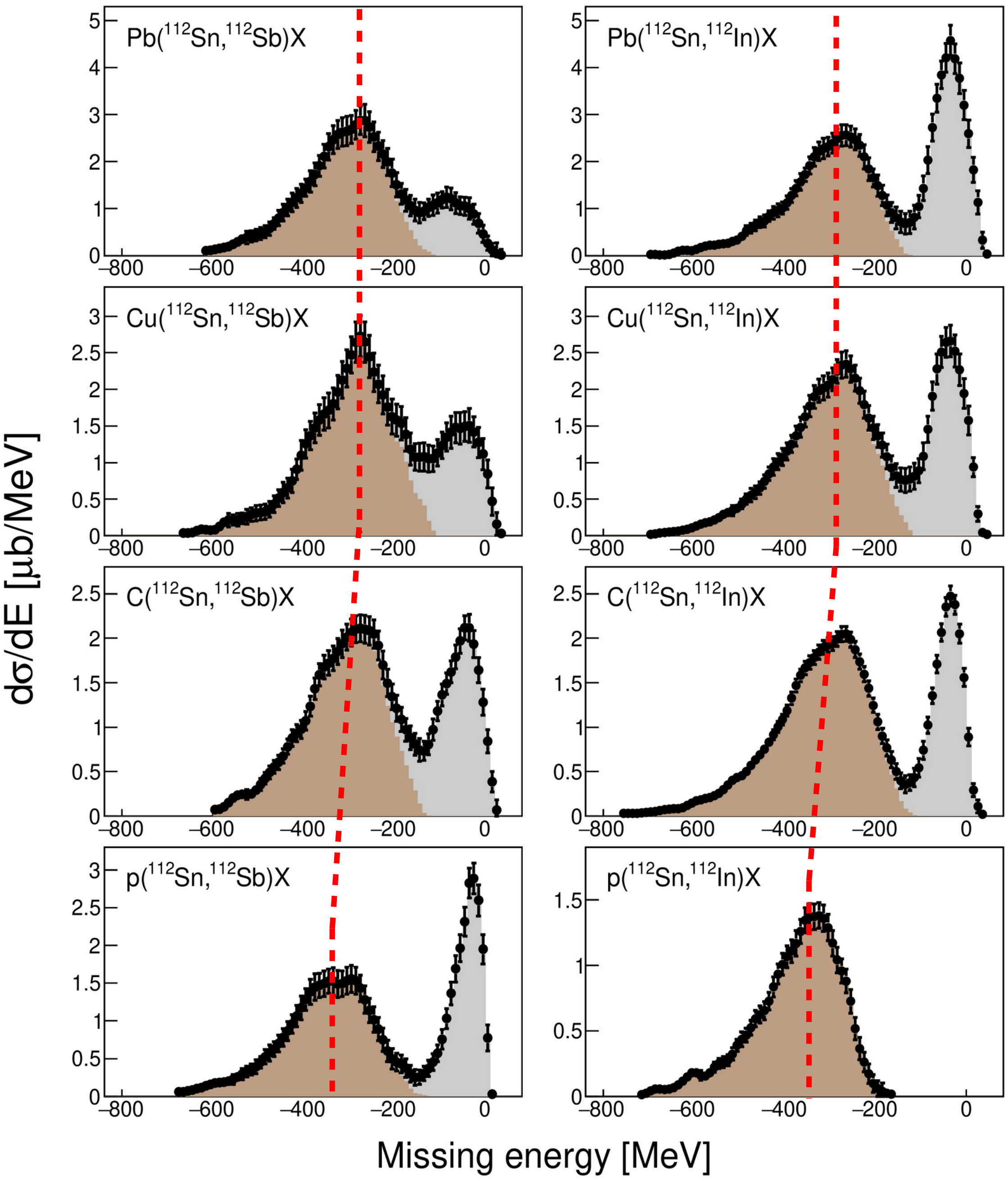




$$\frac{A}{Z} = \frac{e}{u} \frac{B\rho}{\gamma\beta c}$$

Z ~ √ΔE from ionization chambers
Bρ from tracking detectors
β from ToF measurements

Missing energy spectra with ^{112}Sn projectiles



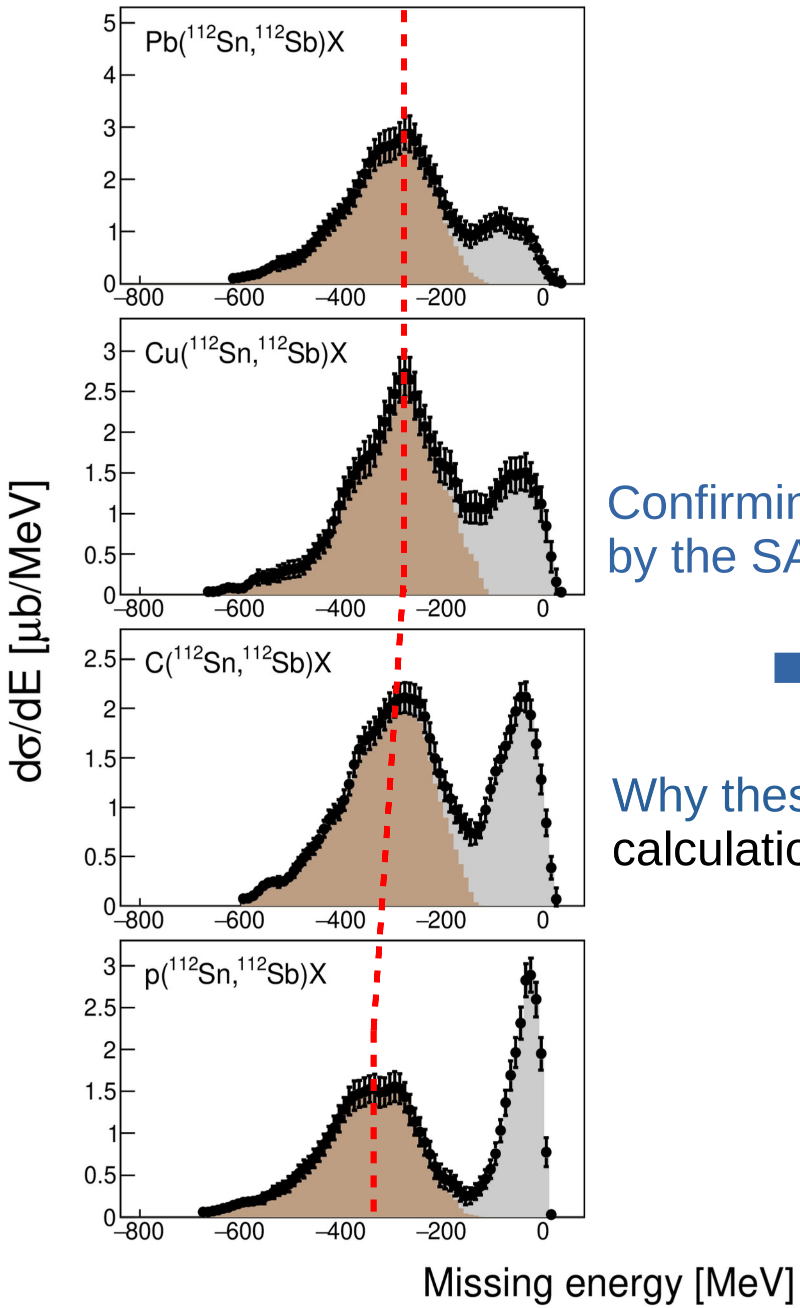
(n,p) and (p,n) channels

- ΔE of 10 MeV
- Gray histograms for quasi-elastic
- Brown histograms for inelastic

