Excitation of Nucleon Resonances in Isobar Charge Exchange Reactions

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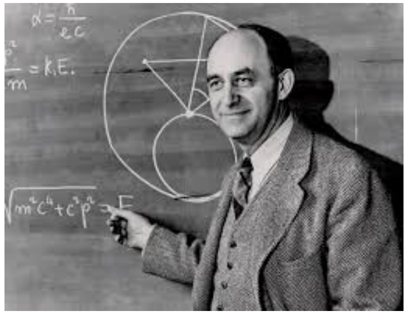
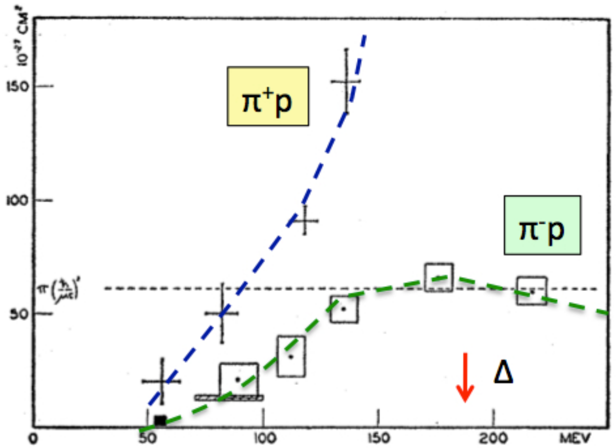
First observation of the Δ(1232) & the Roper N*(1440)

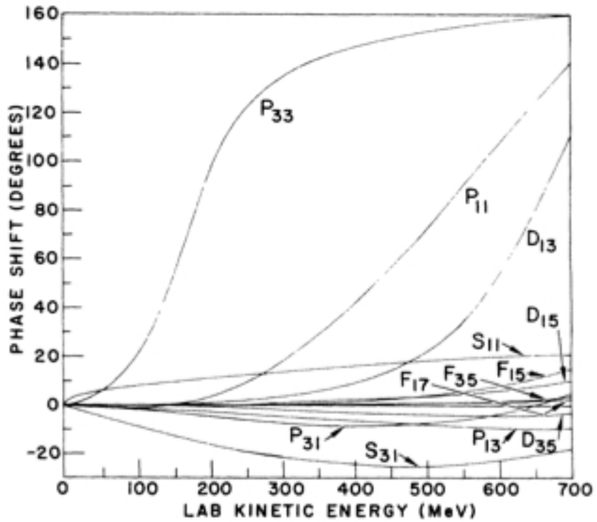


✧ In 1952 Fermi *et al.*, observed the Δ(1232) for the first time in πp scattering



Phys. Rev. 85, 932 (1952)

✧ In 1963 L. David Roper found an unexpected P_{11} resonance at E ~ 1.44 GeV

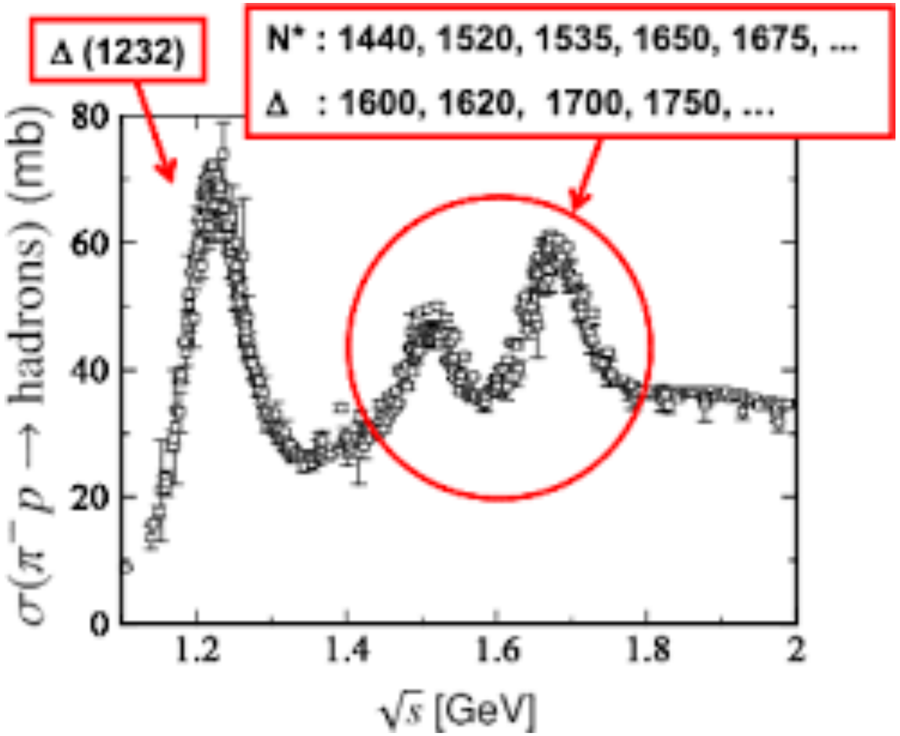


Phys. Rev. Lett. 12, 340 (1964)

Since them many nucleon resonances have been discovered in

- πN elastic scattering
- $\pi N \longrightarrow \eta N$, σN, ωN, ΛK, ΣK, ρN, $\pi\Delta$ reactions
- Electroproduction γN
- More complex processes like e.g., $\pi N \longrightarrow \pi\pi N$, $\pi\rho N$, ωN, ϕN, $K^{*}Y$, …

$\pi N \longrightarrow X$ cross section



2015 status of the Δ & N resonances

22 Δ resonances known with masses from 1232 to 2950 MeV

		Status			Status as seen in —						
Particle	J^P	overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$\Delta(1232)$	$3/2^+$	****	****	****	F						
$\Delta(1600)$	$3/2^+$	***	***	***	o					*	***
$\Delta(1620)$	$1/2^-$	****	****	***		r				***	***
$\Delta(1700)$	$3/2^-$	****	****	****		b				**	***
$\Delta(1750)$	$1/2^+$	*	*				i				
$\Delta(1900)$	$1/2^-$	**	**	**			d		**	**	**
$\Delta(1905)$	$5/2^+$	****	****	****			d		***	**	**
$\Delta(1910)$	$1/2^+$	****	****	**				e	*	*	**
$\Delta(1920)$	$3/2^+$	***	***	**				n	***		**
$\Delta(1930)$	$5/2^-$	***	***								
$\Delta(1940)$	$3/2^-$	**	*	**	F				(seen	in	$\Delta\eta$)
$\Delta(1950)$	$7/2^+$	****	****	****	o				***	*	***
$\Delta(2000)$	$5/2^+$	**				r					**
$\Delta(2150)$	$1/2^-$	*	*			b					
$\Delta(2200)$	$7/2^-$	*	*				i				
$\Delta(2300)$	$9/2^+$	**	**				d				
$\Delta(2350)$	$5/2^-$	*	*				d				
$\Delta(2390)$	$7/2^+$	*	*					e			
$\Delta(2400)$	$9/2^-$	**	**					n			
$\Delta(2420)$	$11/2^+$	****	****	*							
$\Delta(2750)$	$13/2^-$	**	**								
$\Delta(2950)$	$15/2^+$	**	**								

**** 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.

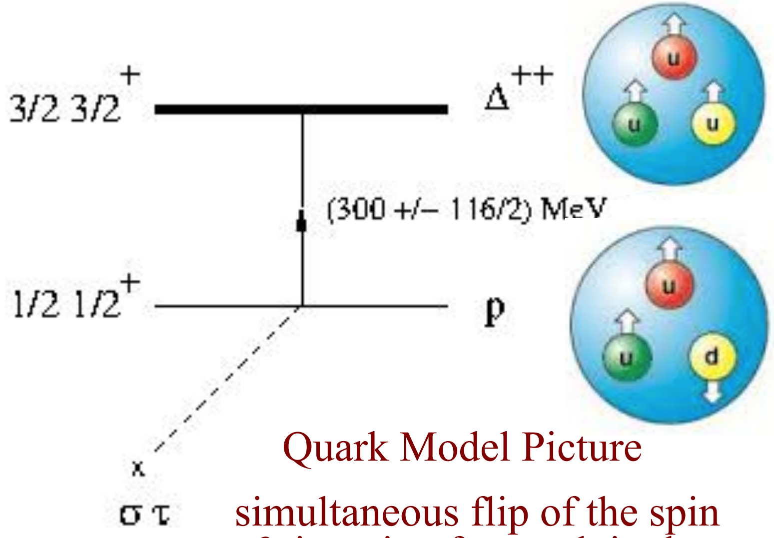
26 N resonances known with masses from 1440 to 2700 MeV

		Status			Status as seen in —						
Particle	J^P	overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	***	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1685)$	$?^?$	*									
$N(1700)$	$3/2^-$	***	***	**	*			*	*	*	***
$N(1710)$	$1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$	$3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$	$5/2^+$	**	**							*	*
$N(1875)$	$3/2^-$	***	*	***			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	*	**	**			**	*		
$N(1900)$	$3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	*	**	**			**	*	**	
$N(2040)$	$3/2^+$	*									
$N(2060)$	$5/2^-$	**	**	**	*				**		
$N(2100)$	$1/2^+$	*									
$N(2150)$	$3/2^-$	**	**	**				**			**
$N(2190)$	$7/2^-$	****	****	***			*	**		*	
$N(2220)$	$9/2^+$	****	****								
$N(2250)$	$9/2^-$	****	****								
$N(2600)$	$11/2^-$	***	***								
$N(2700)$	$13/2^+$	**	**								

PDG estimates (2015)

The Δ(1232)

First spin-isospin excited mode of the nucleon corresponding to ΔS=1 & ΔT=1. Conventionally described as a resonant πN state with relative angular momentum L=1



