Excitation of Nucleon Resonances in Isobar Charge Exchange Reactions

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First observation of the $\Delta(1232)$ & the Roper N$^*(1440)$

- **In 1952** Fermi *et al.*, observed the $\Delta(1232)$ for the first time in $\pi p$ scattering
  
  Phys. Rev. 85, 932 (1952)

- **In 1963** L. David Roper found an unexpected $P_{11}$ resonance at $E \sim 1.44$ GeV
  
  Phys. Rev. Lett. 12, 340 (1964)
Since then many nucleon resonances have been discovered in

- \( \pi N \) elastic scattering
- \( \pi N \rightarrow \eta N, \sigma N, \omega N, \Lambda K, \Sigma K, \rho N, \pi \Delta \) reactions
- Electroproduction \( \gamma N \)
- More complex processes like e.g., \( \pi N \rightarrow \pi \pi N, \pi \rho N, \omega N, \phi N, K^* Y, \ldots \)
### 2015 status of the $\Delta$ & N resonances

#### 22 $\Delta$ resonances known with masses from 1232 to 2950 MeV

<table>
<thead>
<tr>
<th>Particle $J^P$</th>
<th>Status overall</th>
<th>$\pi N$</th>
<th>$\gamma N$</th>
<th>$N_\eta$</th>
<th>$N_\sigma$</th>
<th>$N_\omega$</th>
<th>$\Lambda K$</th>
<th>$\Sigma K$</th>
<th>$N_\rho$</th>
<th>$\Delta \pi$</th>
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<td>$\Delta_{(1232)}$ 3/2$^+$</td>
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<td>$\Delta_{(1940)}$ 3/2$^-$</td>
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<td>$\Delta_{(1950)}$ 7/2$^+$</td>
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<td>$\Delta_{(2000)}$ 5/2$^+$</td>
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<td>$\Delta_{(2150)}$ 1/2$^-$</td>
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<td>$\Delta_{(2200)}$ 7/2$^-$</td>
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<td>$\Delta_{(2300)}$ 9/2$^+$</td>
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<td>$\Delta_{(2350)}$ 5/2$^-$</td>
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<td>$\Delta_{(2390)}$ 7/2$^+$</td>
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<td>$\Delta_{(2400)}$ 9/2$^-$</td>
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<td>$\Delta_{(2420)}$ 11/2$^+$</td>
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<td>$\Delta_{(2750)}$ 13/2$^-$</td>
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<td>$\Delta_{(2950)}$ 15/2$^+$</td>
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***** Existence is certain, and properties are at least fairly well explored.
*** Existence is very likely but further confirmation of quantum numbers and branching fractions is required.
** Evidence of existence is only fair.
* Evidence of existence is poor.

#### 26 N resonances known with masses from 1440 to 2700 MeV

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<td>$N_{(1895)}$ 1/2$^-$</td>
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<td>$N_{(1900)}$ 3/2$^+$</td>
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<td>$N_{(1990)}$ 7/2$^+$</td>
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<td>$N_{(2060)}$ 5/2$^-$</td>
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<td>$N_{(2100)}$ 1/2$^+$</td>
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<td>$N_{(2130)}$ 3/2$^-$</td>
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<td>$N_{(2190)}$ 7/2$^+$</td>
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<td>$N_{(2220)}$ 9/2$^+$</td>
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PDG estimates (2015)
The $\Delta(1232)$

First spin-isospin excited mode of the nucleon corresponding to $\Delta S=1$ & $\Delta T=1$. Conventionally described as a resonant $\pi N$ state with relative angular momentum $L=1$

$\Delta(1232) \ 3/2^+$

\[ I(J^P) = \frac{3}{2}(\frac{3}{2}^+) \]

Breit-Wigner mass (mixed charges) = 1230 to 1234 ($\approx 1232$) MeV
Breit-Wigner full width (mixed charges) = 114 to 120 ($\approx 117$) MeV
Re(pole position) = 1209 to 1211 ($\approx 1210$) MeV
$-2\text{Im}(\text{pole position}) = 98$ to 102 ($\approx 100$) MeV