We found that

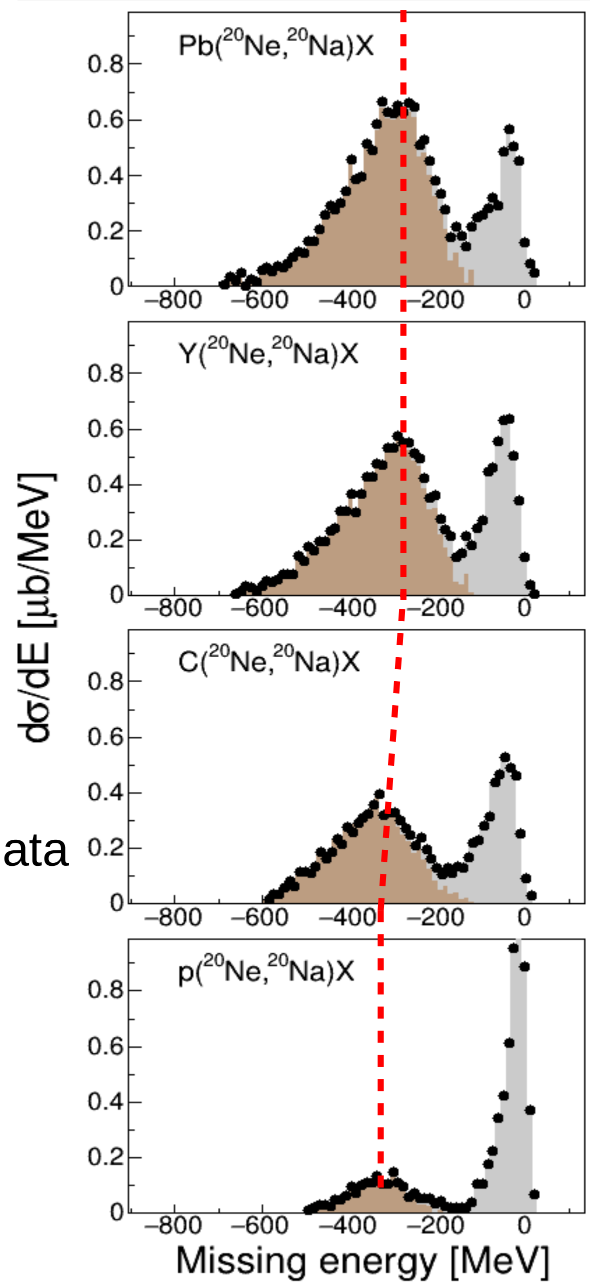
- 70 MeV downward shift observed between p and nuclei response
- Shift dependent on target mass for the (n,p) and (p,n) channels
- Quenching of the quasi-elastic peak for the (n,p) channel

Missing energy spectra with ^{112}Sn projectiles



Confirming the results obtained by the SATURNE collaboration

Why these effects? Model calculations to understand the data

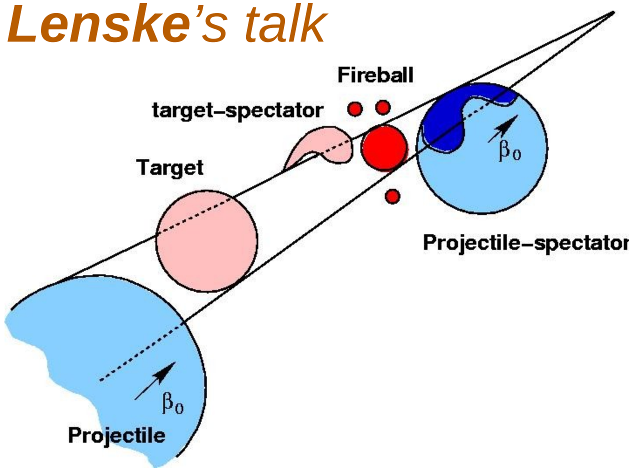


Model calculations

Glauber model & random phase approximation

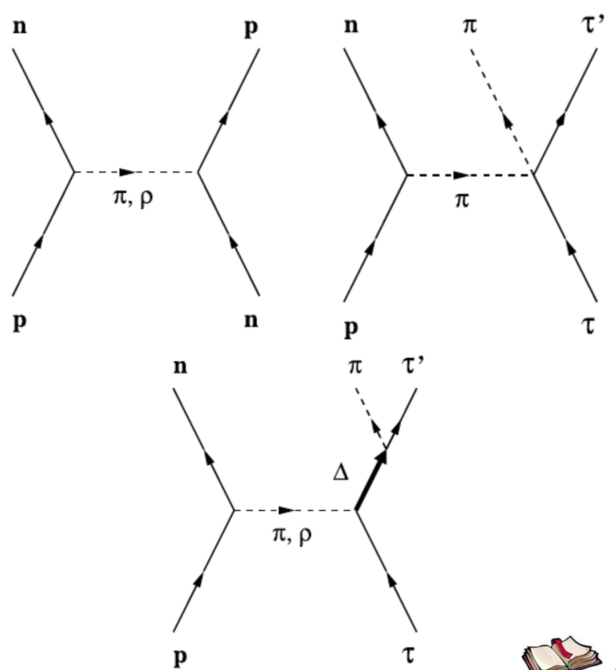
*See **H. Lenske**'s talk*

- *Nucleon-nucleus and nucleus-nucleus cross sections*
- *Fermi momentum effects*
- *Corrections from pion-nucleus interaction*
- *Pauli blocking*
- *Response function approach to obtain the excitation energy of the system*



*H. Lenske et al, Phys. Rev. C **98**, 044620 (2018)*
*J.L. Rodríguez-Sánchez et al, Phys. Lett. B **807**, 135565 (2020) & Phys. Rev. C **106**, 014618 (2022)*

Elementary quasi-elastic and inelastic processes



$({}^AZ, {}^A(Z+1))$ reaction

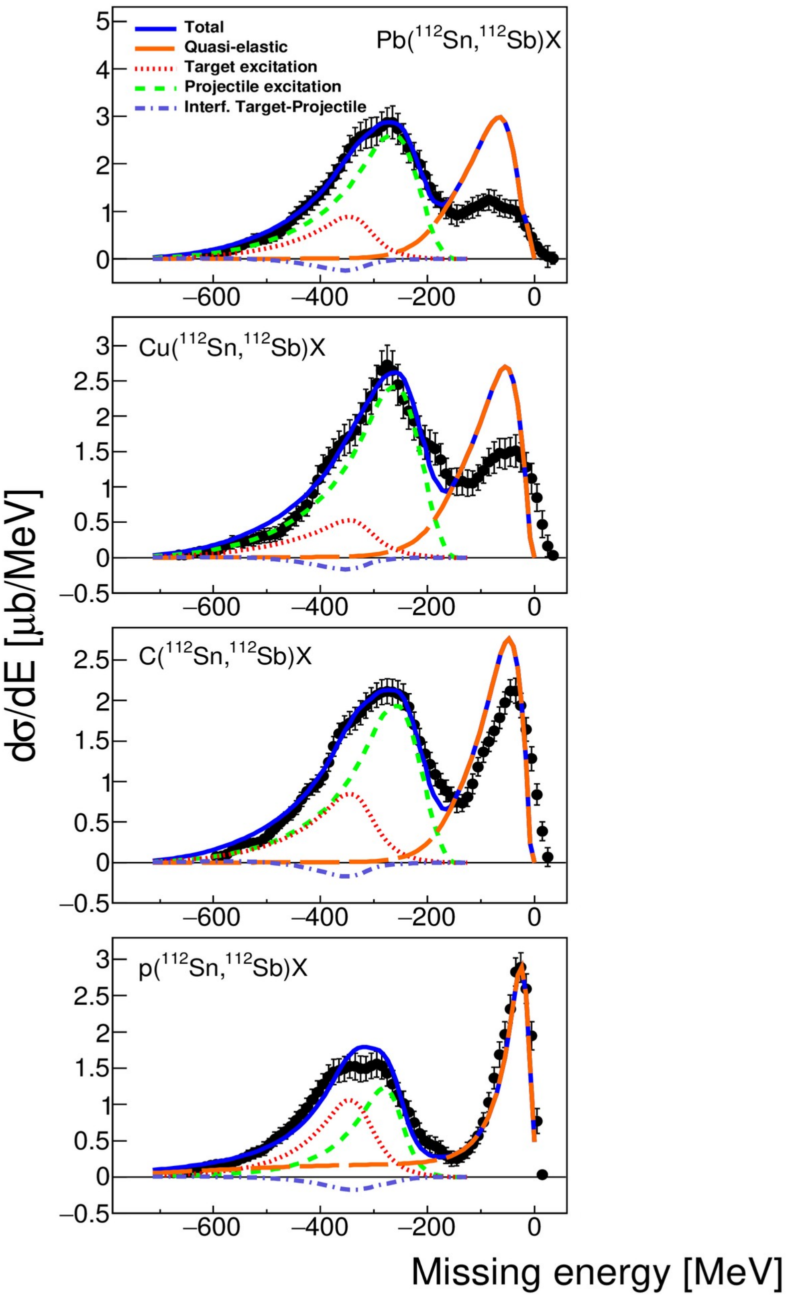
Target excitation	Projectile excitation
$p(n,p)\Delta^0 = p(n,p)n\pi^0$	$p(n,\Delta^0)p = p(n,p\pi^-)p$
$p(n,p)\Delta^0 = p(n,p)p\pi^-$	$p(n,\Delta^+)n = p(n,p\pi^0)n$
$n(n,p)\Delta^- = n(n,p)n\pi^-$	$n(n,\Delta^0)n = n(n,p\pi^-)n$

