Excitation of Nucleon Resonances in Isobaric Charge Exchange Reactions

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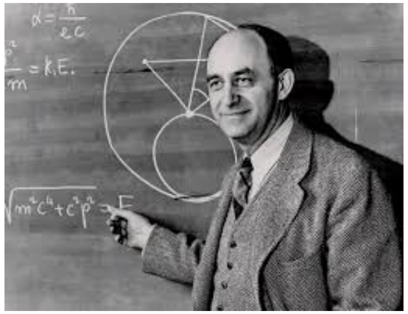
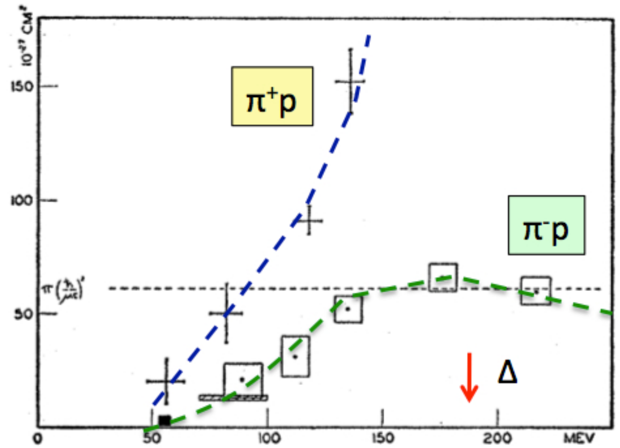
First observation of the Δ(1232) & the Roper $N^{*}(1440)$

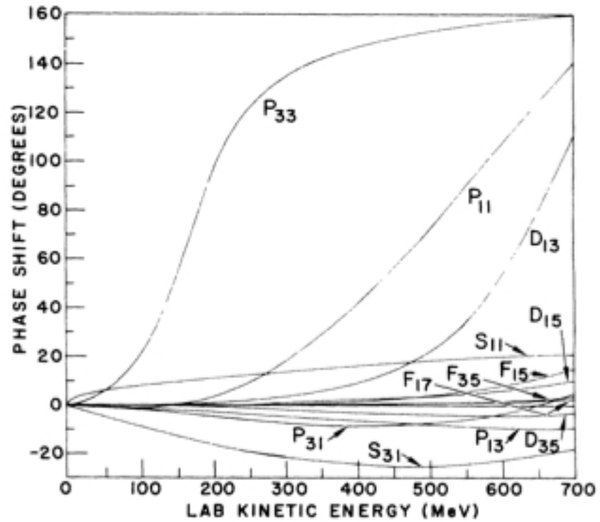


✧ In 1952 Fermi *et al.*, observed the Δ(1232) for the first time in πp scattering



Phys. Rev. 85, 932 (1952)

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

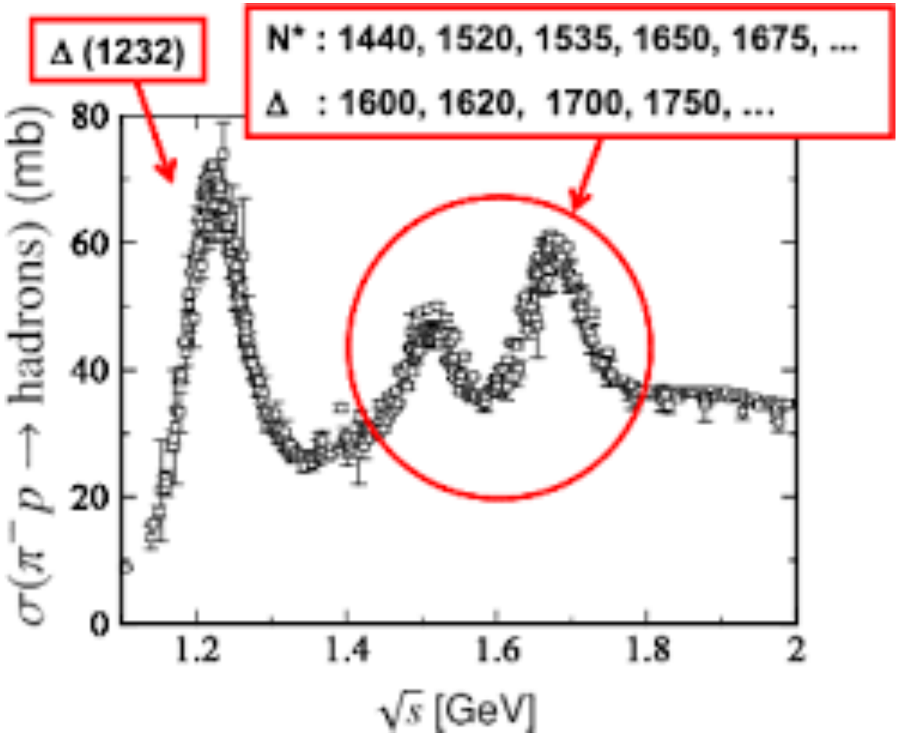


Phys. Rev. Lett. 12, 340 (1964)

Since them many nucleon resonances have been discovered in

- πN elastic scattering
- $\pi N \longrightarrow \eta N, \sigma N, \omega N, \Lambda K, \Sigma K, \rho N, \pi\Delta$ reactions
- Electroproduction γN
- More complex processes like e.g., $\pi N \longrightarrow \pi\pi N, \pi\rho N, \omega N, \phi N, K^*Y, \ldots$

$\pi N \longrightarrow X$ cross section



2015 status of the Δ & N resonances

22 Δ resonances known with masses from 1232 to 2950 MeV

Particle J^P	Status overall	πN	γN	Status as seen in — $N\eta$	$N\sigma$	$N\omega$	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.