<table>
<thead>
<tr>
<th>$\Delta(1232)$ DECAY MODES</th>
<th>Fraction ($\Gamma_f/\Gamma$)</th>
<th>$p$ (MeV/c)</th>
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</thead>
<tbody>
<tr>
<td>$N\pi$</td>
<td>100 %</td>
<td>229</td>
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<tr>
<td>$N\gamma$</td>
<td>0.55-0.65 %</td>
<td>259</td>
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<tr>
<td>$N\gamma$, helicity=1/2</td>
<td>0.11-0.13 %</td>
<td>259</td>
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<tr>
<td>$N\gamma$, helicity=3/2</td>
<td>0.44-0.52 %</td>
<td>259</td>
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PDG estimates (2015)
The $N^*(1440)$

However … its nature is not completely understood

Theoretical descriptions include:

- **Pure Quark Model**: radial excitation of the nucleon (qqq)*
- **Hybrid model**: $N^*(1440)$ as a qqqG state
- **Dual nature of $N^*(1440)$**: as a qqq & qqqqq̅ states
- **$N^*(1440)$** as a collective excitation

- **Coupled-channel** ($\pi N$, $\sigma N$, $\pi \Delta$, $\rho N$) meson exchange description of the $N^*(1440)$ structure. No qqq component at all.
- **Lattice QCD**

<table>
<thead>
<tr>
<th>$N(1440)$ DECAY MODES</th>
<th>Fraction ($\Gamma_f/\Gamma$)</th>
<th>$\rho$ (MeV)</th>
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<tbody>
<tr>
<td>$N\pi$</td>
<td>55–75 %</td>
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<td>$N\eta$</td>
<td>(0.0±1.0) %</td>
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<td>$N\pi\pi$</td>
<td>30–40 %</td>
<td>338</td>
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<tr>
<td>$\Delta\pi$</td>
<td>20–30 %</td>
<td>135</td>
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<tr>
<td>$\Delta(1232)\pi, P$-wave</td>
<td>15–30 %</td>
<td>135</td>
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<tr>
<td>$N\rho$</td>
<td>&lt;8 %</td>
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<tr>
<td>$N\rho, S=1/2, P$-wave</td>
<td>(0.0±1.0) %</td>
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<tr>
<td>$N(\pi\pi)_{S=0}$</td>
<td>10–20 %</td>
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<tr>
<td>$\rho\gamma$</td>
<td>0.035–0.048 %</td>
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<td>$\rho\gamma$, helicity=1/2</td>
<td>0.035–0.048 %</td>
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<tr>
<td>$n\gamma$</td>
<td>0.02–0.04 %</td>
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<tr>
<td>$n\gamma$, helicity=1/2</td>
<td>0.02–0.04 %</td>
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PDG estimates (2015)
Is the study of nucleon resonances still interesting?

After more than 60 years studying nucleon resonances one could think that not, but … determining in-medium (density & isospin dependence) properties of nucleon resonances is essential for a better understanding of …

✧ the underlying dynamics governing many nuclear reactions
✧ three-nucleon force mechanisms
✧ EoS of asymmetric nuclear matter (neutron stars)
✧ …
Isobar Charge Exchange Reactions

- Allow the investigation of nuclear & nucleon (spin-isospin) excitations in nuclei
  - Low energies: GT, spin-dipole, spin-quadrupole, quasi-elastic
  - High energies: excitation of a nucleon into $\Delta$, $N^*$, …
- Being peripheral can provide information on radial distributions (surface & tail) of protons & neutrons in nuclei (neutron skin thickness) → information on (low density) asymmetric nuclear matter

Are important tools to study the spin-isospin dependence of the nuclear force
Past Observations of the $\Delta(1232)$ in Isobar Charge Exchange Reactions

1980’s complete experimental program to measure $\Delta(1232)$ excitation in isobar charge exchange reactions with light & medium mass projectiles at SATURNE accelerator in Saclay

(p,n) reactions  (n,p) reactions

Shift of the $\Delta$ peak to lower energies for medium & heavy targets

What’s its origin?