$({}^AZ, {}^A(Z-1))$ reaction

Target excitation	Projectile excitation
$p(p,n)\Delta^{++} = p(p,n)p\pi^+$	$p(p,\Delta^+)p = p(p,n\pi^+)p$
$n(p,n)\Delta^+ = n(p,n)n\pi^+$	$n(p,\Delta^+)n = n(p,n\pi^+)n$
$n(p,n)\Delta^+ = n(p,n)p\pi^0$	$n(p,\Delta^0)p = n(p,n\pi^0)p$

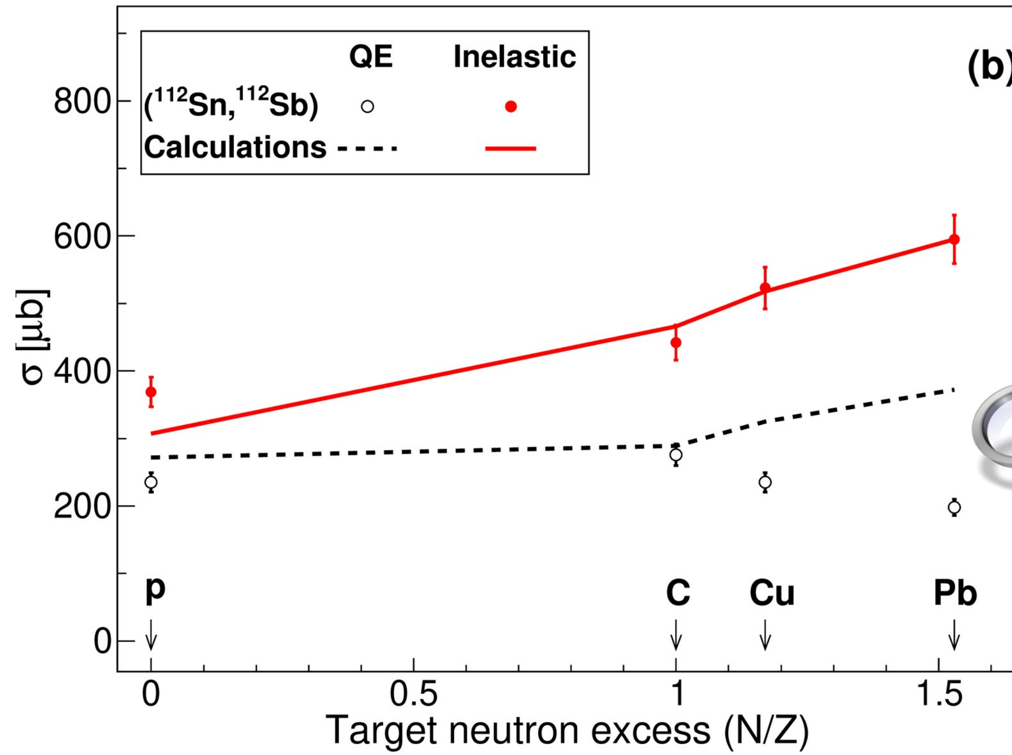
*I. Vidaña et al, EPJ Web Conf. **107**, 10003 (2016)*

Missing energy spectra with ^{112}Sn projectiles



(n,p) channel

- Heavy targets dominated by Δ projectile excitations
- Comparison to calculations shows a clear reduction for the quasi-elastic peak → Gamow-Teller strength dependent on target mass



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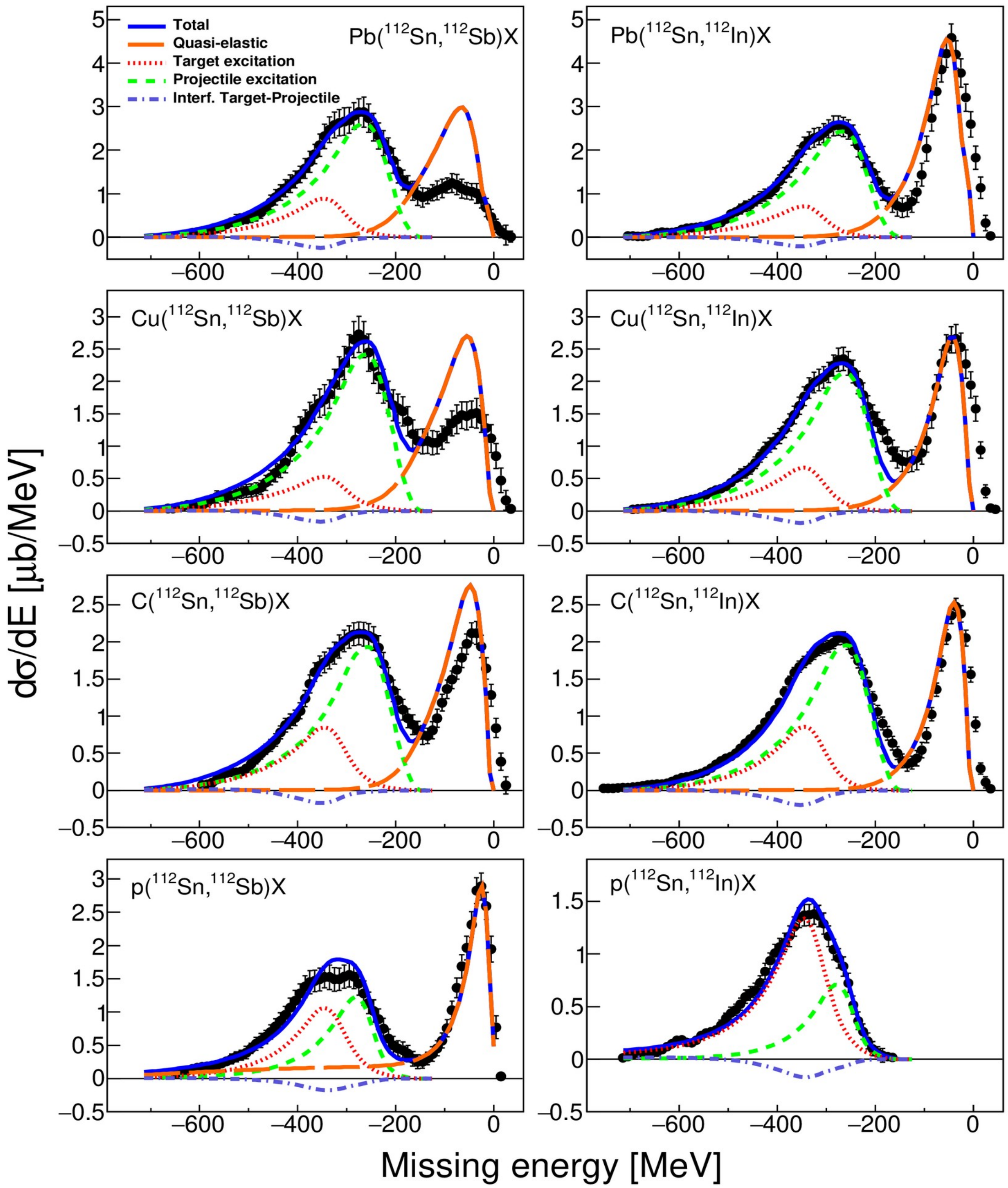