Quark Model Picture

simultaneous flip of the spin & isospin of a quark in the nucleon

Δ(1232) 3/2+ $I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Breit-Wigner mass (mixed charges) = 1230 to 1234 (≈ 1232) MeV
Breit-Wigner full width (mixed charges) = 114 to 120 (≈ 117) MeV
Re(pole position) = 1209 to 1211 (≈ 1210) MeV
−2Im(pole position) = 98 to 102 (≈ 100) MeV

Δ(1232) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	100 %	229
$N\gamma$	0.55–0.65 %	259
$N\gamma$, helicity=1/2	0.11–0.13 %	259
$N\gamma$, helicity=3/2	0.44–0.52 %	259

PDG estimates (2015)

The N*(1440)

PDG estimates (2015)

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

Breit-Wigner mass = 1410 to 1450 (≈ 1430) MeV
Breit-Wigner full width = 250 to 450 (≈ 350) MeV
Re(pole position) = 1350 to 1380 (≈ 1365) MeV
−2Im(pole position) = 160 to 220 (≈ 190) MeV

N(1440) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	55–75 %	391
$N\eta$	(0.0±1.0) %	†
$N\pi\pi$	30–40 %	338
$\Delta\pi$	20–30 %	135
$\Delta(1232)\pi$, P-wave	15–30 %	135
$N\rho$	<8 %	†
$N\rho$, S=1/2, P-wave	(0.0±1.0) %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	10–20 %	−
$p\gamma$	0.035–0.048 %	407
$p\gamma$, helicity=1/2	0.035–0.048 %	407
$n\gamma$	0.02–0.04 %	406
$n\gamma$, helicity=1/2	0.02–0.04 %	406

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 & $qqqq\bar{q}$ states
- ✧ $N^*(1440)$ as a collective excitation

- ✧ Coupled-channel (πN, σN, πΔ, ρN) meson exchange description of the $N^*(1440)$ structure. No qqq component at all.
- ✧ Lattice QCD

Is the study of nucleon resonances still interesting ?

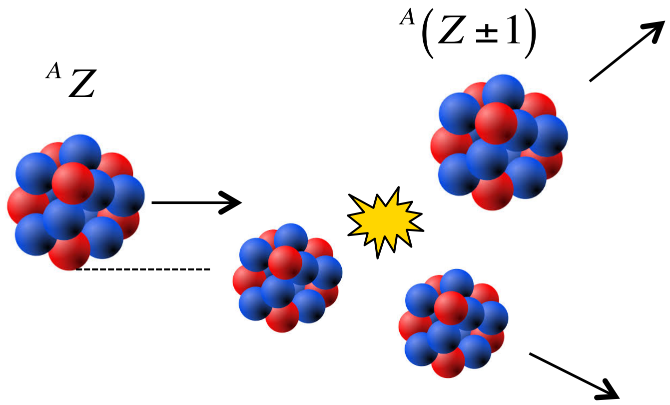
After more than 60 years studying nucleon resonances one could think that not, but … determining in-medium (density & isospin dependence) properties of nucleon resonances is essential for a better understanding of …

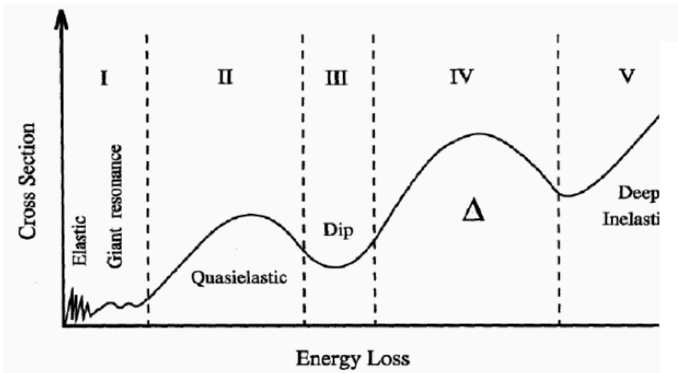
- ✧ the underlying dynamics governing many nuclear reactions
- ✧ three-nucleon force mechanisms
- ✧ EoS of asymmetric nuclear matter (neutron stars)
- ✧ …

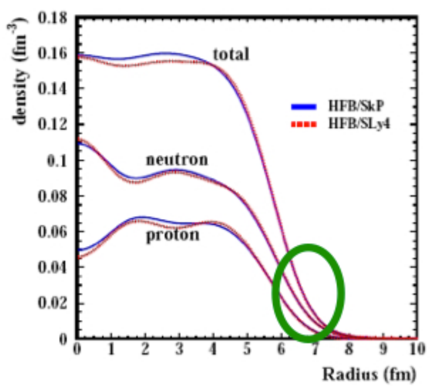
Isobar Charge Exchange Reactions

- 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 Δ, 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



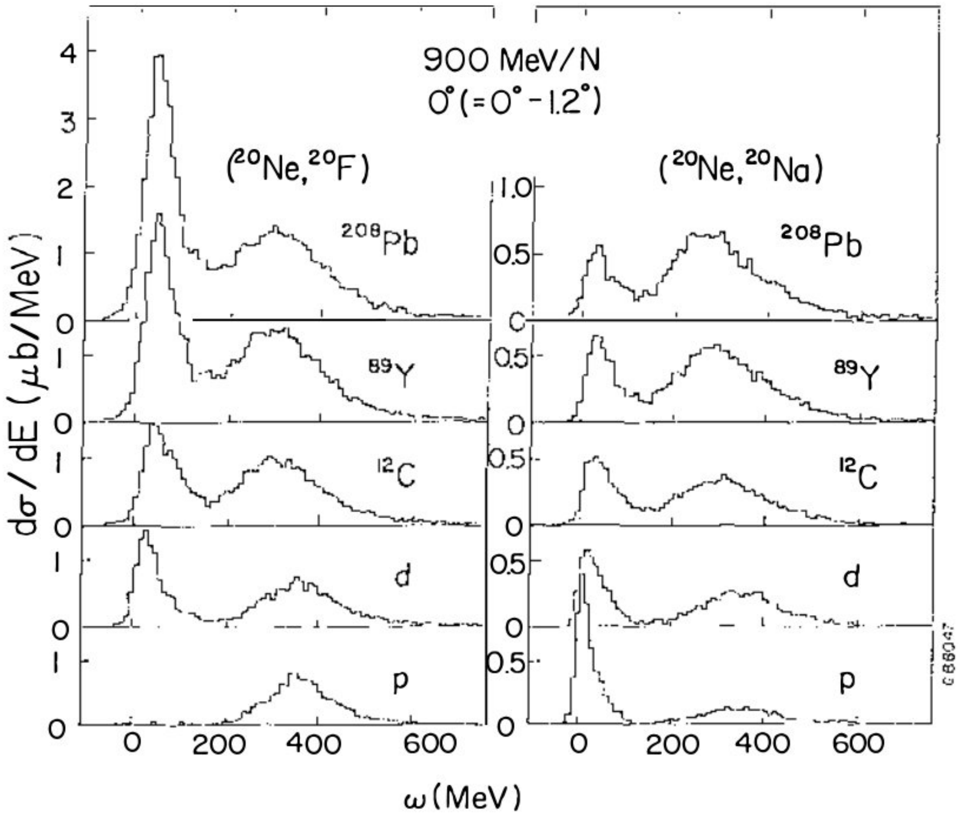




Past Observations of the Δ(1232) in Isobar Charge Exchange Reactions

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

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



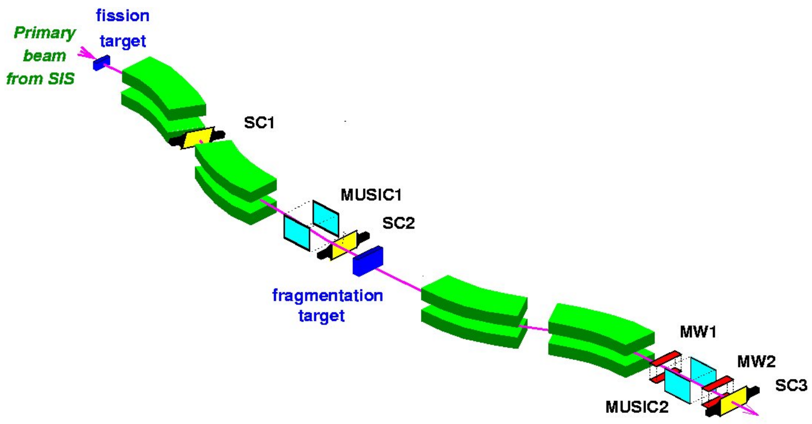
Shift of the Δ peak to lower energies for medium & heavy targets

What's its origin ?