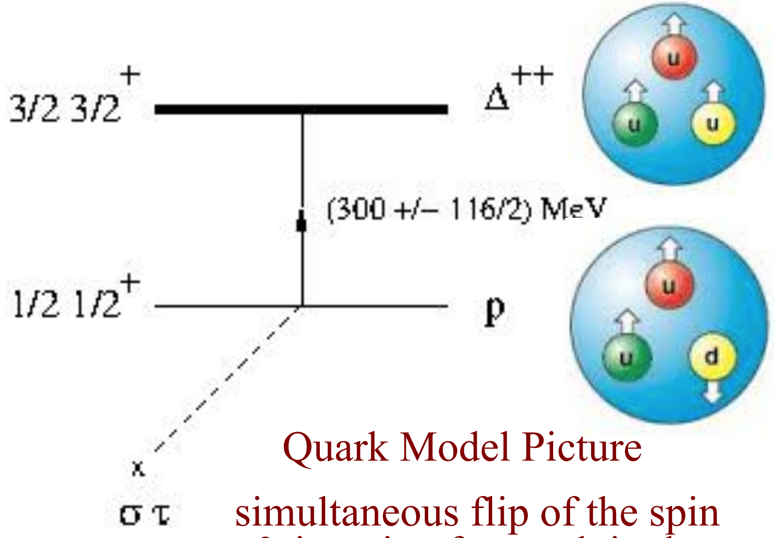
26 N resonances known with masses from 1440 to 2700 MeV

Particle J^P	Status overall	πN	γN	Status as seen in — $N\eta$	$N\sigma$	$N\omega$	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)

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

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:

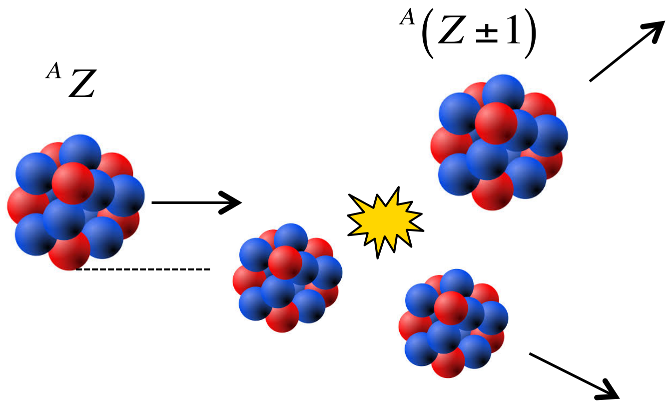
- ✧ Pure Quark Model: radial excitation of the nucleon $(qqq)^*$
- ✧ Hybrid model: N*(1440) as a qqqG state
- ✧ Dual nature of N*(1440) as a qqq & $qqqq\bar{q}$ states
- ✧ N*(1440) as a collective excitation
- ✧ Coupled-channel (πN, σN, πΔ, ρN) meson exchange description of the N*(1440) structure. No qqq component at all.
- ✧ Lattice QCD

Is the study of nucleon resonances still interesting ?

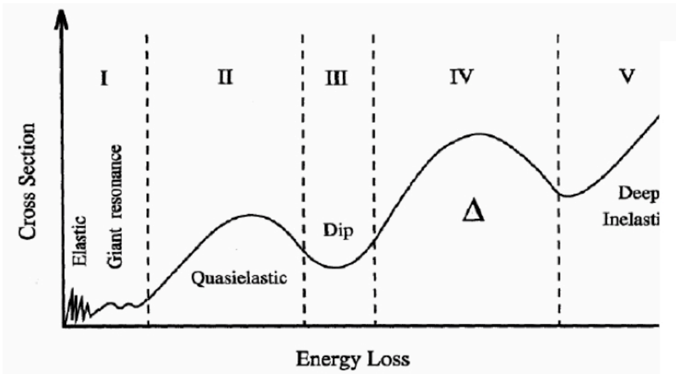
After more than 60 years studying nucleon resonances one could think that not, but … determining in-medium (density & isospin dependence) properties of nucleon resonances is essential for a better understanding of …

- ✧ the underlying dynamics governing many nuclear reactions
- ✧ not yet solved quenching problem of the GT strength
- ✧ three-nucleon force mechanisms
- ✧ EoS of asymmetric nuclear matter (neutron stars)
- ✧ their effect on relativistic heavy ion collisions
- ✧ …