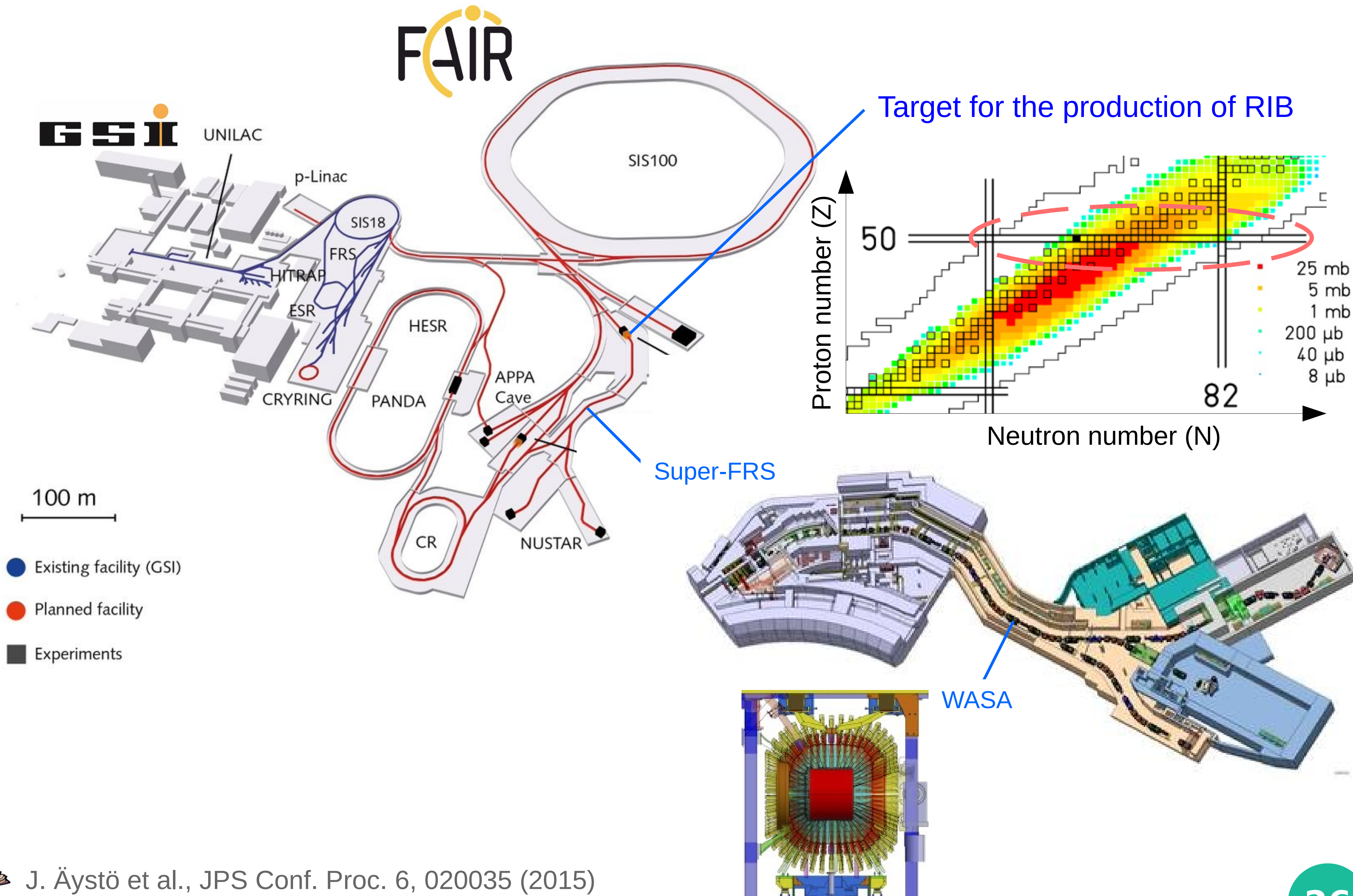
(n,p) channel

- Heavy targets dominated by Δ projectile excitations
- Comparison to calculations shows a clear reduction for the quasi-elastic peak → Gamow-Teller strength dependent on target mass

(p,n) channel

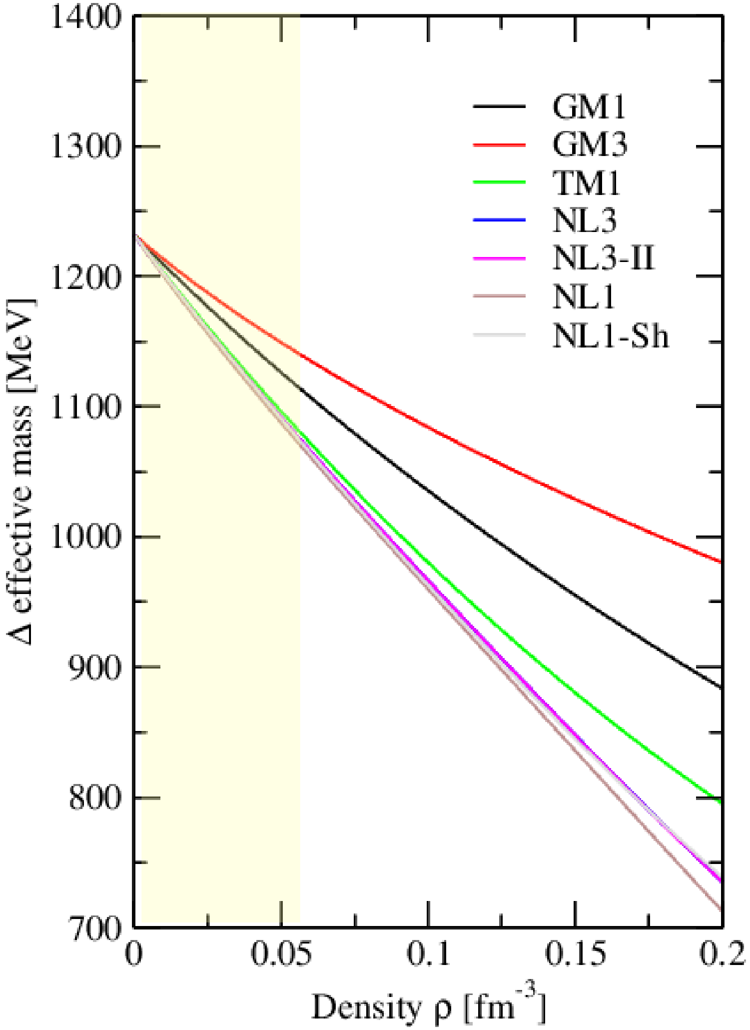
- Proton target dominated by Δ target excitations while heavy targets are dominated by Δ projectile excitations