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

Recent Experiments

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



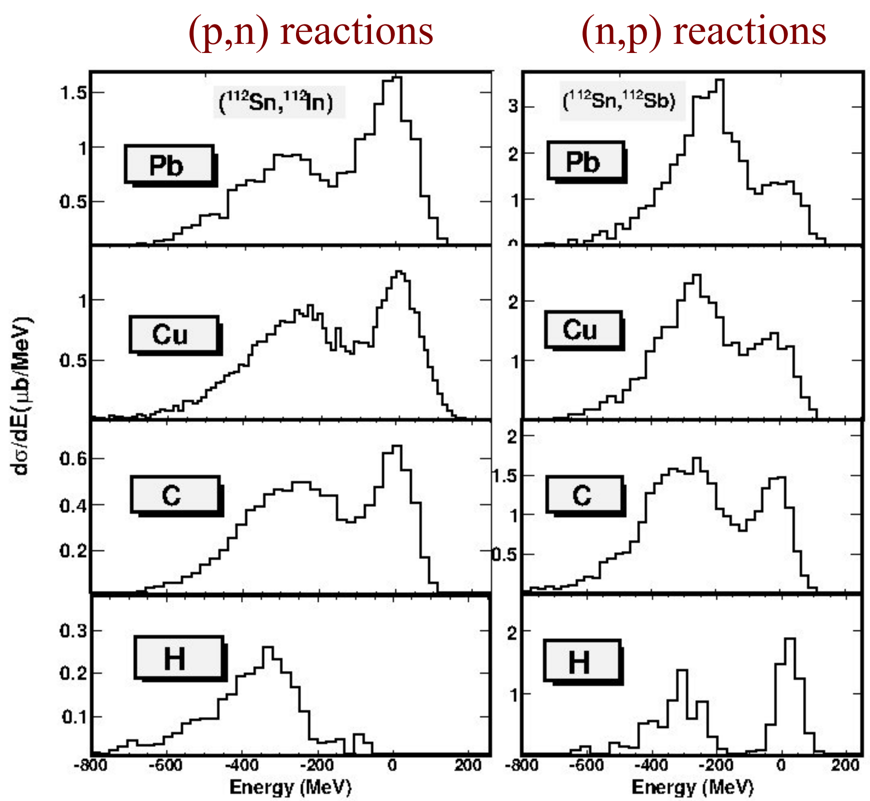


Figure courtesy of J. Benlliure & J. W. Vargas

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

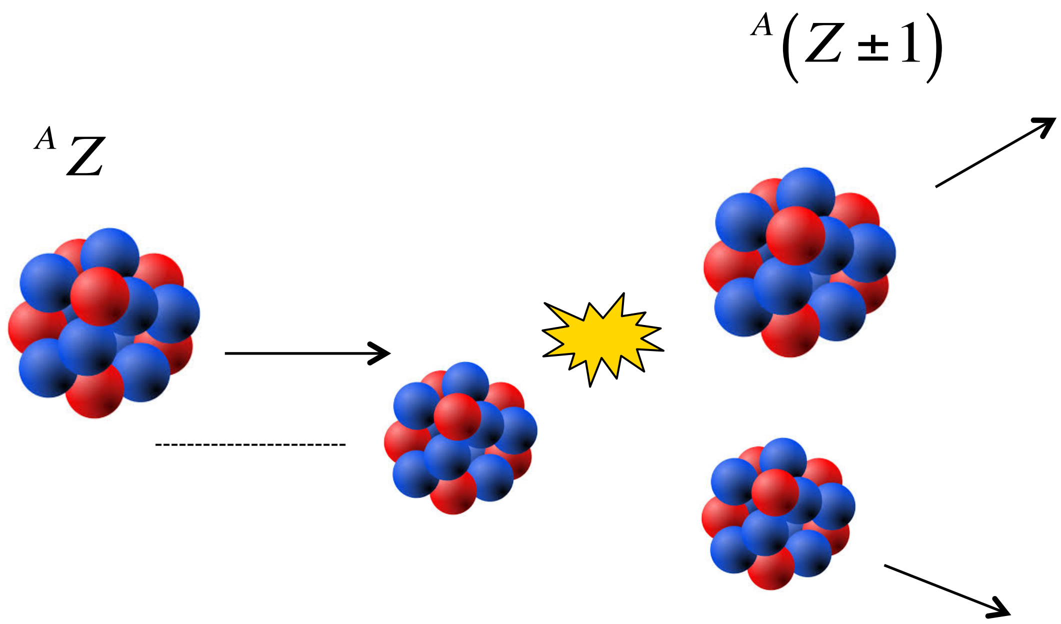
Qualitative agreement with the results of SATURNE

In this work we study the excitation of nucleon (Δ, 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 (π, ρ, σ)
  - Δ & N^* excitation in Target & Projectile
- Results
  - (^{112}Sn,^{112}In) reaction on a proton target at 1GeV/nucleon
  - Origin of the shift of the Δ peak
- Isospin content of projectile tail: inclusive & exclusive measurements. Neutron skin thickness & L from ICER

Model for the reaction



Glauber like model where only the nucleons in the overlap region participate on the reaction & the rest are simply spectators

Double differential cross section (spectrum) calculated as

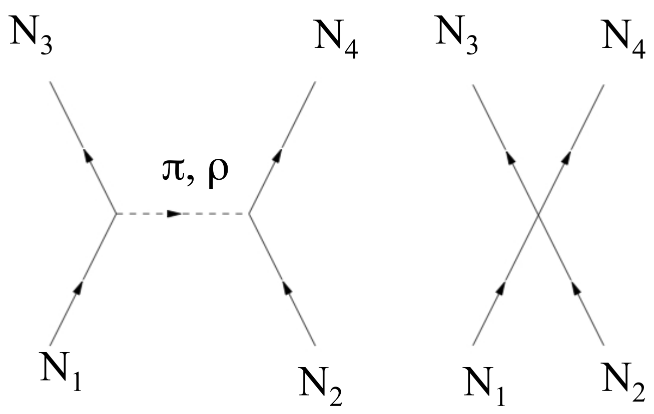
$$\left.\frac{d^2\sigma}{dE\,d\Omega}\right|_{(^{A}Z,\,^{A}(Z\pm1))} = \sum_{N_2=n,p}\ \sum_{c=el,in} \underbrace{\left(\frac{d^2\sigma}{dE_3\,d\Omega_3}\right)_c}_{\text{elementary cross sections}} N_{N_1N_2}$$

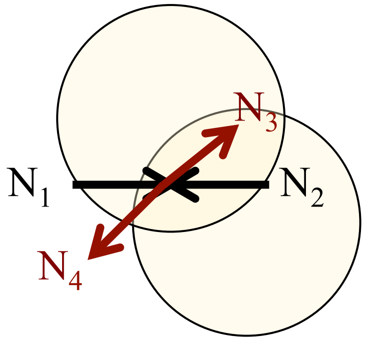
effective number of elementary processes contributing to the reaction

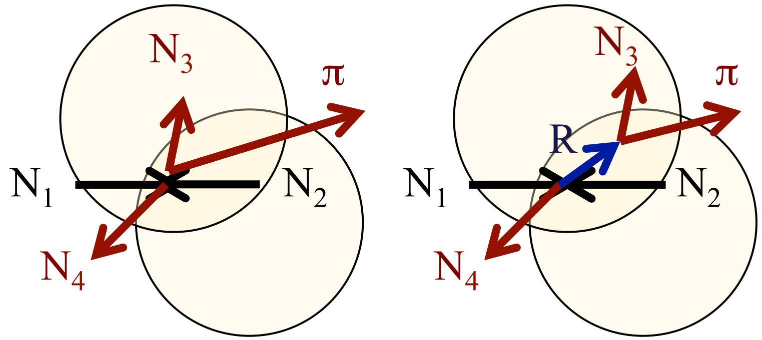
Elementary Processes

The model includes contributions from

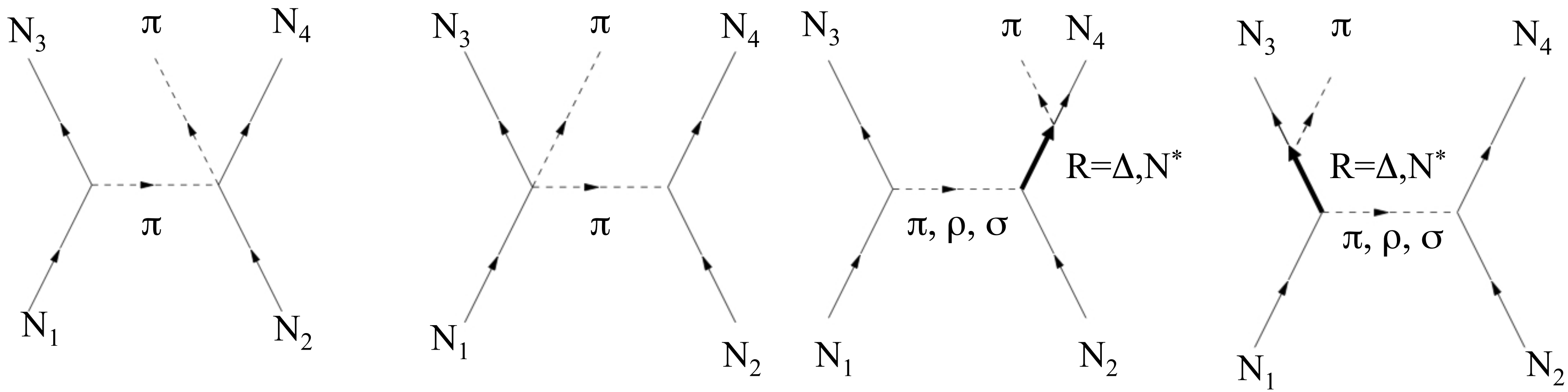
✧ <u>Elastic NN $\longrightarrow$ NN processes</u>