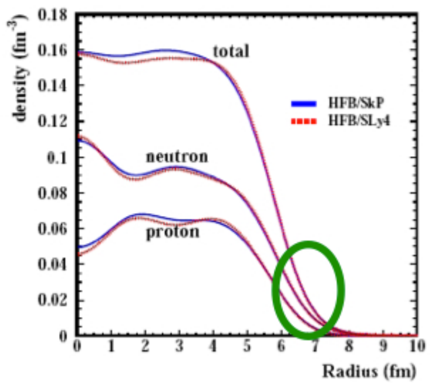
Isobar Charge Exchange Reactions



- 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

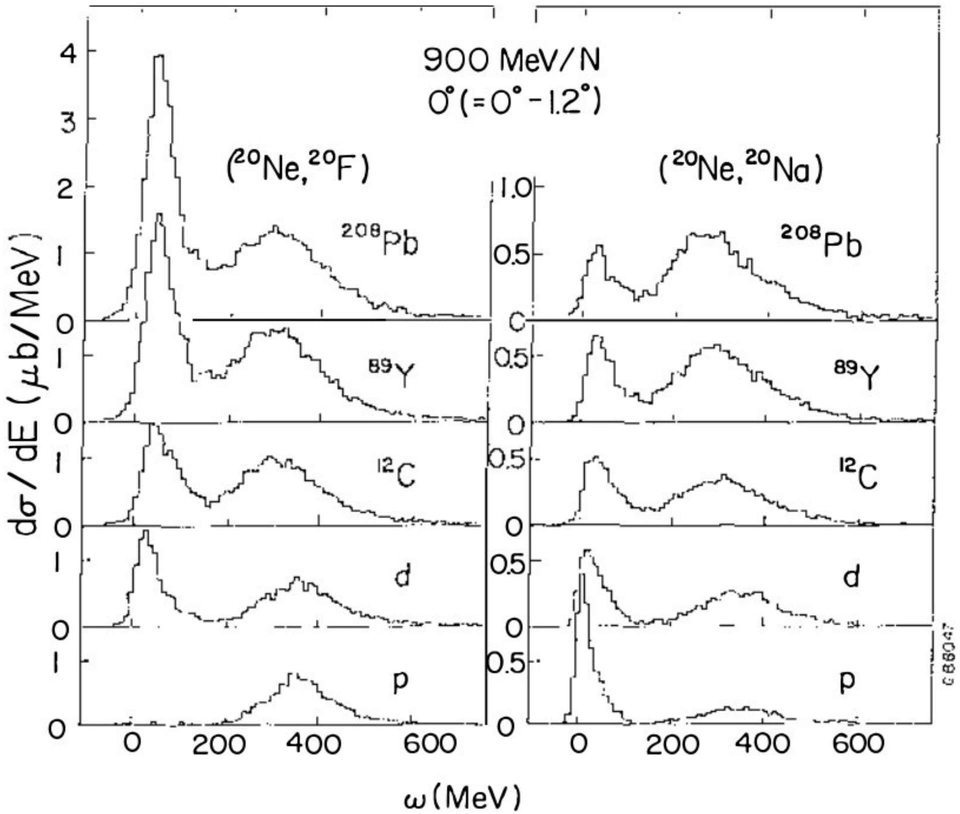


Are important tools to study the spin-isospin dependence of the nuclear force

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



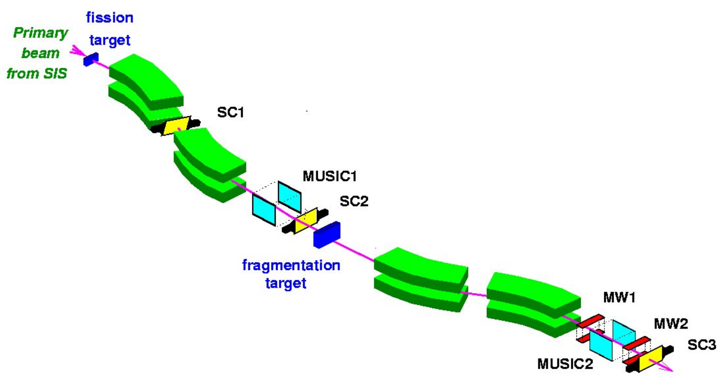
Shift of the Δ peak to lower energies for medium & heavy targets

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



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

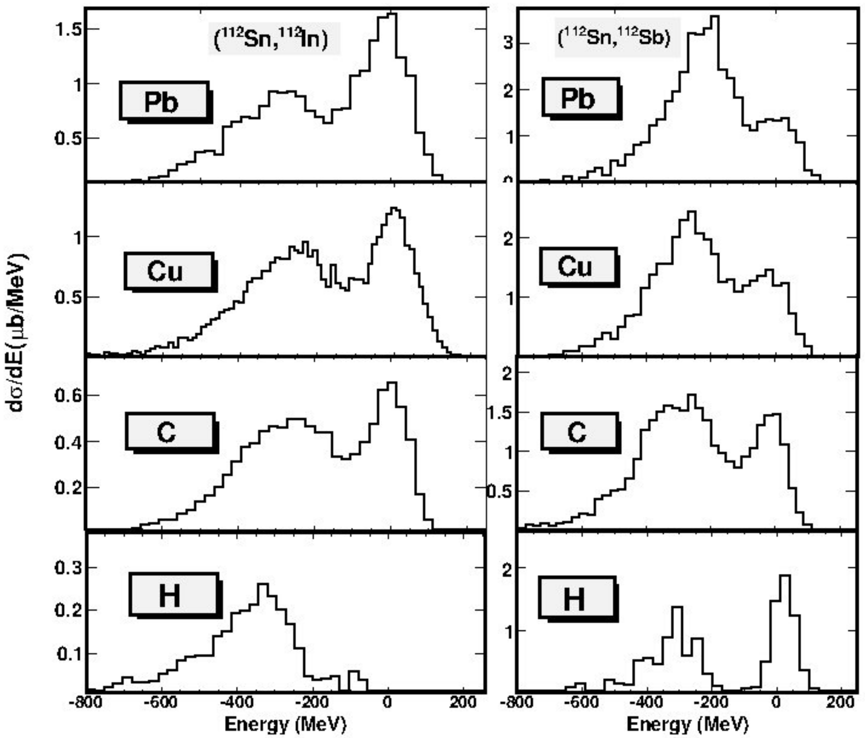
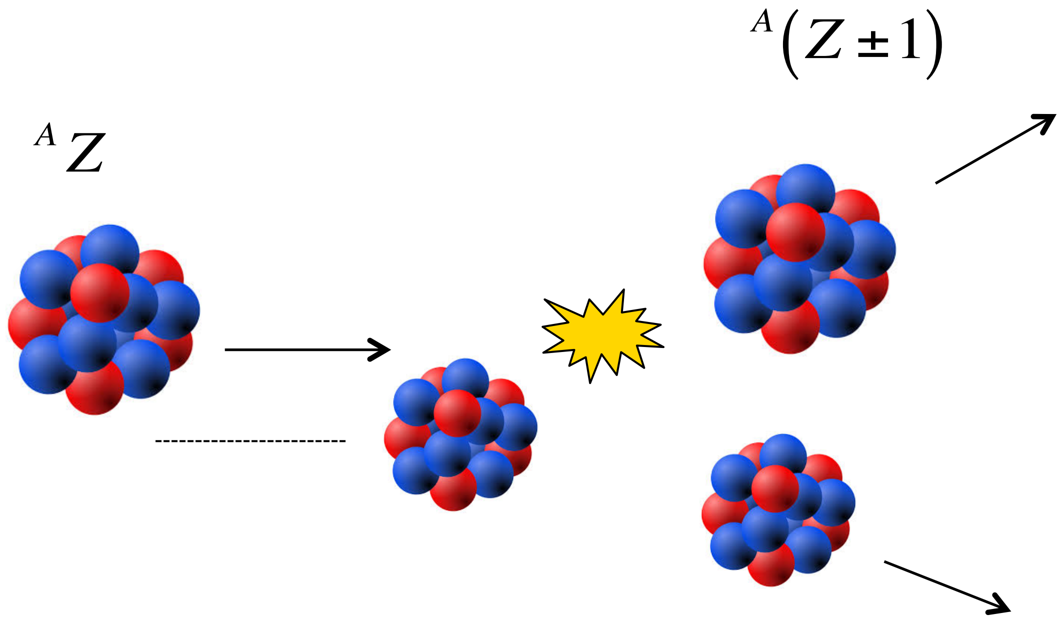