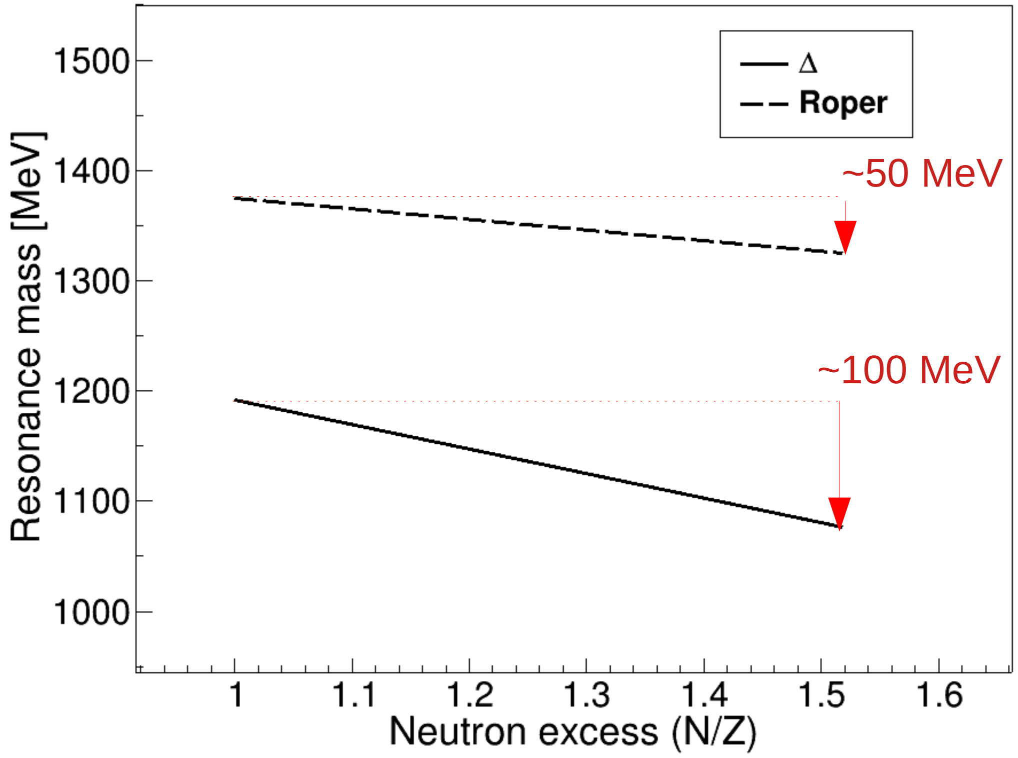
Future experiments at GSI-FAIR



J. Äystö et al., JPS Conf. Proc. 6, 020035 (2015)

- Exclusive measurements of baryon resonance decays in nuclear matter
- Dependence of their properties (mass, width,...) on isospin





Calculations courtesy of Isaac Vidaña

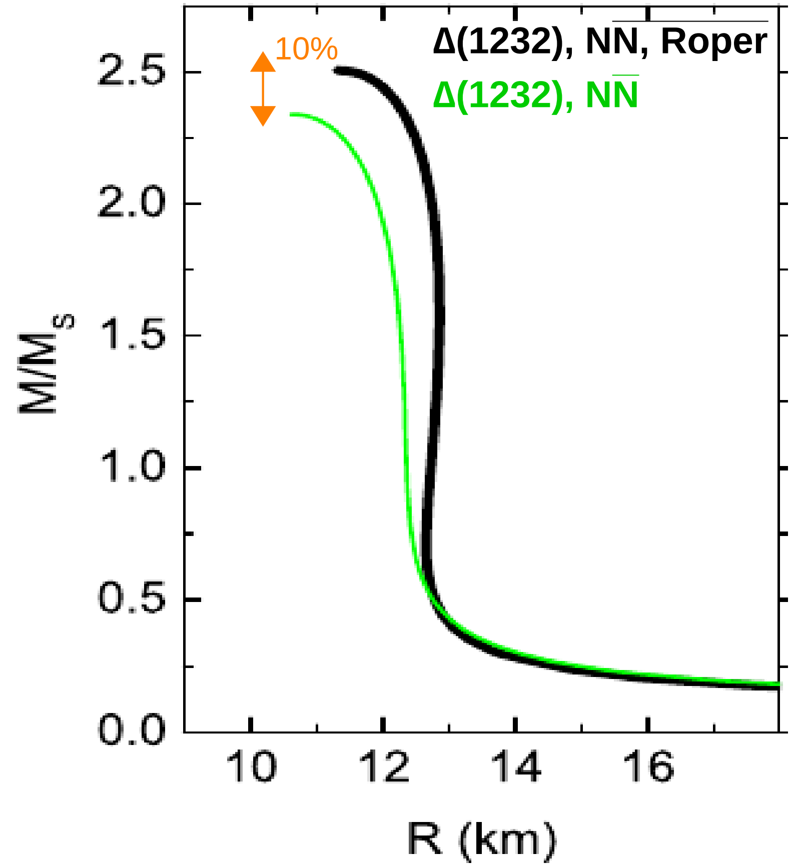
- Exclusive measurements of baryon resonance decays in nuclear matter
- Dependence of their properties (mass, width,...) on isospin
- Production of heavy resonances like the Roper

PDG estimate

$N(1440)$ 1/2$^+$ $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Re(pole position) = 1360 to 1380 (≈ 1370) MeV
−2Im(pole position) = 160 to 190 (≈ 175) MeV
Breit-Wigner mass = 1410 to 1470 (≈ 1440) MeV
Breit-Wigner full width = 250 to 450 (≈ 350) MeV

$N(1440)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	55–75 %	398
$N\eta$	<1 %	†
$N\pi\pi$	17–50 %	347
$\Delta(1232)\pi$, P-wave	6–27 %	147
$N\sigma$	11–23 %	–
$p\gamma$, helicity=1/2	0.035–0.048 %	414
$n\gamma$, helicity=1/2	0.02–0.04 %	413



PDG, Phys. Rev. D 98, 030001 (2018)

Z. H. Li et al., Inter. J. Mod. Phys. E 19, 1727 (2010)

Some of the many faces of the Roper resonance

- Hybrid state with a large gluonic component (q^3g)

  S. Capstick, P. Page, PRD 60 (1999) ; PRC 66 (2002)
- Collective excitation (breathing mode): bag models, skyrmion

  G. Brown, J. Durso, M. Johnson, NPA 397 (1983); U. Kaulfuss, U. Meissner, PLB 154 (1985)
- Rotational state in a deformed oscillator potential