✧ <u>Inelastic NN $\longrightarrow$ NNπ processes</u>



s-wave π production

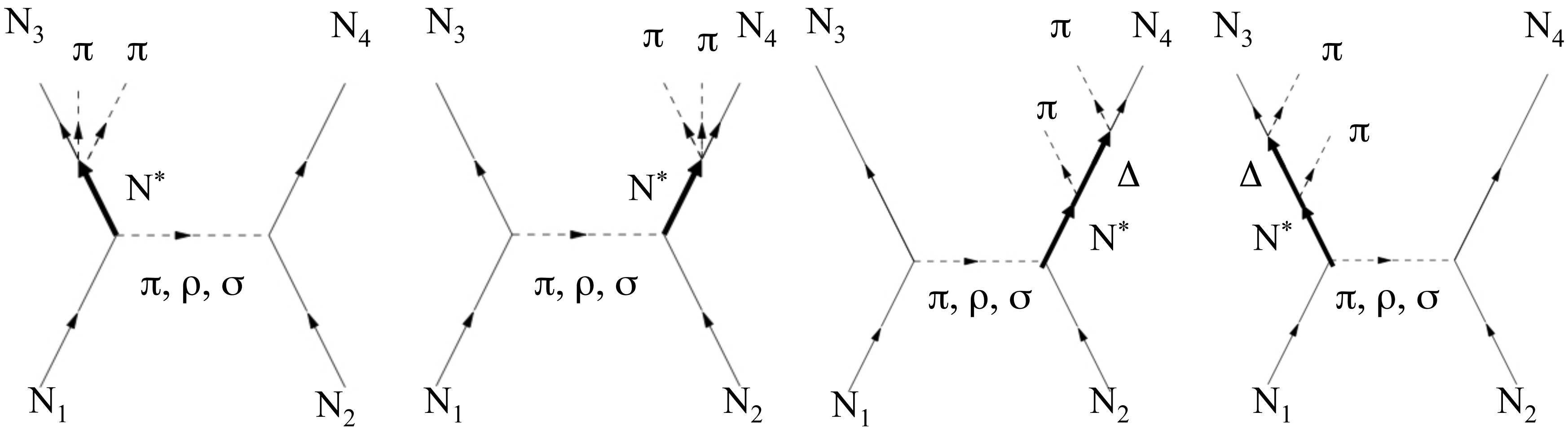
p-wave (resonance pole) π production

Two Pion Emission Elementary Processes

Note that

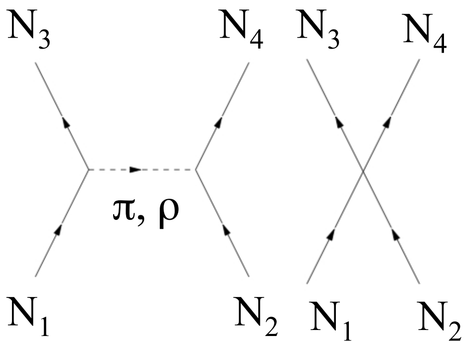
$N(1440)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	55–75 %	391
$N\eta$	(0.0 ± 1.0) %	†
$N\pi\pi$	30–40 %	338
$\Delta\pi$	20–30 %	135
$\Delta(1232)\pi$, P-wave	15–30 %	135

→ Important elementary process (but not included here yet) are



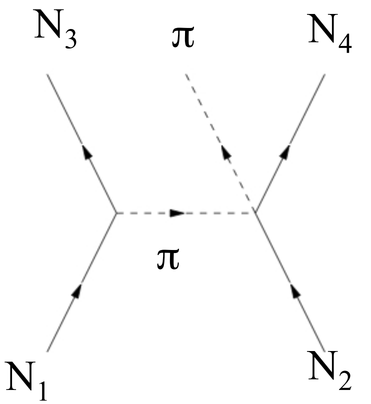
List of elementary (p,n) processes

✧ Elastic $N_2(N_1,N_3)N_4$ process

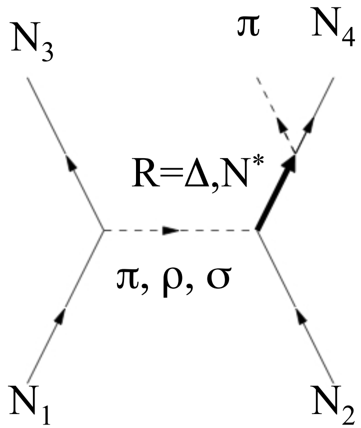


$$n(p,n)p$$

✧ Inelastic $N_2(N_1,N_3)N_4\pi$ &$N_2(N_1,N_3\pi)N_4$ processes

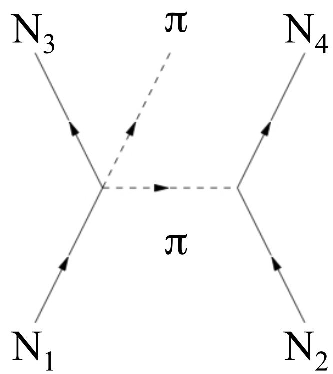


$$p(p,n)p\pi^+$$
$$n(p,n)p\pi^0$$
$$n(p,n)n\pi^+$$

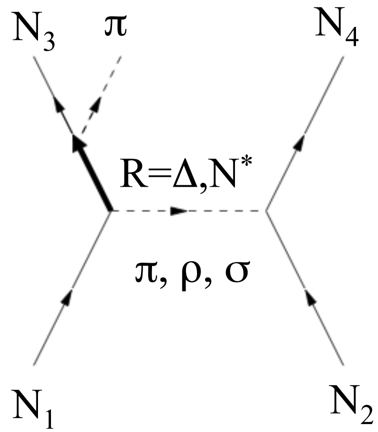


$$p(p,n)\Delta^{++} = p(p,n)p\pi^+$$
$$n(p,n)\Delta^+ = n(p,n)n\pi^+$$
$$n(p,n)\Delta^+ = n(p,n)p\pi^0$$

$$n(p,n)P_{11}^+ = n(p,n)n\pi^+$$
$$n(p,n)P_{11}^+ = n(p,n)p\pi^0$$



$$p(p,n\pi^+)p$$
$$n(p,n\pi^0)p$$
$$n(p,n\pi^+)n$$

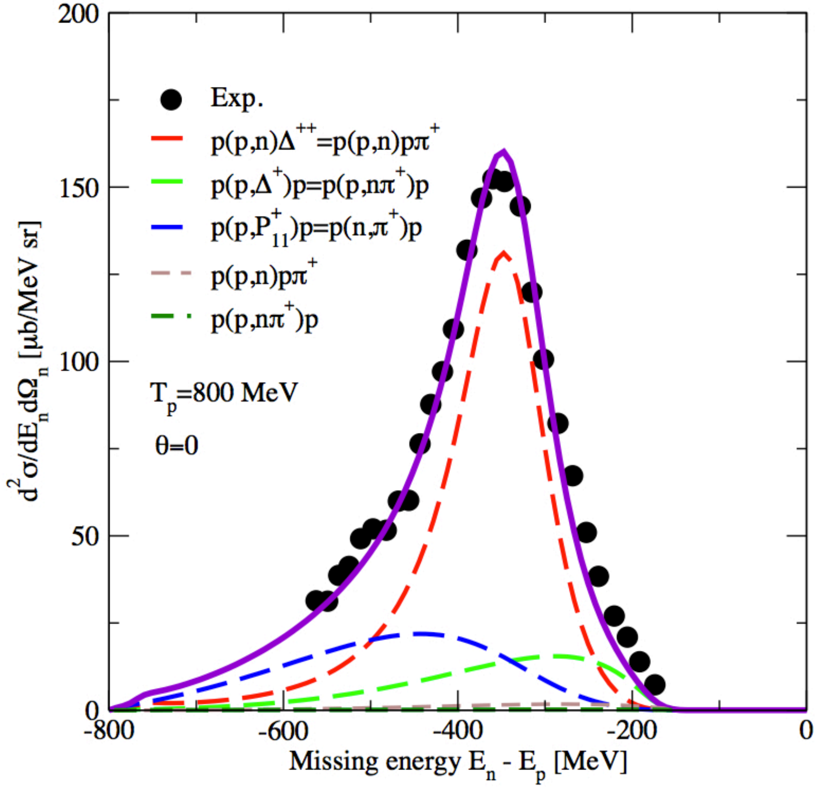


$$p(p,\Delta^+)p = p(p,n\pi^+)p$$
$$n(p,\Delta^+)n = n(p,n\pi^+)n$$
$$n(p,\Delta^0)p = n(p,n\pi^0)p$$

$$p(p,P_{11}^+)p = p(p,n\pi^+)p$$
$$n(p,P_{11}^+)n = n(p,n\pi^+)n$$
$$n(p,P_{11}^0)p = n(p,n\pi^0)p$$

Example: (p,n) reaction on a proton target

$$pp \rightarrow np\pi^+$$



- 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

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

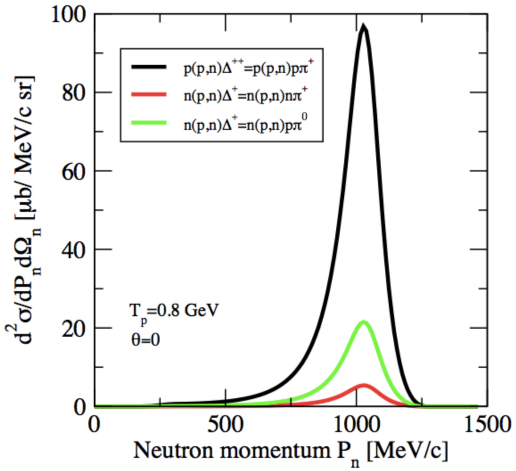
✧ Δ^+ & $P_{11}{}^+$ excitation in Projectile

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

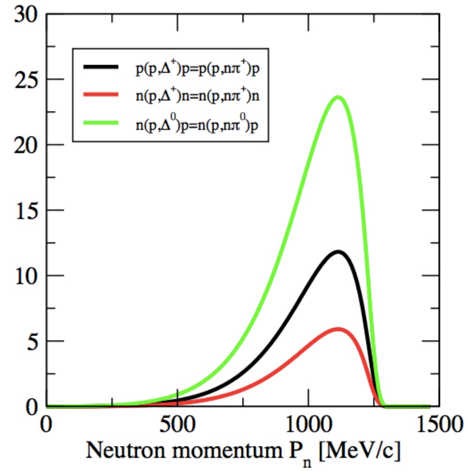
Elementary (p,n) cross sections

✧ Δ(1232) excitation

Excitation in Target

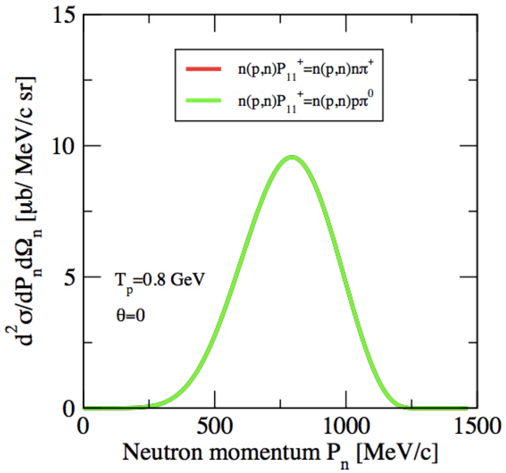


Excitation in Projectile

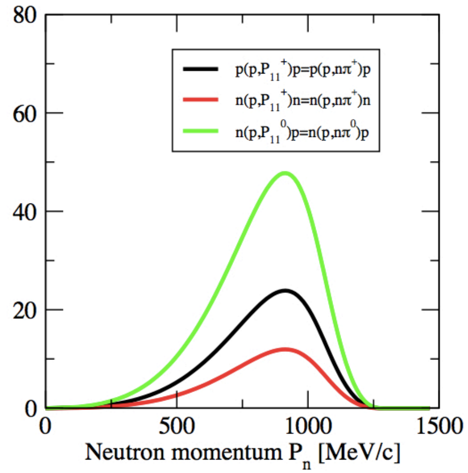


✧ N^*(1440) excitation

Excitation in Target



Excitation in Projectile



Different shape & strength of c.s.
→ shift reson. pos. in nuclei ?