Figure courtesy of J. Benlliure & J. W. Vargas

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

Model for the reaction



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

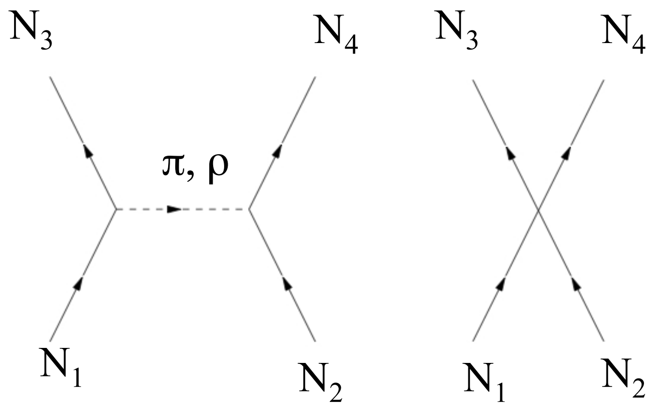
Differential cross section calculated as

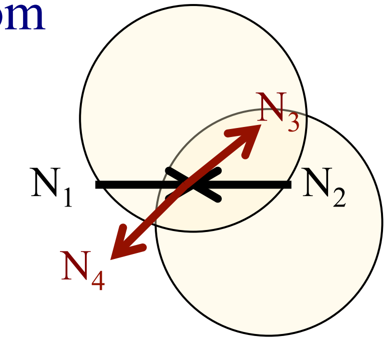
$$\frac{d\sigma}{dE} = (\text{Elem. proc. cross sec.}) \times (\text{Av. numb. of participants}) \times (\text{Nuclear Response})$$

Elementary Processes

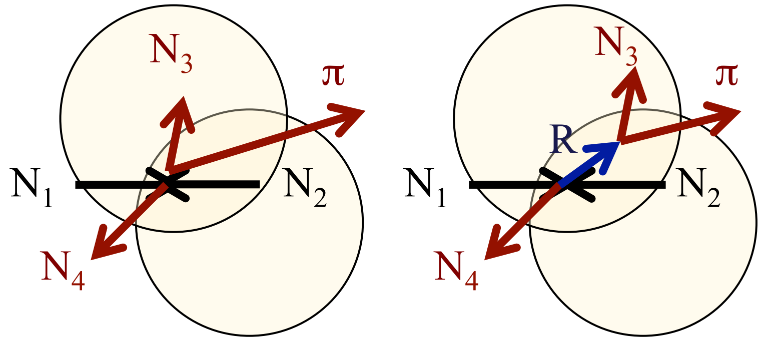
Model includes Direct + Exchange contributions from