  A. Hosaka, H. Toki and H. Ejiri, Nucl. Phys. A 629 (1998)
- Admixture of qqq and $qqq(q\bar{q})$ (3-25 %) states

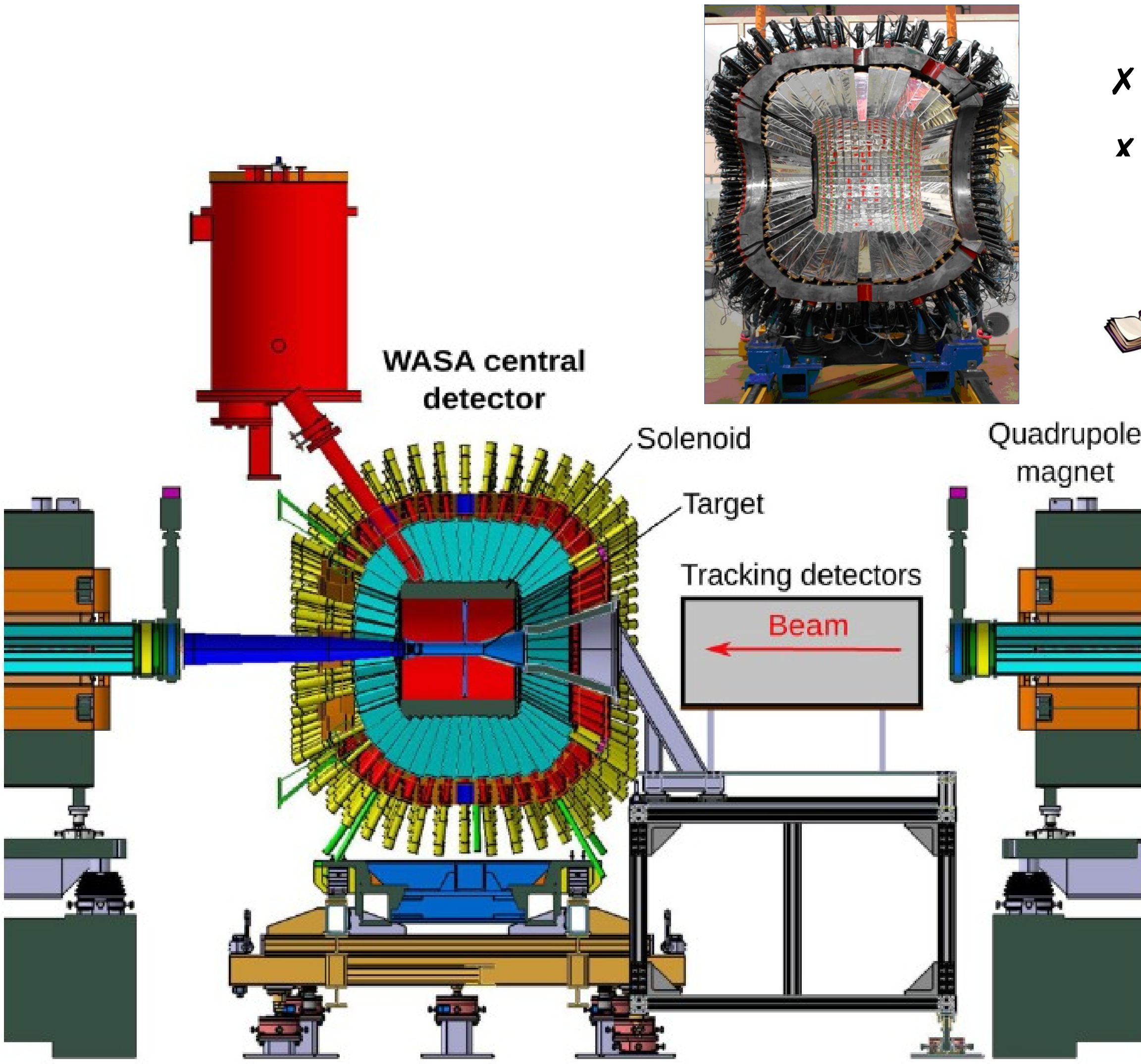
  B. Julia-Diaz, D. Riska, NPA 780 (2006)
- Dynamically generated state from πN, σN, $\pi\Delta$, ρN coupled channels

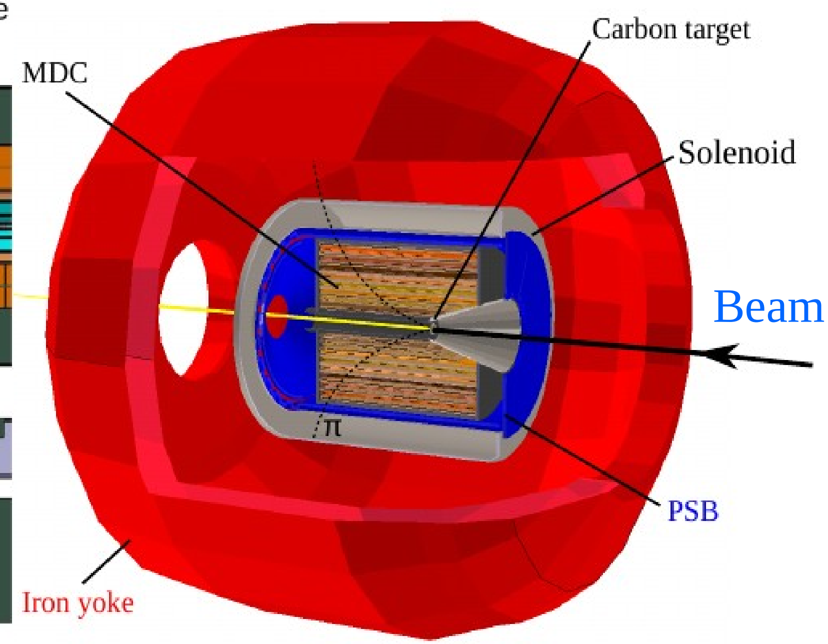
  O. Krehl et al., PRC 62 (2000); Suzuki et al., PRL 104 (2010)

WASA (Wide Angle Shower Apparatus) detector will be used to measure the pions in coincidence with the isobaric charge-exchange reactions

- ✗ Solenoid with a magnetic field of ~1.3 T
- ✗ Plastic scintillator barrel and Mini drift chamber detector covering polar angles from 18º to 165º