✓ Reaction with a proton Target

- c.s. of Δ excitation in target ~ 9 times larger than c.s. of Δ excitation in projectile

✓ Reaction with a neutron Target

- similar strength of the c.s.

✓ Reaction with a proton Target

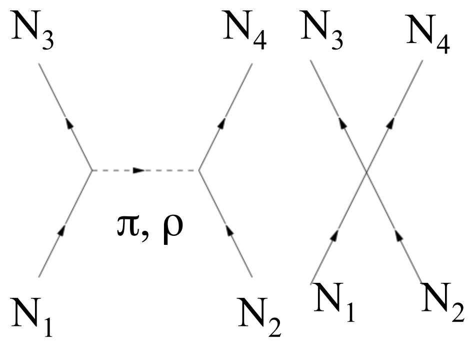
- P_{11}^+ excited only in Projectile

✓ Reaction with a neutron Target

- strength of c.s. for N^* excitation in projectile ~ 1 - 5 than of N^* in target

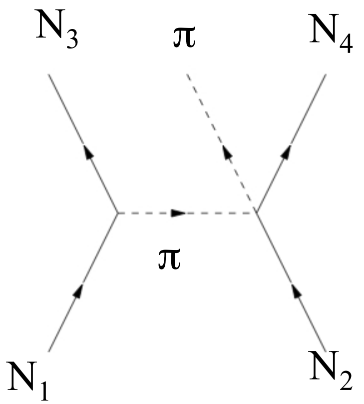
List of elementary (n,p) processes

✧ Elastic $N_2(N_1,N_3)N_4$ process

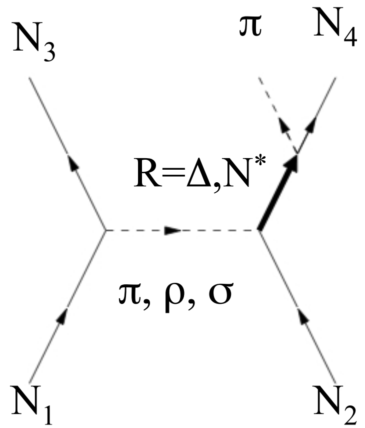


$$p(n,p)n$$

✧ Inelastic $N_2(N_1,N_3)N_4\pi$ & $N_2(N_1,N_3\pi)N_4$ processes

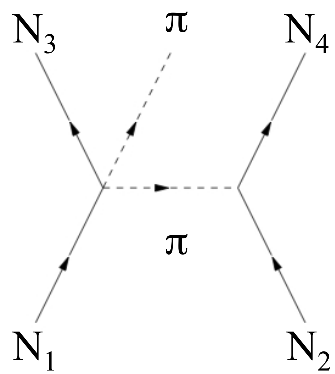


$$p(n,p)n\pi^0$$
$$p(n,p)p\pi^-$$
$$n(n,p)n\pi^-$$

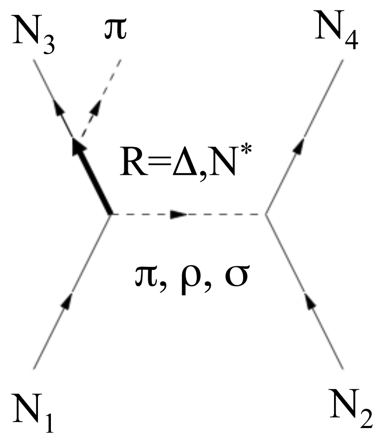


$$p(n,p)\Delta^0 = p(n,p)n\pi^0$$
$$p(n,p)\Delta^0 = p(n,p)p\pi^-$$
$$n(n,p)\Delta^- = n(n,p)n\pi^-$$

$$p(n,p)P_{11}^0 = p(n,p)n\pi^0$$
$$p(n,p)P_{11}^0 = p(n,p)p\pi^-$$



$$p(n,p\pi^0)n$$
$$p(n,p\pi^-)p$$
$$n(n,p\pi^-)n$$



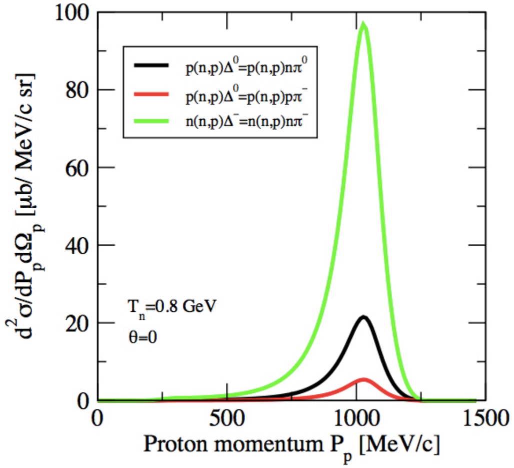
$$p(n,\Delta^0)p = p(n,p\pi^-)p$$
$$p(n,\Delta^+)n = p(n,p\pi^0)n$$
$$n(n,\Delta^0)n = n(n,p\pi^-)n$$

$$p(n,P_{11}^0)p = p(n,p\pi^-)p$$
$$p(n,P_{11}^+)n = p(n,p\pi^0)n$$
$$n(n,P_{11}^0)n = n(n,p\pi^-)n$$

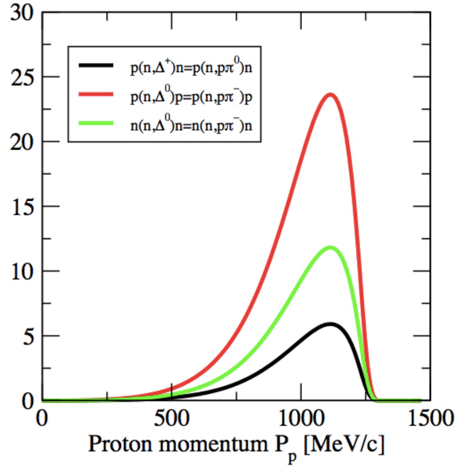
Elementary (n,p) cross sections

✧ Δ(1232) excitation

Excitation in Target



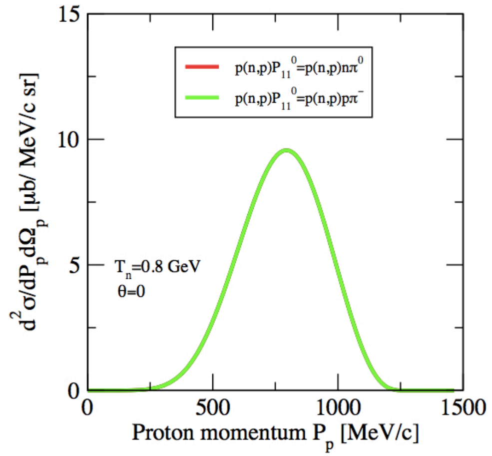
Excitation in Projectile



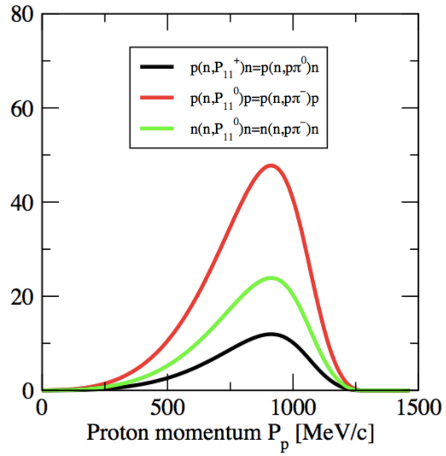
- ✓ Reaction with a proton Target
  - similar strength of the c.s.
- ✓ Reaction with a neutron Target
  - c.s. of Δ excitation in target ~ 9 times larger than c.s. of Δ excitation in projectile

✧ N^*(1440) excitation

Excitation in Target



Excitation in Projectile



- ✓ 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 ~ 1 - 5 than of N^* in target

Number of elementary processes N_{N1N2}

$$N_{N_1N_2} = \int d^2\vec{b}\,\rho^{N_1N_2}_{overlap}(b)\left[1 - T(b)\right]P_\pi(b)$$

- ✧ N_1N_2 density of overlap region

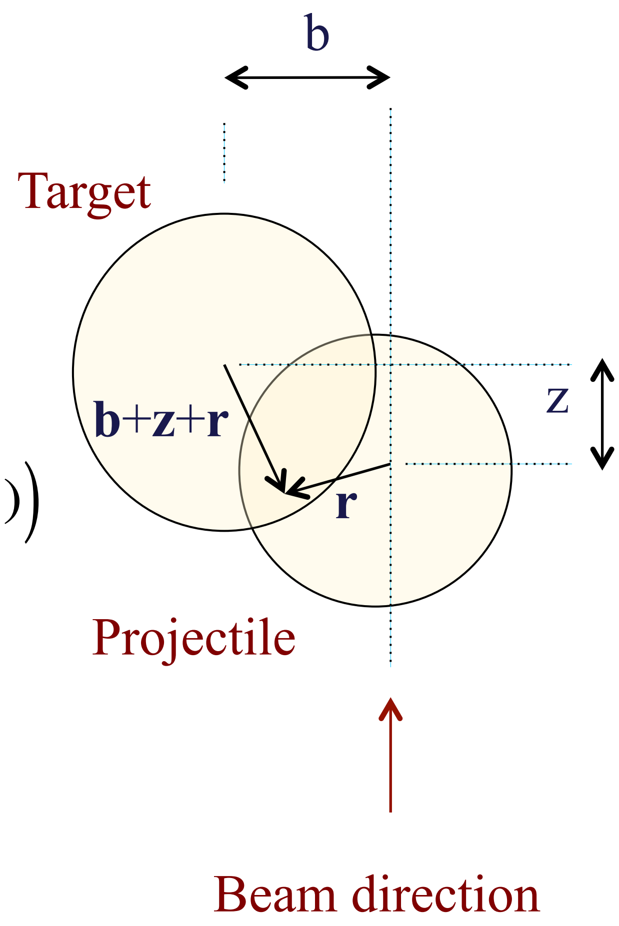
$$\rho^{N_1N_2}_{overlap}(b) = \int dz \int d^3\vec{r}\,\rho^{N_1}_P(\vec{r})\rho^{N_2}_T(\vec{b}+\vec{z}+\vec{r})$$