D. Bachelier, et al., PLB 172, 23(1986)
Recent experiments have been performed with the FRS at GSI using stable ($^{112}$Sn, $^{124}$Sn) & unstable ($^{110}$Sn, $^{120}$Sn, $^{122}$Sn) tin projectiles on different targets. The use of relativistic nuclei far off stability allows to explore the isospin degree of freedom enlarging our present knowledge of the properties of isospin-rich nuclear systems. Qualitative agreement with the results of SATURNE.
In this work we study the excitation of nucleon ($\Delta$, $N^*$) resonances in isobar charge exchange reactions with heavy nuclei to analyze recent measurements at GSI.

In the next I will present:

- **Model for the reaction**
  - OME ($\pi$, $\rho$, $\sigma$)
  - $\Delta$ & $N^*$ excitation in Target & Projectile

- **Results**
  - $(^{112}\text{Sn},^{112}\text{In})$ reaction on a proton target at 1GeV/nucleon
  - Origin of the shift of the $\Delta$ peak

- **Isospin content of projectile tail**: inclusive & exclusive measurements. Neutron skin thickness & $L$ from ICER
Model for the reaction

\[ \frac{d^2\sigma}{dE d\Omega} \left( ^A Z, ^A(Z\pm1) \right) = \sum N_2=n,p \sum c=el,in \left( \frac{d^2\sigma}{dE_3 d\Omega_3} \right)_c N_{N_1N_2} \]

Double differential cross section (spectrum) calculated as

Glauber-like model where only the nucleons in the overlap region participate in the reaction & the rest are simply spectators.
Elementary Processes

The model includes contributions from

✧ Elastic NN \(\rightarrow\) NN processes

✧ Inelastic NN \(\rightarrow\) NN\(\pi\) processes

s-wave \(\pi\) production

p-wave (resonance pole) \(\pi\) production
Two Pion Emission Elementary Processes

Note that

<table>
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<tr>
<th>$\boldsymbol{N(1440)}$ DECAY MODES</th>
<th>Fraction ($\Gamma_i/\Gamma$)</th>
<th>$p$ (MeV/c)</th>
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<tr>
<td>$\Delta \pi$</td>
<td>20–30 %</td>
<td>135</td>
</tr>
<tr>
<td>$\Delta(1232) \pi$, $P$-wave</td>
<td>15–30 %</td>
<td>135</td>
</tr>
</tbody>
</table>

Important elementary process (but not included here yet) are
List of elementary (p,n) processes

✧ Elastic $N_2(N_1,N_3)N_4$ process

✧ Inelastic $N_2(N_1,N_3)N_4\pi$ & $N_2(N_1,N_3\pi)N_4$ processes
Example: \((p,n)\) reaction on a proton target

\[ pp \rightarrow np\pi^+ \]

Contribution from 5 processes

- s-wave \(\pi\) emission in Target
  \[ p(p,n)p\pi^+ \]

- s-wave \(\pi\) emission in Projectile
  \[ p(p,n\pi^+)p \]

- \(\Delta^{++}\) excitation in Target
  \[ p(p,n)\Delta^{++} = p(p,n)p\pi^+ \]

- \(\Delta^+\) & \(P_{11}^+\) excitation in Projectile
  \[ p(p,\Delta^+)p = p(p,n\pi^+)p \]
  \[ p(p,P_{11}^+)p = p(p,n\pi^+)p \]

- Clear dominance of \(\Delta^{++}\) excitation in the target

Data from G. Glass et al., PRD 15, 36 (1977)
Elementary \((p,n)\) cross sections

- **\(\Delta(1232)\) excitation**
  - Reaction with a proton Target
    - c.s. of \(\Delta\) excitation in target \(\sim 9\) times larger than c.s. of \(\Delta\) excitation in projectile
  - Reaction with a neutron Target
    - similar strength of the c.s.

- **\(N^*(1440)\) excitation**
  - Reaction with a proton Target
    - \(P_{11}^+\) excited only in Projectile
  - Reaction with a neutron Target
    - strength of c.s. for \(N^*\) excitation in projectile \(\sim 1 - 5\) than of \(N^*\) in target
List of elementary \((n,p)\) processes

- **Elastic** \(N_2(N_1,N_3)N_4\) process

  \[
  p(n,p)n
  \]