R. Sekiya et al., NIM A 1034, 166745 (2022)



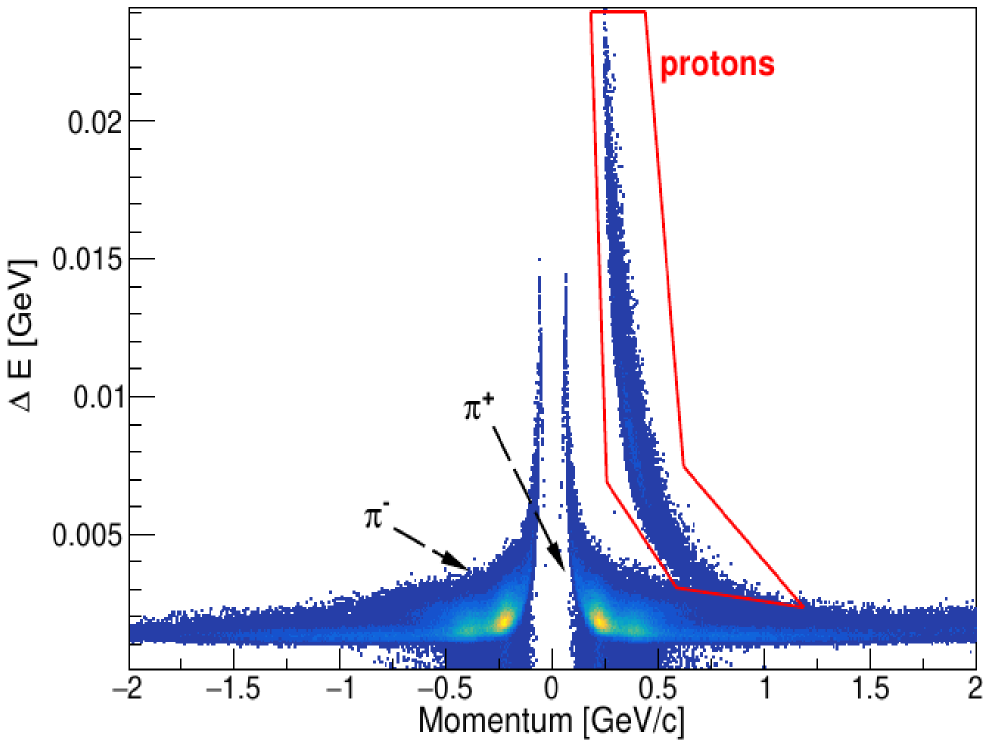


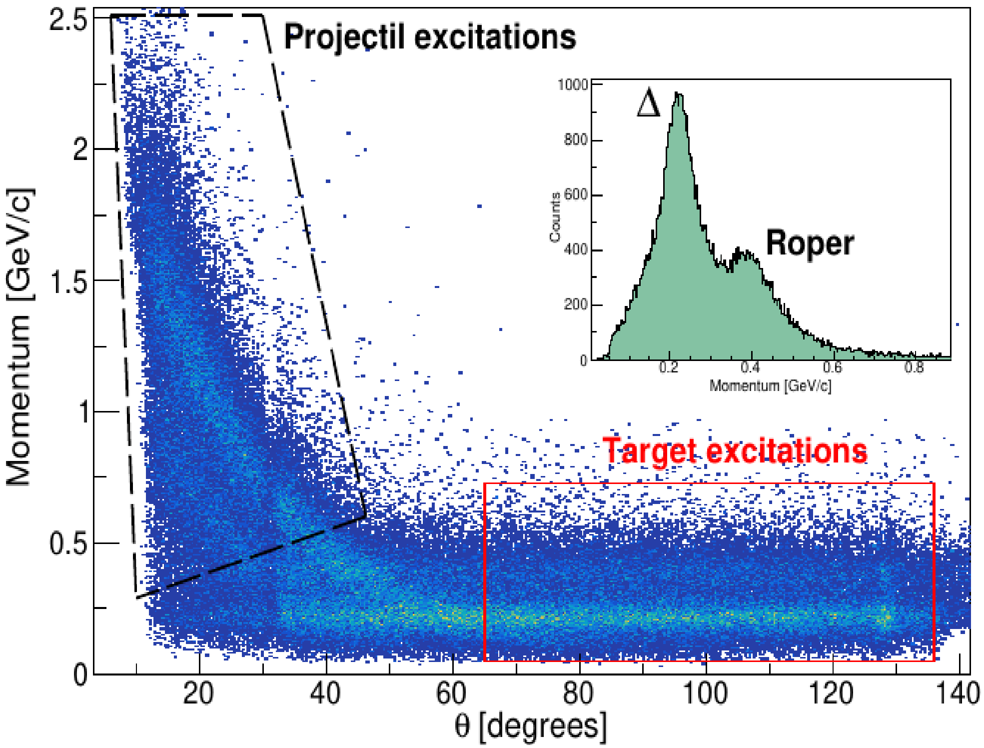
Chr. Bargholtzl et al., NIM A 594, 339 (2008)

See Y. Tanaka's talk

Exclusive measurements will help us to

- ✗ Separate the target and projectile Δ excitations by using the kinematics
- ✗ Distinguish Δ and Roper resonances using the invariant mass
- ✗ Clear identification of the Roper resonance using the two pion decay



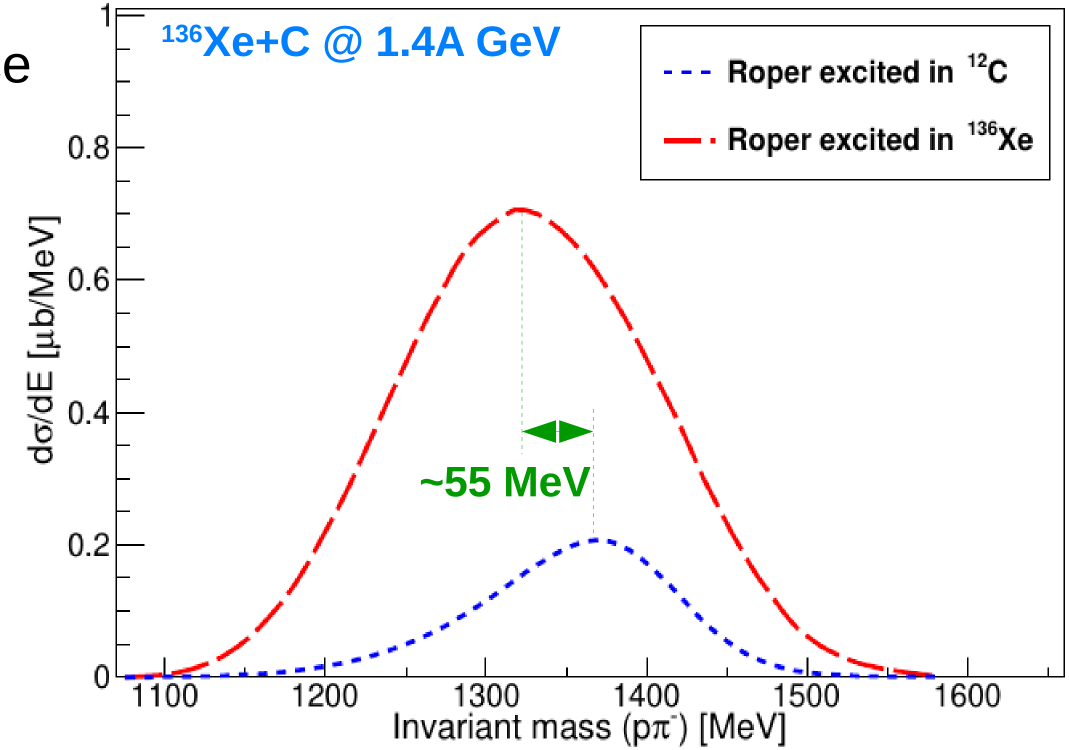


Channel decay	$\Delta p/p(\%)$	Efficiency (%)
One pion from target excitation	3	74
One pion from projectile excitation	3-6	76
Two pions from target excitation	3	64
Two pions from projectile excitation	3-6	66

Missing energy spectra with resolutions of 6 MeV

Exclusive measurements will help us to

- ✗ Study the mass and width dependence on the neutron-to-proton asymmetry:
  - Δ(1232): 115 MeV for mass
    60 MeV for width
  - Roper: 55 MeV for mass
    50 MeV for width
- ✗ Evolution of the charge-exchange cross sections (of around 100μb) with the neutron-to-proton asymmetry



Decay channel	Cross section $[\mu b]$	Events	Decay channel	Cross section $[\mu b]$	Events
$\Delta \rightarrow N\pi$ in ^{12}C	180	33×10^3	Roper$\rightarrow N\pi\pi$ in ^{12}C	25	4×10^3
$\Delta \rightarrow N\pi$ in ^{124}Xe	80	14×10^3	Roper$\rightarrow N\pi\pi$ in ^{124}Xe	100	16×10^3
$\Delta \rightarrow N\pi$ in ^{136}Xe	90	16.5×10^3	Roper$\rightarrow N\pi\pi$ in ^{136}Xe	110	17.5×10^3
Roper$\rightarrow N\pi$ in ^{12}C	45	8.2×10^3	Roper$\rightarrow \Delta\pi \rightarrow N\pi\pi$ in ^{12}C	25	4×10^3
Roper$\rightarrow N\pi$ in ^{124}Xe	180	33×10^3	Roper$\rightarrow \Delta\pi \rightarrow N\pi\pi$ in ^{124}Xe	100	16×10^3
Roper$\rightarrow N\pi$ in ^{136}Xe	200	36×10^3	Roper$\rightarrow \Delta\pi \rightarrow N\pi\pi$ in ^{136}Xe	110	17.5×10^3

Conclusions & Perspectives

Δ resonance excitations in medium-mass projectiles of Sn were investigated for the first time within isobaric charge-exchange reactions identified with the Fragment Separator FRS at GSI

- Full identification of the isobaric charge-exchange residues
- Missing-energy spectra obtained with a resolution of 10 MeV

Missing-energy spectra show

- Energy shift of around 70 MeV in the inelastic peak between proton and heavy nuclei target with A>12 due to the target and projectile excitations
- Quenching of the quasi-elastic peak for the (n,p) channel

Total, quasi-elastic and inelastic cross sections of isobaric charge-exchange reactions are sensitive to the abundance of neutrons and protons at the nuclear surface of the colliding nuclei and thus it can be used to study the competition between the Gamow-Teller and Δ resonance excitations with the neutron-to-proton asymmetry

Exclusive measurements could be performed with the WASA detectors @ FRS/Super-FRS

- Super-FRS opens unique opportunities to study the excitation of Δ resonances in neutron-rich nuclei
- Tagging of pions will allow us to separate the quasi-elastic and inelastic components
- Invariant mass and kinematics can be used to distinguish between projectile and target excitations
- Identification of other resonances, like Roper …

Collaborators

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T. Aumann, J. Atkinson, K. Boretzky, A. Estrade, H. Geissel, E. Haettner, A. Kelic-Heil, Y. Litvinov, S. Pietri, A. Prochazka, C. Scheidenberger, M. Takechi, Y. Tanaka, H. Weick, J. Winfield