- ✧ Transmission function

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

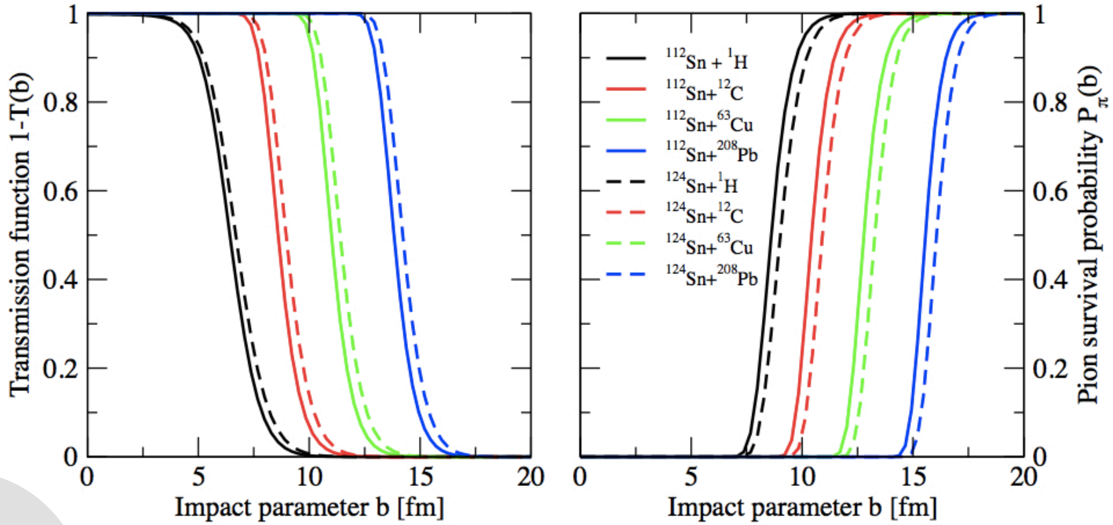
- ✧ Pion survival probability

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



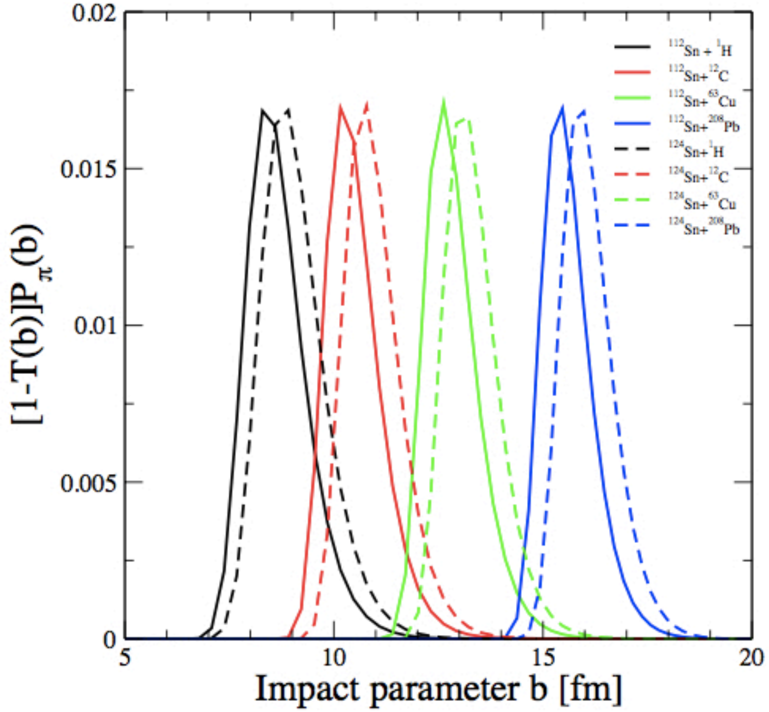
N.B. Density distributions from RMF or SHF calculations

Peripheral character of the reaction



The reaction is peripheral

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



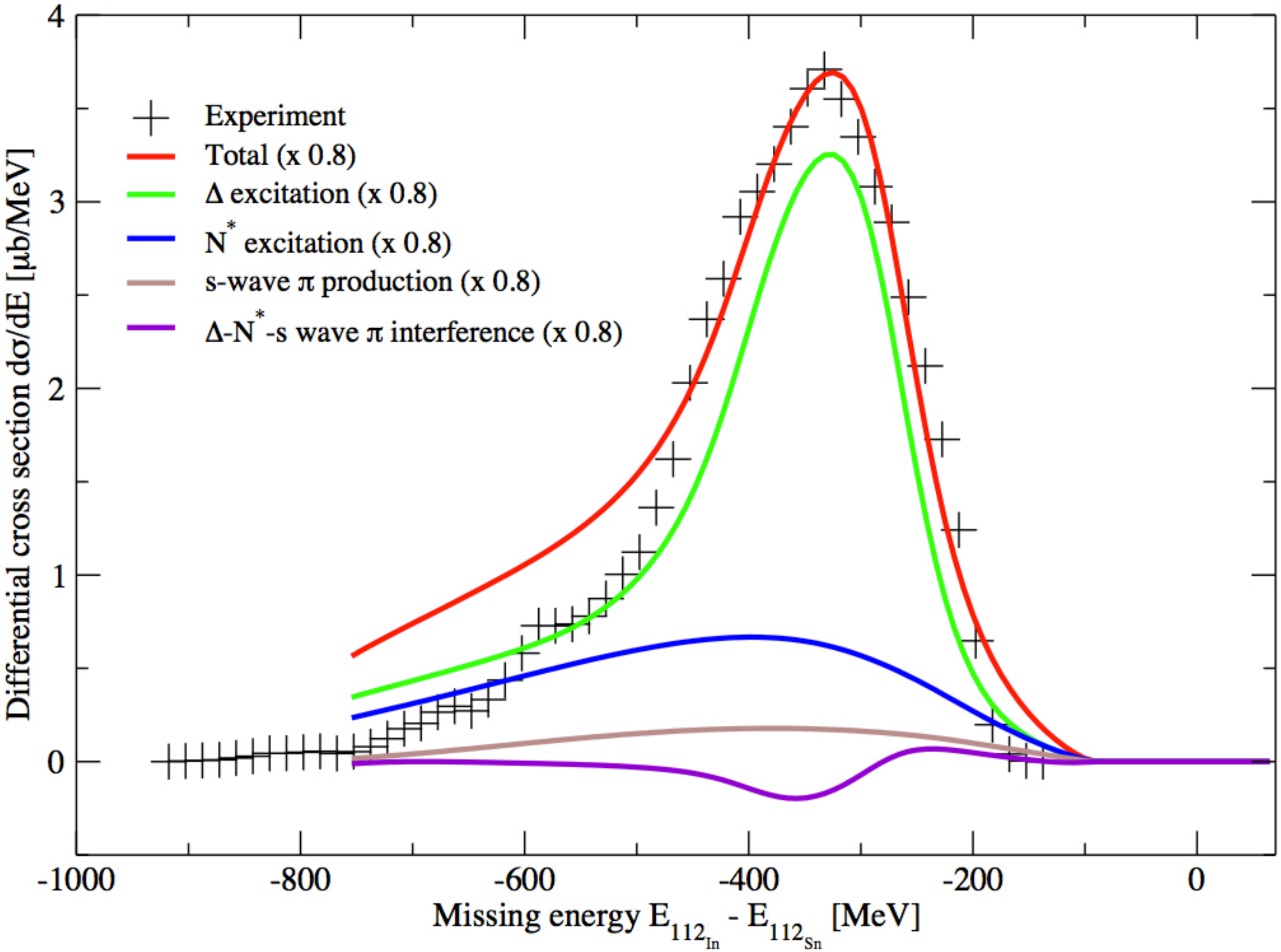
Number of elementary processes N_{N1N2}

$$N_{N_1N_2} = \int d^2\vec{b}\,\rho^{N_1N_2}_{overlap}(b)\left[1-T(b)\right]P_\pi(b),\quad \rho^{N_1N_2}_{overlap}(b) = \int dz \int d^3\vec{r}\,\rho^{N_1}_P(\vec{r})\rho^{N_2}_T(\vec{b}+\vec{z}+\vec{r})$$

reaction	N_R	N_{pp}	N_{pn}	N_{np}	N_{nn}
^{112}Sn+^{1}H	0.017	0.006	0	0.011	0
^{112}Sn+^{12}C	0.019	0.003	0.003	0.007	0.006
^{112}Sn+^{63}Cu	0.022	0.003	0.004	0.006	0.009
^{112}Sn+^{208}Pb	0.027	0.001	0.007	0.004	0.015