- **Inelastic** \(N_2(N_1,N_3)N_4\pi\) & \(N_2(N_1,N_3\pi)N_4\) processes

  \[
  p(n,p\pi^0)n
  p(n,p\pi^-)p
  n(n,p\pi^-)n
  \]

  \[
  p(n,\Delta^0)p = p(n,p\pi^-)p
  p(n,\Delta^+)n = p(n,p\pi^0)n
  n(n,\Delta^0)n = n(n,p\pi^-)n
  \]

  \[
  p(n,\Delta^0)n = p(n,p\pi^-)n
  n(n,\Delta^0)n = n(n,p\pi^-)n
  \]
Elementary \((n,p)\) cross sections

\(\Delta(1232)\) excitation

- Reaction with a proton Target
  - similar strength of the c.s.
- Reaction with a neutron Target
  - c.s. of \(\Delta\) excitation in target \(\sim 9\) times larger than c.s. of \(\Delta\) excitation in projectile

\(N^*(1440)\) excitation

- \(N^*\) excited in reaction with both proton & neutron targets
  - \(P_{11}^+\) state excited only in projectile
  - \(P_{11}^0\) state excited both in projectile & target.
  - strength of c.s. for \(N^*\) excitation in projectile \(\sim 1 - 5\) than of \(N^*\) in target
Number of elementary processes $N_{N_1N_2}$

$$N_{N_1N_2} = \int d^2 \vec{b} \rho_{\text{overlap}}^{N_1N_2}(b)[1 - T(b)] P_\pi(b)$$

- $N_1N_2$ density of overlap region
  $$\rho_{\text{overlap}}^{N_1N_2}(b) = \int dz \int d^3 \vec{r} \rho_P^{N_1}(\vec{r}) \rho_T^{N_2}(\vec{b} + \vec{z} + \vec{r})$$

- Transmission function
  $$1 - T(b) = 1 - \exp\left(- \int dz \int d^3 \vec{r} \sigma_{\text{NN}} \rho_P(\vec{r}) \rho_T(\vec{b} + \vec{z} + \vec{r})\right)$$

- Pion survival probability
  $$P_\pi(b) = \exp\left(- \int dz \int d^3 \vec{r} \sigma_{\pi N} \rho_P(\vec{r}) \rho_T(\vec{b} + \vec{z} + \vec{r})\right)$$

N.B. Density distributions from RMF or SHF calculations
Peripheral character of the reaction

The reaction is peripheral

- Low impact parameters
  - Strong pion absorption due to large overlap. Therefore, $[1-T(b)]P_\pi(b)$ very small

- High impact parameters
  - Small overlap. Therefore, $[1-T(b)]P_\pi(b)$ very small
Number of elementary processes $N_{N1N2}$

$$N_{N_1N_2} = \int d^2\vec{b}\rho_{\text{overlap}}^{N_1N_2}(b)[1 - T(b)]P(\pi)(b), \quad \rho_{\text{overlap}}^{N_1N_2}(b) = \int dz\int d^3\vec{r}\rho_{\pi\nu}^{N_1}(\vec{r})\rho_{\pi\nu}^{N_2}(\vec{b} + \vec{z} + \vec{r})$$

<table>
<thead>
<tr>
<th>reaction</th>
<th>$N_R$</th>
<th>$N_{pp}$</th>
<th>$N_{pn}$</th>
<th>$N_{np}$</th>
<th>$N_{nn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{112}\text{Sn}^+\text{H}$</td>
<td>0.017</td>
<td>0.006</td>
<td>0</td>
<td>0.011</td>
<td>0</td>
</tr>
<tr>
<td>$^{112}\text{Sn}^+\text{C}$</td>
<td>0.019</td>
<td>0.003</td>
<td>0.003</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>$^{112}\text{Sn}^+\text{Cu}$</td>
<td>0.022</td>
<td>0.003</td>
<td>0.004</td>
<td>0.006</td>
<td>0.009</td>
</tr>
<tr>
<td>$^{112}\text{Sn}^+\text{Pb}$</td>
<td>0.027</td>
<td>0.001</td>
<td>0.007</td>
<td>0.004</td>
<td>0.015</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>$N_R$</th>
<th>$N_{pp}$</th>
<th>$N_{pn}$</th>
<th>$N_{np}$</th>
<th>$N_{nn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{124}\text{Sn}^+\text{H}$</td>
<td>0.019</td>
<td>0.004</td>
<td>0</td>
<td>0.015</td>
<td>0</td>
</tr>
<tr>
<td>$^{124}\text{Sn}^+\text{C}$</td>
<td>0.023</td>
<td>0.002</td>
<td>0.002</td>
<td>0.010</td>
<td>0.009</td>
</tr>
<tr>
<td>$^{124}\text{Sn}^+\text{Cu}$</td>
<td>0.024</td>
<td>0.001</td>
<td>0.002</td>
<td>0.009</td>
<td>0.010</td>
</tr>
<tr>
<td>$^{124}\text{Sn}^+\text{Pb}$</td>
<td>0.029</td>
<td>0.0006</td>
<td>0.003</td>
<td>0.005</td>
<td>0.020</td>
</tr>
</tbody>
</table>
The \((^{112}\text{Sn},^{112}\text{In})\) reaction on a proton target at 1 GeV/nucleon
Origin of the shift of the $\Delta$ peak