I. Vidaña

T.R. Saito
K. Itahashi

E. Casarejos

H. Lenske

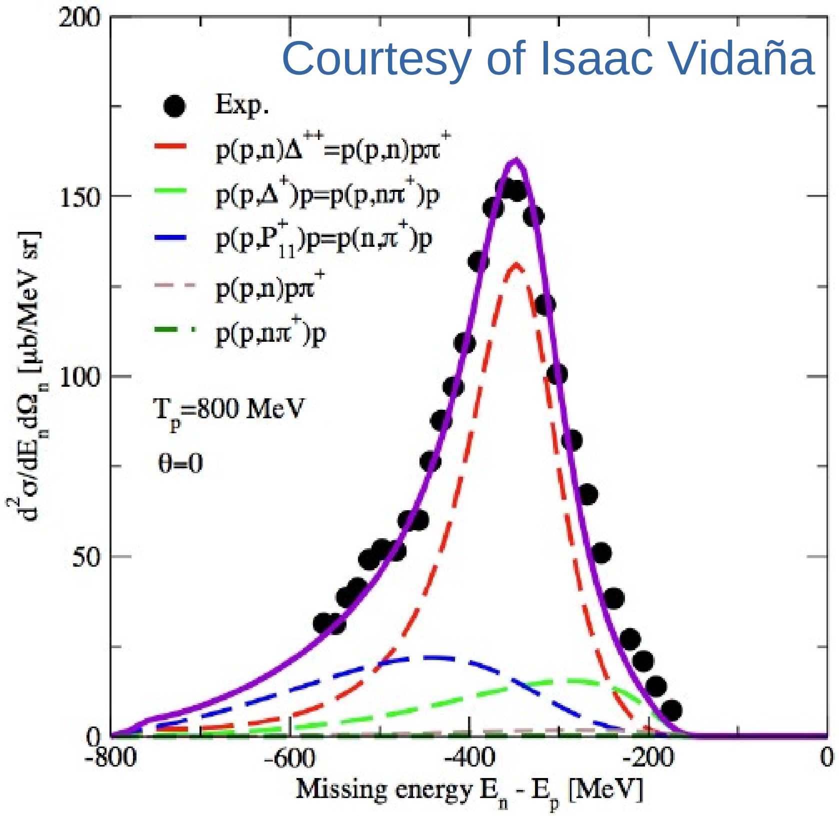
S. Schadmand
V. Serdyuk

L. Alvarez-Ruso

Thank you for your attention

(p,n) reaction on a proton target

$$pp \to np\pi^+$$



- Clear dominance of Δ^{++} excitation in the target

Data from G. Glass et al., PRD 15, 36 (1977)

Contribution from 5 processes

✧ s-wave π emission in Target

$$p(p,n)p\pi^+$$

✧ s-wave π emission in Projectile

$$p\left(p,n\pi^+\right)p$$

✧ Δ^{++} excitation in Target

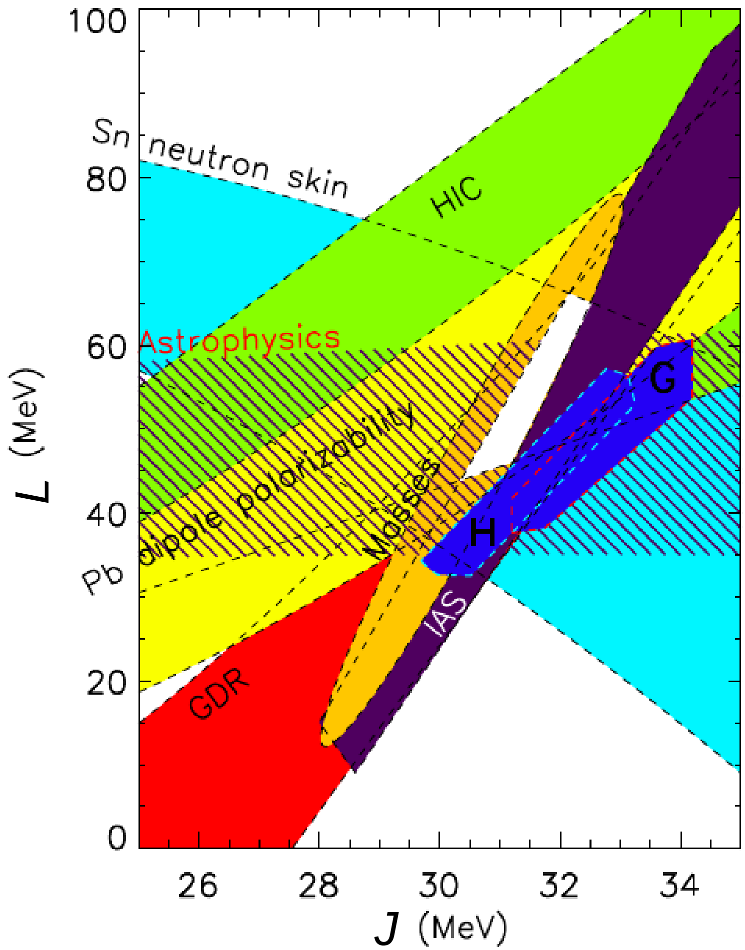
$$p(p,n)\Delta^{++} = p(p,n)p\pi^+$$

✧ Δ^+ & $P_{11}{}^+$ excitation in Projectile

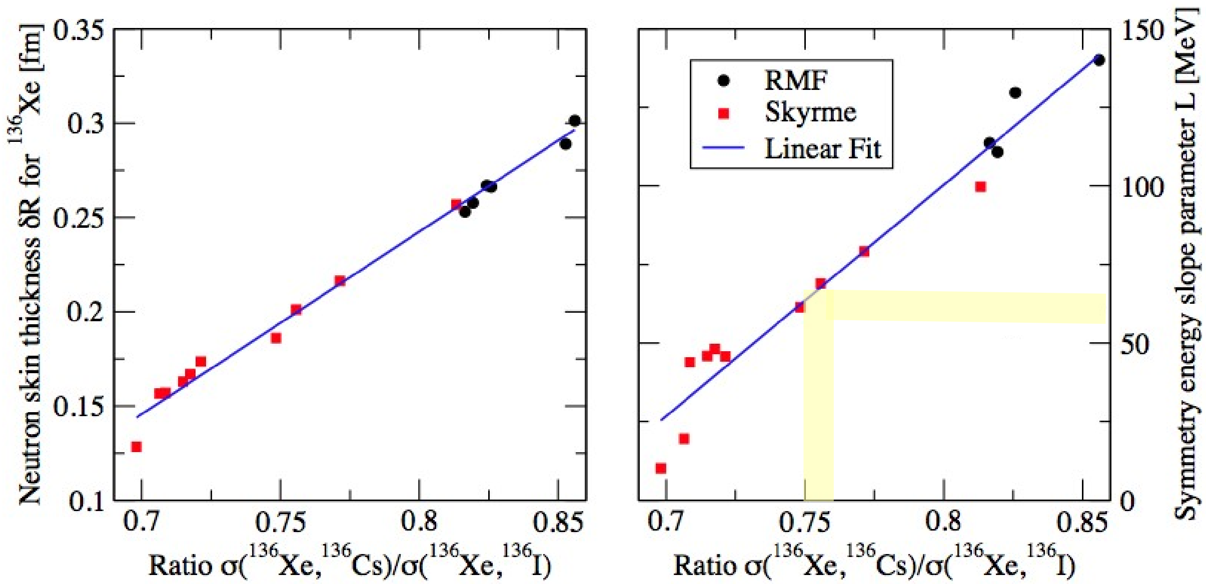
$$p(p,\Delta^+)p = p(p,n\pi^+)p$$
$$p(p,P_{11}^+)p = p(p,n\pi^+)p$$

Proof-of-concept to constrain the equation of state, in particular, the slope of the symmetry energy *L*

$$S(\rho) = J + L\frac{\rho-\rho_0}{3\rho_0} + \frac{1}{2}K_{\rm sym}(\frac{\rho-\rho_0}{3\rho_0})^2 + \mathcal{O}[(\rho-\rho_0)^3]$$



Linear correlations between cross section ratio and neutron skins/slope L



Measurement of cross sections with uncertainties of 1% would constrain the symmetry energy slope with an accuracy of 6 MeV