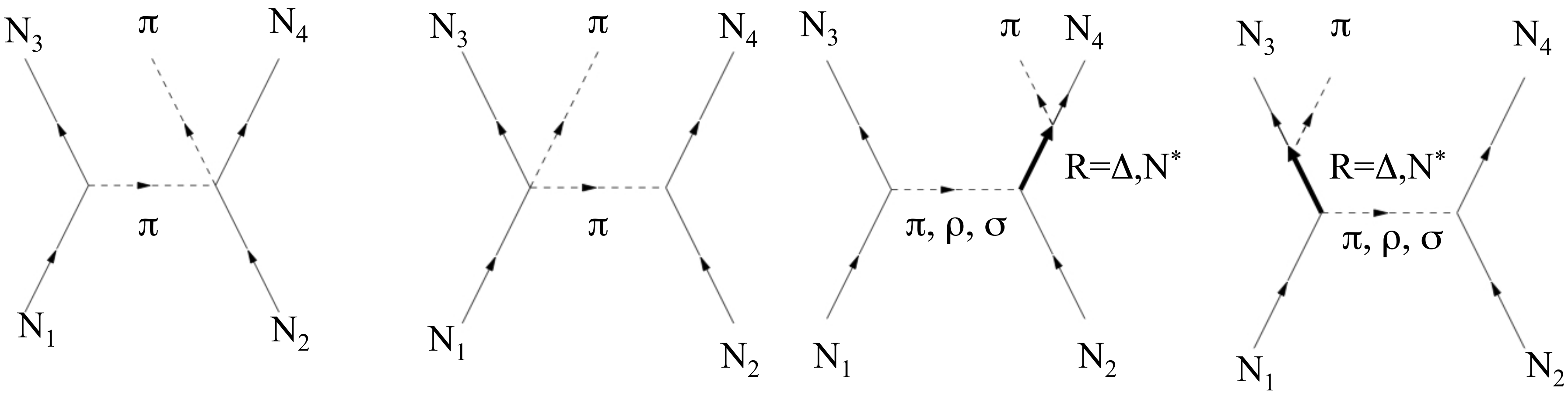
✧ Elastic NN ⟶ NN processes





✧ Inelastic NN ⟶ NNπ processes



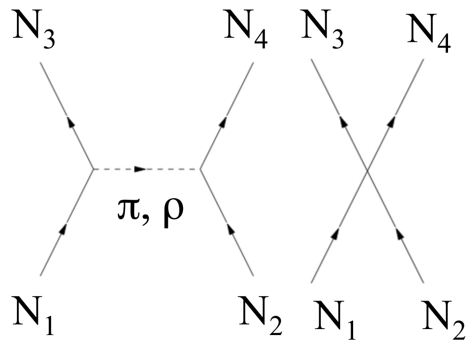


s-wave π production

p-wave (resonance pole) π production

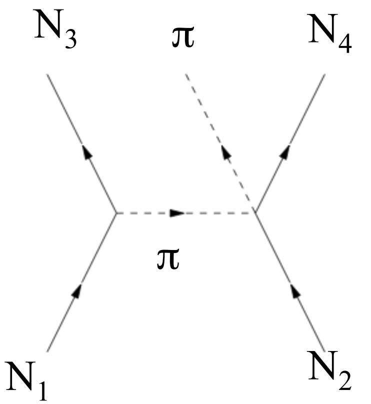
Elementary processes contributing to $({}^{A}Z, {}^{A}(Z-1))$

- ✧ Elastic $N_2(N_1,N_3)N_4$ process

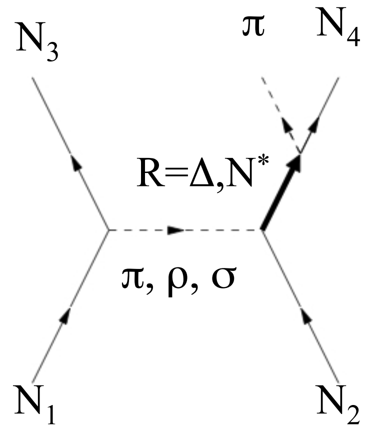


$$n(p,n)p$$

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

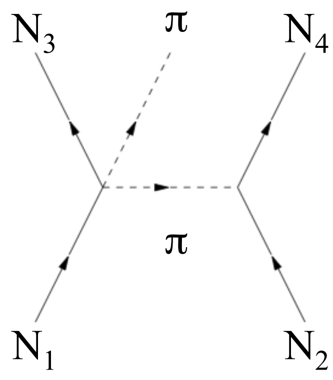


$$p(p,n)p\pi^{+}$$
$$n(p,n)p\pi^{0}$$
$$n(p,n)n\pi^{+}$$

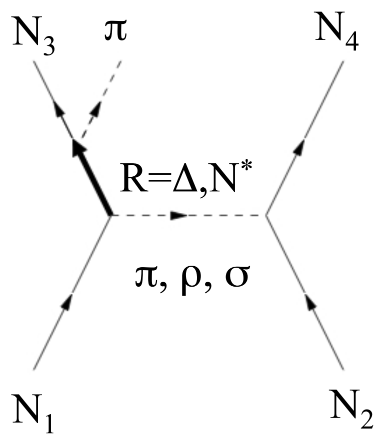


$$p(p,n)\Delta^{++} = p(p,n)p\pi^{+}$$
$$n(p,n)\Delta^{+} = n(p,n)n\pi^{+}$$
$$n(p,n)\Delta^{+} = n(p,n)p\pi^{0}$$

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



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

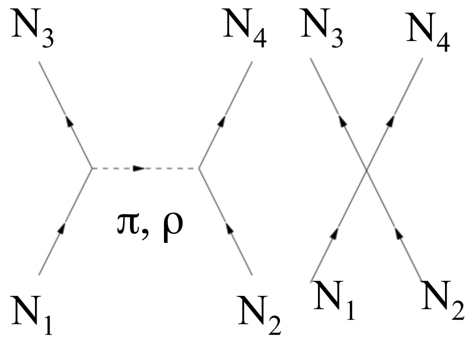


$$p(p,\Delta^{+})p = p(p,n\pi^{+})p$$
$$n(p,\Delta^{+})n = n(p,n\pi^{+})n$$
$$n(p,\Delta^{0})p = n(p,n\pi^{0})p$$

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

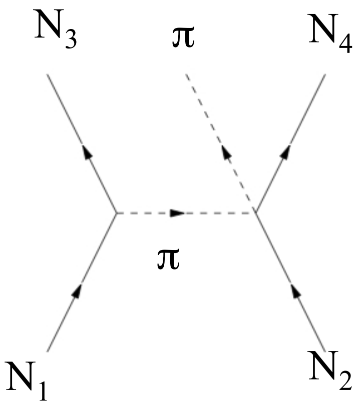
Elementary processes contributing to $({}^{A}Z, {}^{A}(Z+1))$