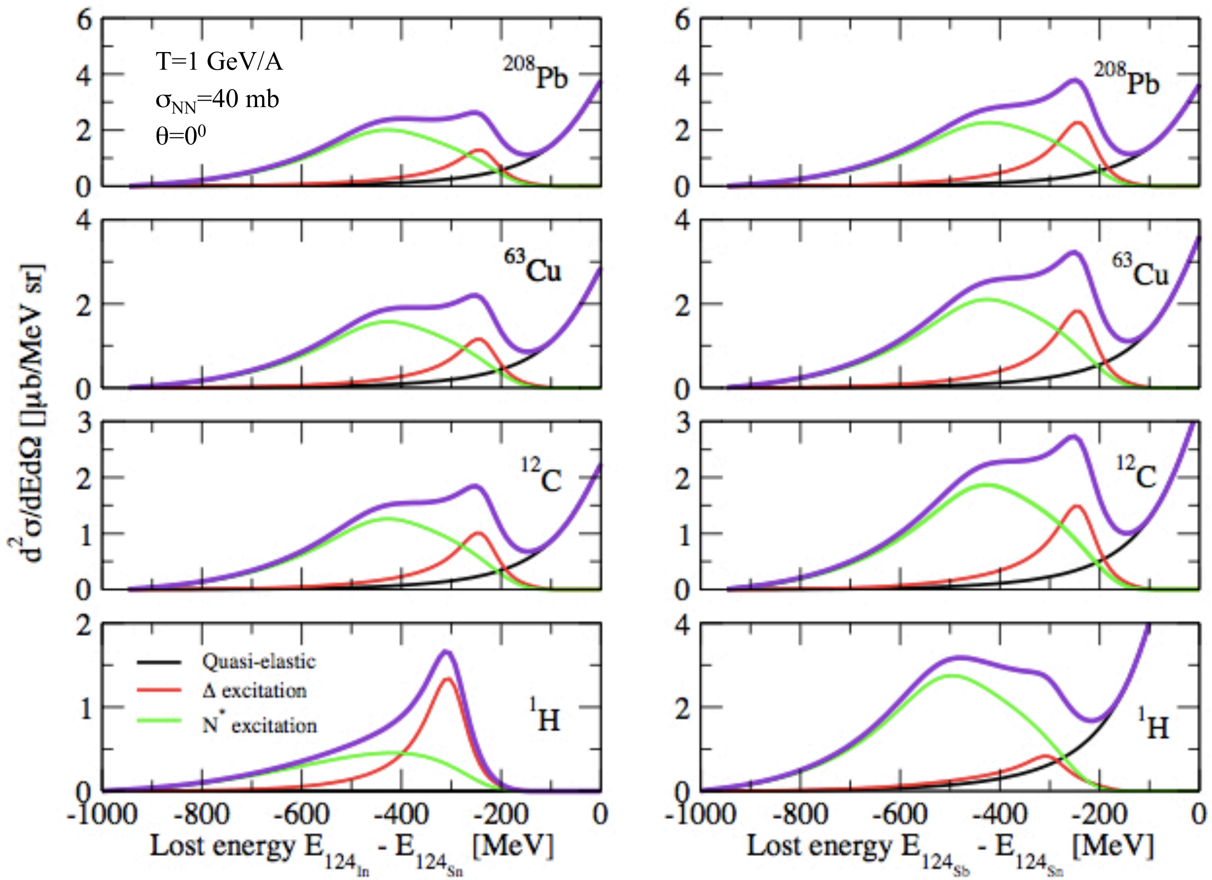
reaction	N_R	N_{pp}	N_{pn}	N_{np}	N_{nn}
^{124}Sn+^{1}H	0.019	0.004	0	0.015	0
^{124}Sn+^{12}C	0.023	0.002	0.002	0.010	0.009
^{124}Sn+^{63}Cu	0.024	0.001	0.002	0.009	0.010
^{124}Sn+^{208}Pb	0.029	0.0006	0.003	0.005	0.020

The (^{112}Sn,^{112}In) reaction on a proton target at 1 GeV/nucleon



Origin of the shift of the Δ peak

$(^{124}Sn, ^{124}In)$ $(^{124}Sn, ^{124}Sb)$



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

NO: in-medium (density) modification of Δ & N^* properties because the reaction is very peripheral & density is small

YES: excitation mechanisms of Δ (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

(n,p) channel	(p,n) channel
$\left({}^{A}Z, {}^{A}(Z+1)\right)$	$\left({}^{A}Z, {}^{A}(Z-1)\right)$

Consider the ratio $$R = \frac{\sigma_{({}^{A}Z,{}^{A}(Z+1))}}{\sigma_{({}^{A}Z,{}^{A}(Z-1))}}$$

In the model
$$R = \frac{\sigma_{nn\to pn\pi^-} N_{nn} + \sigma_{np\to pp\pi^-} N_{np} + \sigma_{np\to pn\pi^0} N_{np}}{\sigma_{pp\to np\pi^+} N_{pp} + \sigma_{pn\to nn\pi^+} N_{pn} + \sigma_{pn\to np\pi^0} N_{pn}}$$
$$\approx \frac{N_n^{(P)}}{N_p^{(P)}} \times \left(\frac{\sigma_{nn\to pn\pi^-} N_n^{(T)} + \sigma_{np\to pp\pi^-} N_p^{(T)} + \sigma_{np\to pn\pi^0} N_p^{(T)}}{\sigma_{pp\to np\pi^+} N_p^{(T)} + \sigma_{pn\to nn\pi^+} N_n^{(T)} + \sigma_{pn\to np\pi^0} N_n^{(T)}} \right)$$

This suggest $\longrightarrow$ $$\frac{N_n^{(P)}}{N_p^{(P)}} \propto f\left(N_n^{(T)}, N_p^{(T)}\right) R$$

How to disentangle ?. With exclusive measurements ?

Exclusive measurements & isospin content of the projectile tail

(n,p) channel

$$(1):\ {}^{A}Z + X \to {}^{A}(Z+1) + \pi^{-} + X'$$

$$(2):\ {}^{A}Z + X \to {}^{A}(Z+1) + \pi^{0} + X''$$

(p,n) channel

$$(3):\ {}^{A}Z + X \to {}^{A}(Z-1) + \pi^{+} + \tilde{X}$$

$$(4):\ {}^{A}Z + X \to {}^{A}(Z-1) + \pi^{0} + \tilde{X}''$$

Consider the ratios $R_1 = \dfrac{\sigma^{(1)}_{({}^{A}Z,{}^{A}(Z+1))}}{\sigma^{(3)}_{({}^{A}Z,{}^{A}(Z-1))}},\quad R_2 = \dfrac{\sigma^{(2)}_{({}^{A}Z,{}^{A}(Z+1))}}{\sigma^{(4)}_{({}^{A}Z,{}^{A}(Z-1))}}$

In the model

$$R_1 = \frac{\sigma_{nn\to pn\pi^-} N_{nn} + \sigma_{np\to pp\pi^-} N_{np}}{\sigma_{pp\to np\pi^+} N_{pp} + \sigma_{pn\to nn\pi^+} N_{pn}} \approx \frac{N_n^{(P)}}{N_p^{(P)}} \times \left(\frac{\sigma_{nn\to pn\pi^-} N_n^{(T)} + \sigma_{np\to pp\pi^-} N_p^{(T)}}{\sigma_{pp\to np\pi^+} N_p^{(T)} + \sigma_{pn\to nn\pi^+} N_n^{(T)}} \right)$$

$$R_2 = \frac{\sigma_{np\to pn\pi^0} N_{np}}{\sigma_{pn\to np\pi^0} N_{pn}} \approx \frac{N_n^{(P)}}{N_p^{(P)}} \times \left(\frac{\sigma_{np\to pn\pi^0} N_p^{(T)}}{\sigma_{pn\to np\pi^0} N_n^{(T)}} \right)$$

Seems as entangled as before !!

This suggest $\longrightarrow$ $\dfrac{N_n^{(P)}}{N_p^{(P)}} \propto f(N_n^{(T)}, N_p^{(T)}) R_1,\quad \dfrac{N_n^{(P)}}{N_p^{(P)}} \propto g(N_n^{(T)}, N_p^{(T)}) R_2$

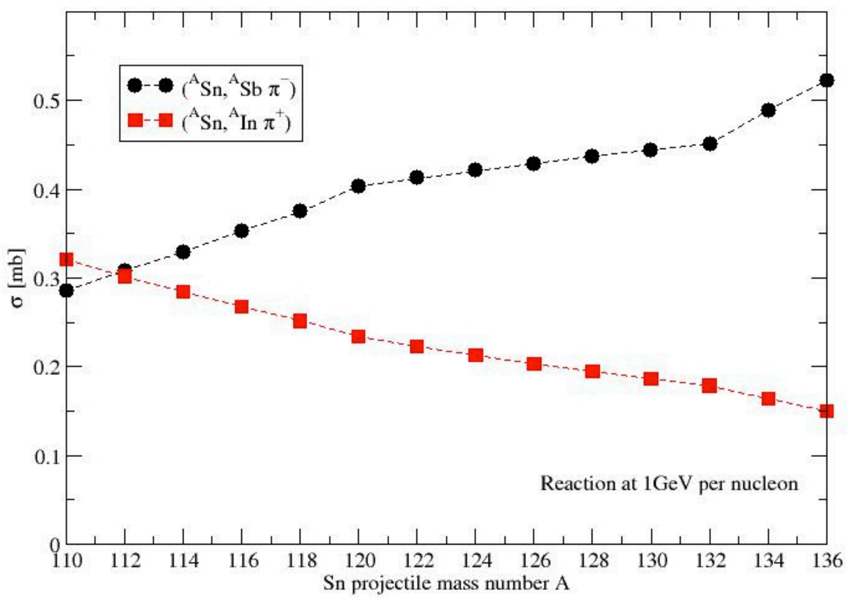
The cleanest case: measurements with a proton target