\((^{124}\text{Sn},^{124}\text{In})\)  \(\rightarrow\) \((^{124}\text{Sn},^{124}\text{Sb})\)

Is the shift due to in-medium effects? If yes, then why it seems to be almost the same for all targets?

\textbf{NO:} in-medium (density) modification of $\Delta$ & $N^*$ properties because the reaction is very peripheral & density is small

\textbf{YES:} excitation mechanisms of $\Delta$ ($N^*$) in both Target & Projectile

Conclusion already pointed out in the analysis of charge exchange reactions with lighter nuclei (e.g., E. Oset, E. Shiino & H. Toki, PLB 224, 249 (1989))
Isospin content of the projectile tail: inclusive measurements

<table>
<thead>
<tr>
<th>(n,p) channel</th>
<th>(p,n) channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{A}Z, ^{A}(Z+1))</td>
<td>(^{A}Z, ^{A}(Z-1))</td>
</tr>
</tbody>
</table>

Consider the ratio

\[ R = \frac{\sigma\left(^{A}Z, ^{A}(Z+1)\right)}{\sigma\left(^{A}Z, ^{A}(Z-1)\right)} \]

In the model

\[ R = \frac{\sigma_{nn \rightarrow pn\pi^{-}}N_{nn} + \sigma_{np \rightarrow pp\pi^{-}}N_{np} + \sigma_{np \rightarrow pn\pi^{0}}N_{np}}{\sigma_{pp \rightarrow np\pi^{+}}N_{pp} + \sigma_{pn \rightarrow nn\pi^{+}}N_{pn} + \sigma_{pn \rightarrow np\pi^{0}}N_{pn}} \]

\[ \approx \frac{N_{n}^{(P)}}{N_{p}^{(P)}} \times \left( \frac{\sigma_{nn \rightarrow pn\pi^{-}}N_{n}^{(T)} + \sigma_{np \rightarrow pp\pi^{-}}N_{p}^{(T)} + \sigma_{np \rightarrow pn\pi^{0}}N_{p}^{(T)}}{\sigma_{pp \rightarrow np\pi^{+}}N_{p}^{(T)} + \sigma_{pn \rightarrow nn\pi^{+}}N_{n}^{(T)} + \sigma_{pn \rightarrow np\pi^{0}}N_{n}^{(T)}} \right) \]

This suggest

\[ \frac{N_{n}^{(P)}}{N_{p}^{(P)}} \propto f\left(N_{n}^{(T)}, N_{p}^{(T)}\right) R \]

How to disentangle ?. With exclusive measurements ?
Exclusive measurements & isospin content of the projectile tail

\[ (n,p) \text{ channel} \]

(1): \(^A Z + X \rightarrow ^A (Z+1) + \pi^- + X'\]
(2): \(^A Z + X \rightarrow ^A (Z+1) + \pi^0 + X''\]

\[ (p,n) \text{ channel} \]

(3): \(^A Z + X \rightarrow ^A (Z-1) + \pi^+ + \tilde{X}\]
(4): \(^A Z + X \rightarrow ^A (Z-1) + \pi^0 + \tilde{X}''\]

Consider the ratios

\[ R_1 = \frac{\sigma^{(1)}_{(A Z, A (Z+1))}}{\sigma^{(3)}_{(A Z, A (Z+1))}}, \quad R_2 = \frac{\sigma^{(2)}_{(A Z, A (Z+1))}}{\sigma^{(4)}_{(A Z, A (Z+1))}} \]