✧ Elastic $N_2(N_1,N_3)N_4$ process

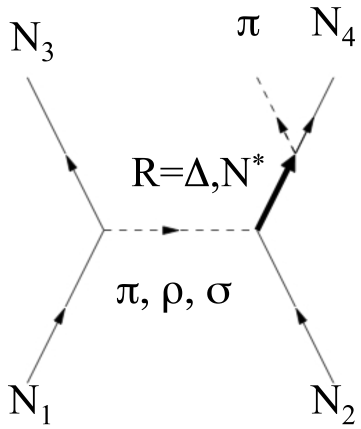


$$p(n,p)n$$

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

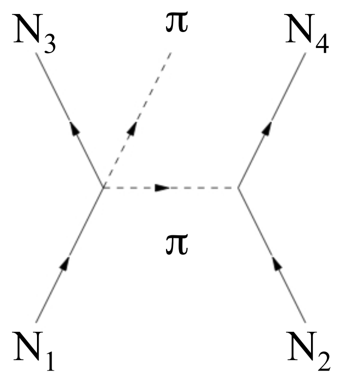


$$p(n,p)n\pi^0$$
$$p(n,p)p\pi^-$$
$$n(n,p)n\pi^-$$

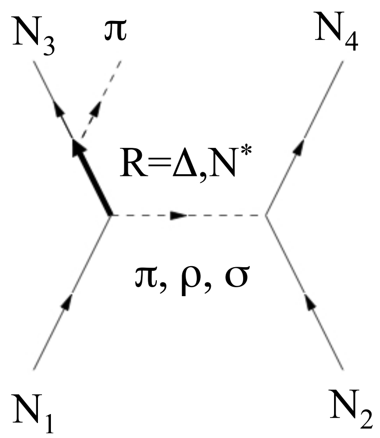


$$p(n,p)\Delta^0 = p(n,p)n\pi^0$$
$$p(n,p)\Delta^0 = p(n,p)p\pi^-$$
$$n(n,p)\Delta^- = n(n,p)n\pi^-$$

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



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



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

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

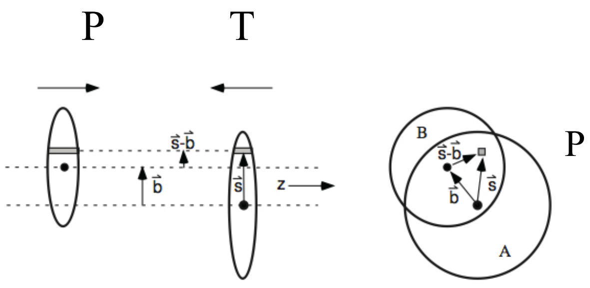
Average Number of Participants

$$\langle N_p^{(P)} \rangle = Z_P \frac{\sigma_T}{\sigma_{PT}}, \quad \langle N_n^{(P)} \rangle = (A_P - Z_P)\frac{\sigma_T}{\sigma_{PT}}, \quad \langle N_p^{(T)} \rangle = Z_T \frac{\sigma_P}{\sigma_{PT}}, \quad \langle N_n^{(T)} \rangle = (A_T - Z_T)\frac{\sigma_P}{\sigma_{PT}}$$

$$\sigma_{P(T)} = \int d\vec{b}\left(1-\left(1-T_{P(T)}(b)\sigma_{NN}\right)^{A_{P(T)}}\right), \quad \sigma_{PT} = \int d\vec{b}\left(1-\left(1-T_{PT}(b)\sigma_{NN}\right)^{A_P A_T}\right)$$

nucleon-nucleus total cross section

nucleus-nucleus total cross section



a) Side View

b) Beam-line View

Probability/area of a given nucleon being located in the projectile/target flux tube

$$T_P(|\vec{s}-\vec{b}|) = \int \rho_P(|\vec{s}-\vec{b}|, z_P)\, dz_P$$

$$T_T(s) = \int \rho_T(s, z_T)\, dz_T$$

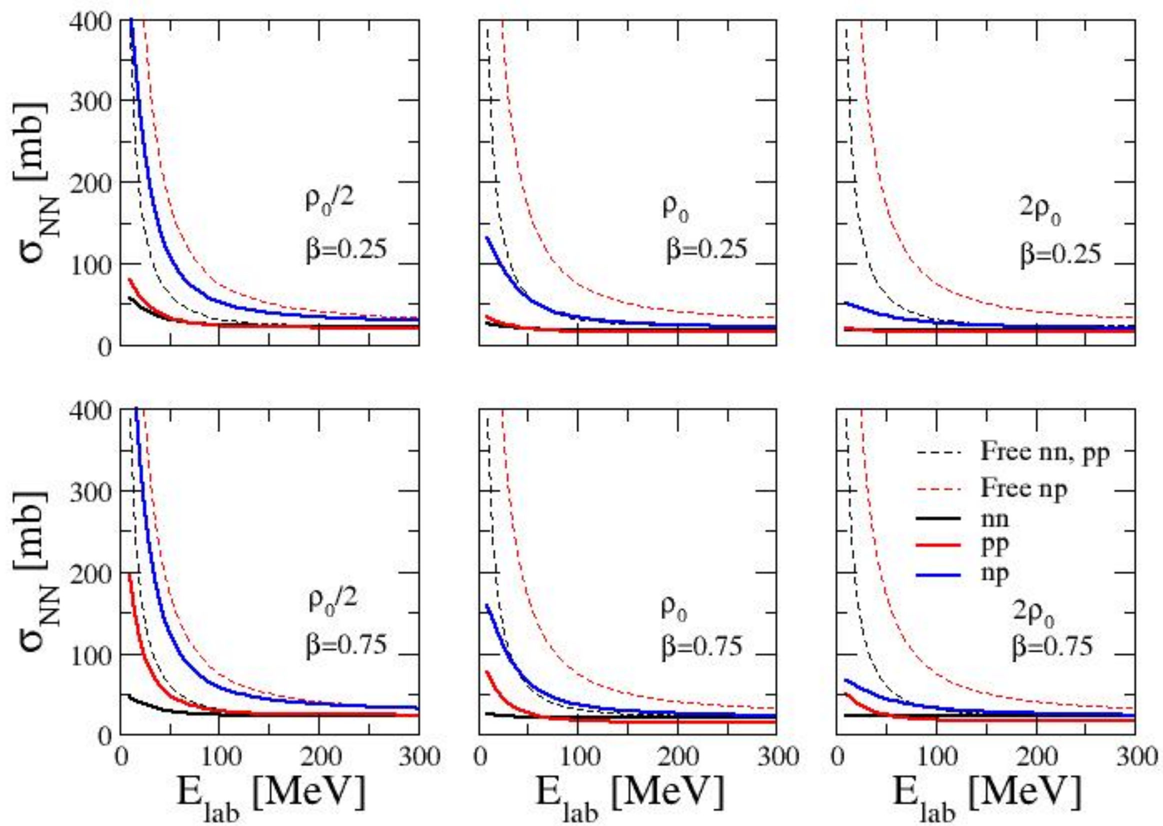
$$T_{PT}(b) = \int T_P(|\vec{s}-\vec{b}|) T_T(s)\, d\vec{s}$$