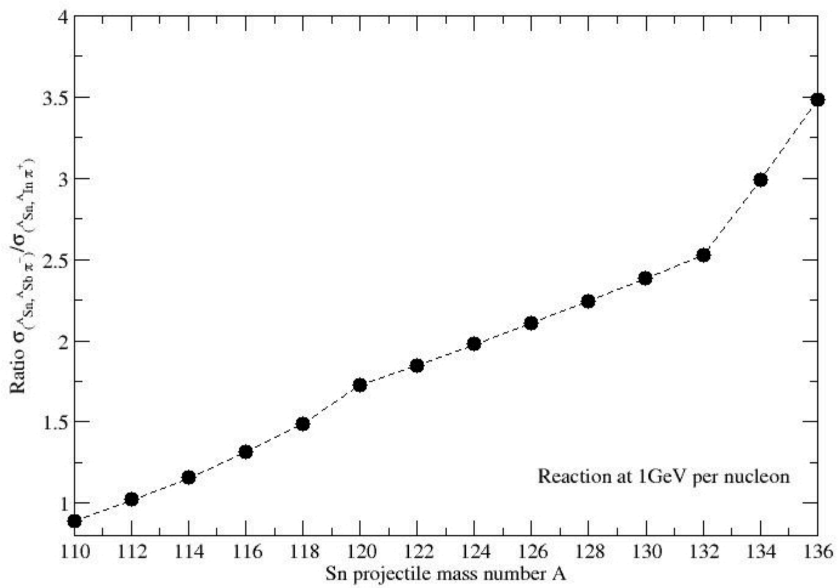
In this case we can consider just one ratio

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

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

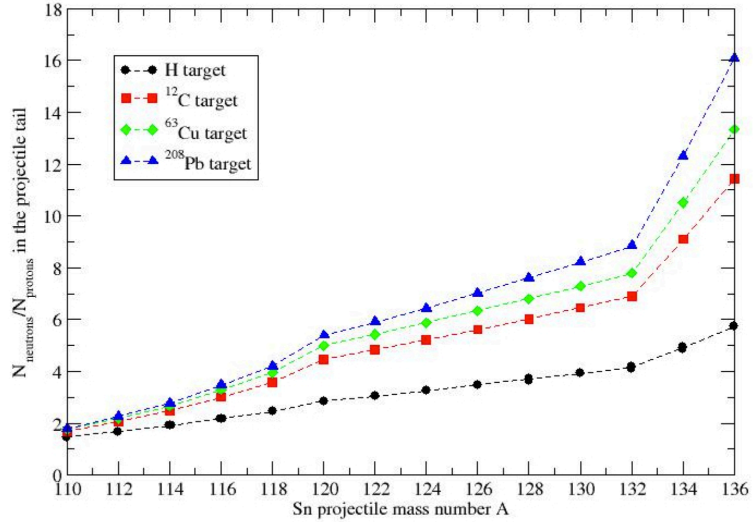
in this case $\longrightarrow$ $\dfrac{N_n^{(P)}}{N_p^{(P)}} \propto R_1$

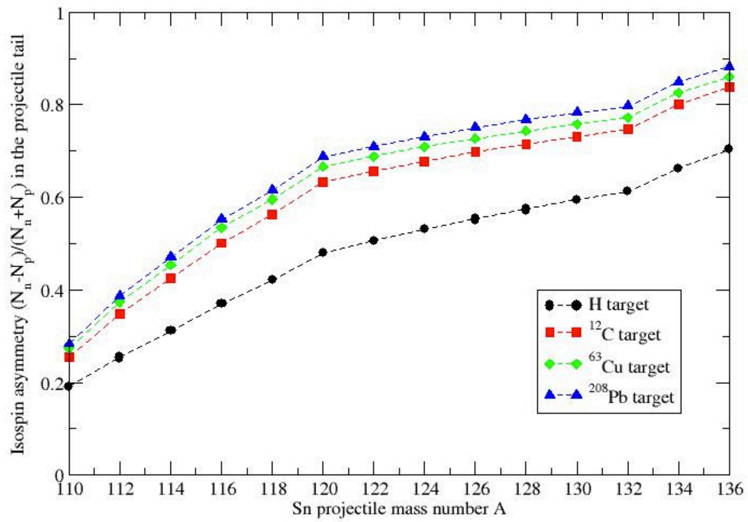




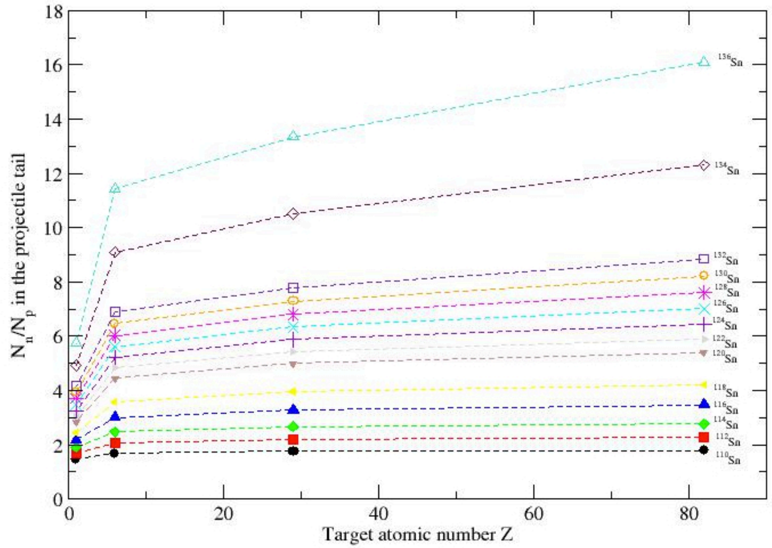
Isospin content of the projectile: model estimations

✧ Projectile mass number dependence





✧ Target atomic number dependence



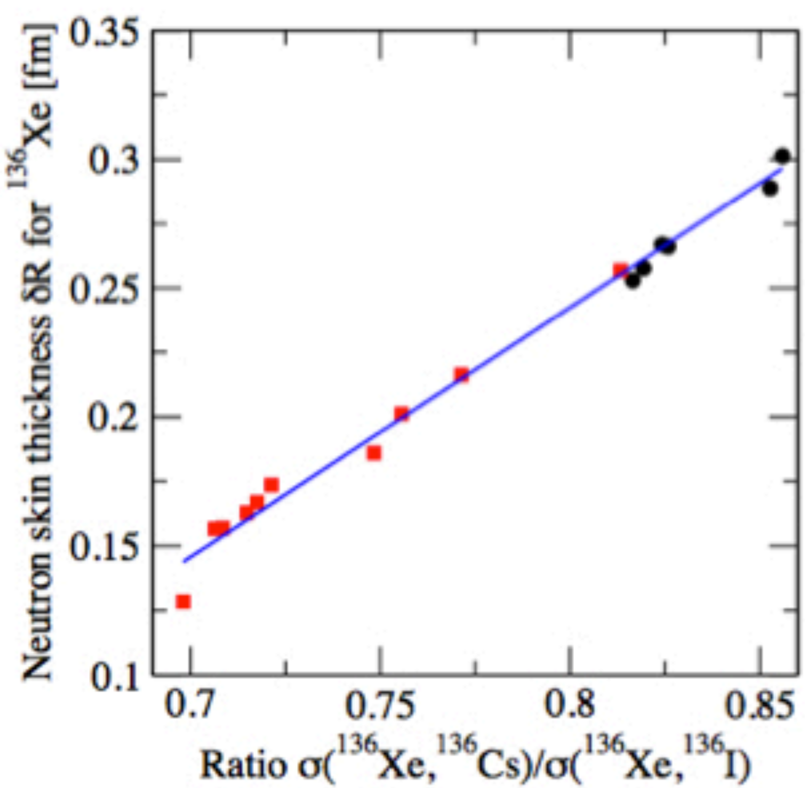
Neutron Skin Thickness & Symmetry Energy

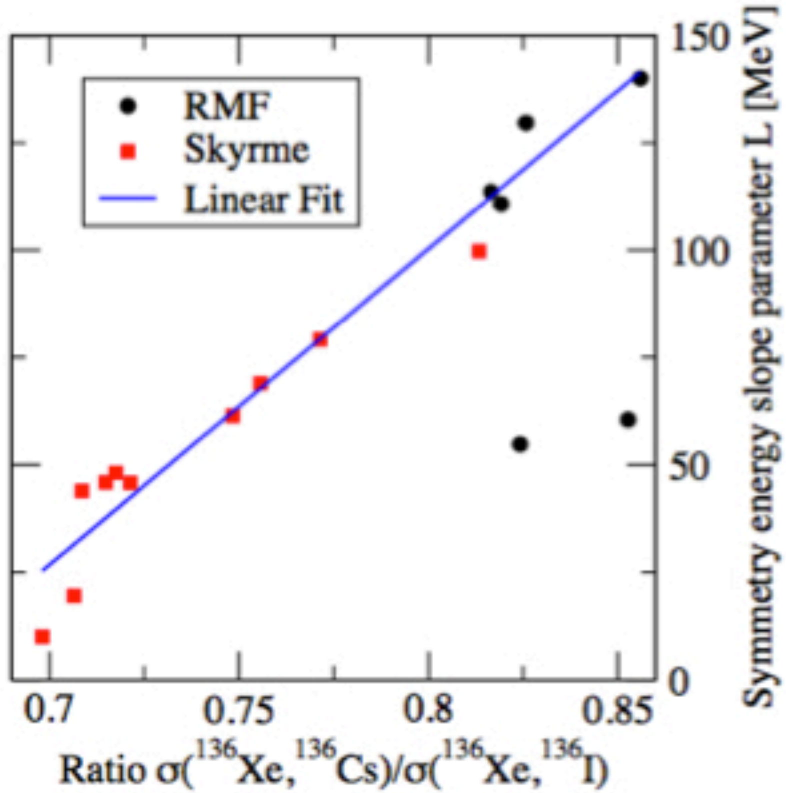
Accurate measurements of

$$R = \frac{\sigma_{({}^{A}Z,\,{}^{A}(Z+1))}}{\sigma_{({}^{A}Z,\,{}^{A}(Z-1))}}$$

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

^{136}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

<u>Experiment</u>

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

<u>Theory</u>

- 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 …