In the model

\[ R_1 = \frac{\sigma_{nn \rightarrow pn \pi^-} N_{nn} + \sigma_{np \rightarrow pp \pi^-} N_{np}}{\sigma_{pp \rightarrow np \pi^0} N_{pp} + \sigma_{pn \rightarrow nn \pi^0} N_{pn}} \approx \frac{N^{(P)}_{n}}{N^{(P)}_{p}} \times \left( \frac{\sigma_{nn \rightarrow pn \pi^-} N^{(T)}_{n} + \sigma_{np \rightarrow pp \pi^-} N^{(T)}_{p}}{\sigma_{pp \rightarrow np \pi^0} N^{(T)}_{p} + \sigma_{pn \rightarrow nn \pi^0} N^{(T)}_{n}} \right) \]
\[ R_2 = \frac{\sigma_{np \rightarrow pn \pi^0} N_{np}}{\sigma_{pn \rightarrow np \pi^0} N_{pn}} \approx \frac{N^{(P)}_{n}}{N^{(P)}_{p}} \times \left( \frac{\sigma_{np \rightarrow pn \pi^0} N^{(T)}_{n}}{\sigma_{pn \rightarrow np \pi^0} N^{(T)}_{n}} \right) \]

This suggests

\[ \frac{N^{(P)}_{n}}{N^{(P)}_{p}} \propto f(N^{(T)}_{n}, N^{(T)}_{p})R_1, \quad \frac{N^{(P)}_{n}}{N^{(P)}_{p}} \propto g(N^{(T)}_{n}, N^{(T)}_{p})R_2 \]

Seems as entangled as before!!
The cleanest case: measurements with a proton target

In this case we can consider just one ratio

\[ R_1 = \frac{\sigma^{(1)}_{A Z, A (Z+1)}}{\sigma^{(3)}_{A Z, A (Z-1)}} \]

\[ R_1 = \frac{\sigma_{np\rightarrow pp\pi^-}}{\sigma_{pp\rightarrow np\pi^+}} \frac{N_{np}}{N_{pp}} \sim \frac{\sigma_{np\rightarrow pp\pi^-}}{\sigma_{pp\rightarrow np\pi^+}} \frac{N_n^{(P)} N_p^{(T)}}{N_p^{(P)} N_p^{(T)}} = \frac{N_n^{(P)}}{N_p^{(P)}} \times \left( \frac{\sigma_{np\rightarrow pp\pi^-}}{\sigma_{pp\rightarrow np\pi^+}} \right) \]

in this case

\[ \frac{N_n^{(P)}}{N_p^{(P)}} \propto R_1 \]
Isospin content of the projectile: model estimations

✧ **Projectile mass number dependence**

✧ **Target atomic number dependence**
Neutron Skin Thickness & Symmetry Energy

Accurate measurements of

\[ R = \frac{\sigma^{(A_Z, A(Z+1))}}{\sigma^{(A_Z, A(Z-1))}} \]

can be used to extract the neutron skin thickness of heavy nuclei &  

\(^{136}\text{Xe}\) on a proton target at 1GeV/A
Summary & Future Perspectives

✧ Summary
Study of nucleon (Δ, N*) resonances in isobar charge reactions with heavy nuclei

- Model based on OME. Δ & N* excitation in Target & Projectile
- Reasonably good agreement with recent measurements
- Origin of Δ shift in medium & heavy targets due to excitation in Target & Projectile. Not to in-medium (density) effects as pointed out in analysis of reactions with lighter nuclei (e.g., Oset et al., PLB (1989))

✧ Future Perspectives

**Experiment**
- Exclusive measurements to identify the different reaction mechanisms.
  - Sensitivity to the isospin content of projectile tail.
  - Neutron skin thickness from ICE reactions

**Theory**
- Inclusion of other reaction mechanism (2π emission)
- You for your time & attention

- Ignazio, Angela, Alejandro, Laura & Michele for their invitation

- My collaborators from the SuperFRS collaboration J. Benlliure, H. Geissel, C. Sheidenberger, H. Lenske & many many others …