Effective overlap density where a nucleon of P can interact with a nucleon of T ("Thickness function")

In-medium NN cross sections

G-matrix gives access to in-medium NN cross sections

$$\sigma_{\tau\tau'} = \frac{m^*_\tau m^*_{\tau'}}{16\pi^2\hbar^4} \sum_{LL'SJ} \frac{2J+1}{4\pi} \left| G^{LL'SJ}_{\tau\tau' \to \tau\tau'} \right|^2, \quad \tau\tau' = nn, pp, np$$



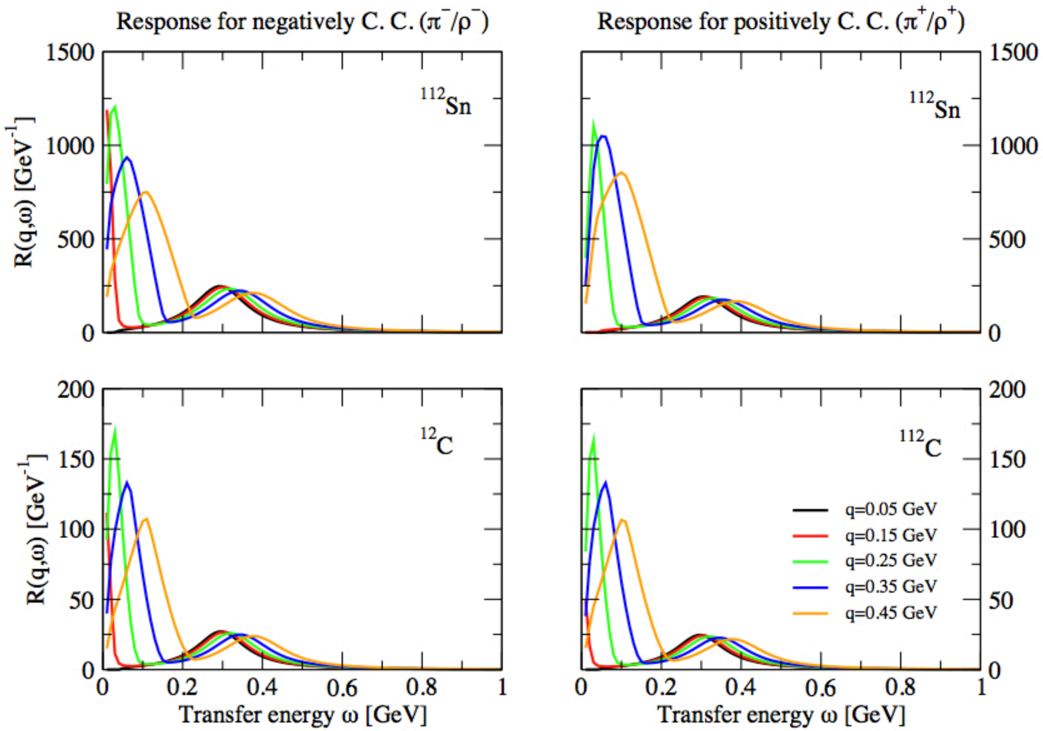
- ✓ microscopically based
- ✓ density dependence (Pauli blocking)
- ✓ isospin dependence (ρ_n different from ρ_p)

We use, however, free NN cross sections

Nuclear Response

Nuclear response to the projectile/target scattering probe

$$R(q,\omega)=\frac{\sum_{if}\left|\langle\psi_f|O_q|\psi_i\rangle\right|^2\delta(E_f-E_i-\omega)}{\sum_i\langle\psi_f|O_q^*O_q|\psi_i\rangle}$$



Calculated by Horst Lenske (Giessen Univ.) in local density approximation

Nucleus-Nucleus Differential Cross Section

✧ Quasi-elastic contribution $A_1 + A_2 \longrightarrow A_3 + A_4$

$$\left.\frac{d^2\sigma}{dE_3 d\Omega_3}\right|_{QE} = \frac{2 p_3 m_1 m_2 m_3 m_4}{(2\pi)^2 \lambda^{1/2}(s, m_1^2, m_2^2)} \frac{|M_{QE}|^2}{E_2} \langle N_{part} \rangle \int d\omega R_P(p_3 - p_1, \omega) R_T(p_3 - p_1, \omega - k_1 - k_2 + k_3 + k_4)$$

✧ Inelastic contribution $A_1 + A_2 \longrightarrow A_3 + A_4 + \pi$

$$\sum_{in} \left.\frac{d^2\sigma}{dE_3 d\Omega_3}\right|_{in} = \frac{p_3 m_1 m_2 m_3 m_4}{(2\pi)^5 \lambda^{1/2}(s, m_1^2, m_2^2)} \langle N_{part} \rangle \int \frac{d^3 p_\pi}{E_4 E_\pi} \left|\sum_c M_{in,c}\right|^2 \int d\omega_1 d\omega_2 R_P(p_3 - p_1, \omega_1) R_T(p_3 - p_1, \omega_2)$$

Integrating over the solid angle

$$\frac{d\sigma}{dE_3} = \int d\Omega_3 \left(\left.\frac{d^2\sigma}{dE_3 d\Omega_3}\right|_{QE} + \sum_{in} \left.\frac{d^2\sigma}{dE_3 d\Omega_3}\right|_{in} \right)$$

In the calculation, since the reaction is very peripheral doub. diff. cross sect. are evaluated at θ=0 & the integration is done over the solid angle covered by the experiment

Fermi Motion

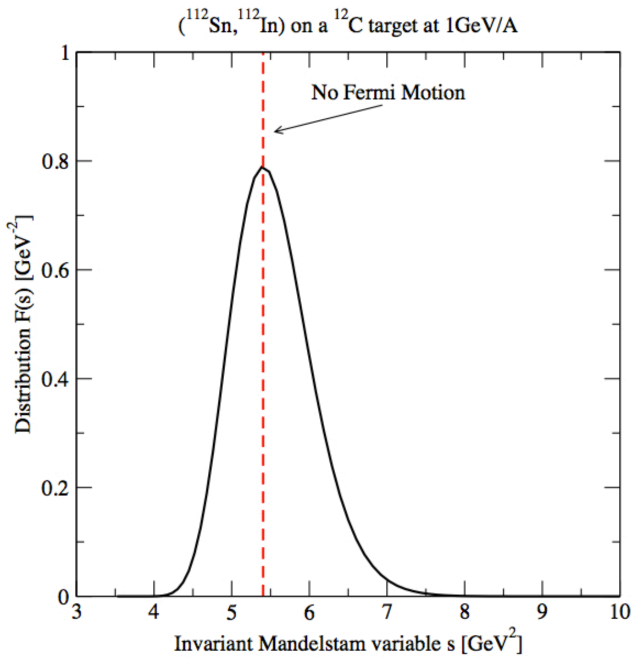
Fermi Motion is incorporated by averaging the differential cross section over a range of values of the the invariant $s=(p_1+p_2)^2$

$$\frac{d\sigma}{dE_3}(E_3) = \frac{\int dsF(s)\frac{d\sigma}{dE_3}(E_3,s)}{\int dsF(s)}$$

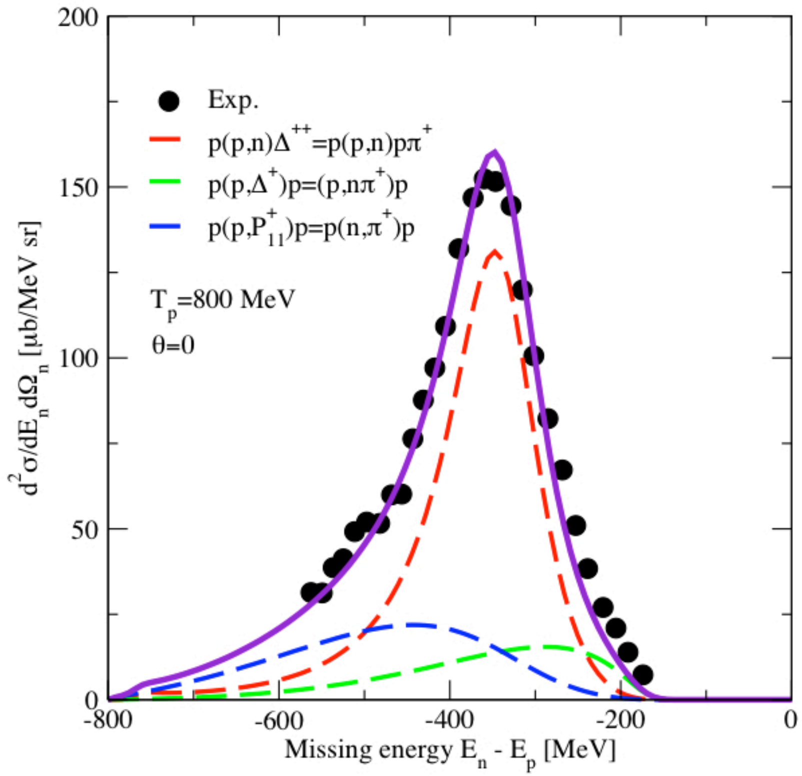
distribution of the invariant s

$$F(s) = \int d\vec{k}_1\, d\vec{k}_2 \rho_1(\vec{k}_1)\rho_2(\vec{k}_2)\delta(s-2m-2E_1E_2+2\vec{k}_1\cdot\vec{k}_2)$$

Calculations are done using the analytical expressions of F(s) given in Sandel et al., PRC 20, 744 (1999)



(p.n) elementary reaction on a proton target at 0.8 GeV



- Clear dominance of Δ^{++} excitation in the target
- Good agreement between data & model

Contribution from 5 processes

✧ s-wave π emission in Target

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

✧ s-wave π emission in Projectile

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

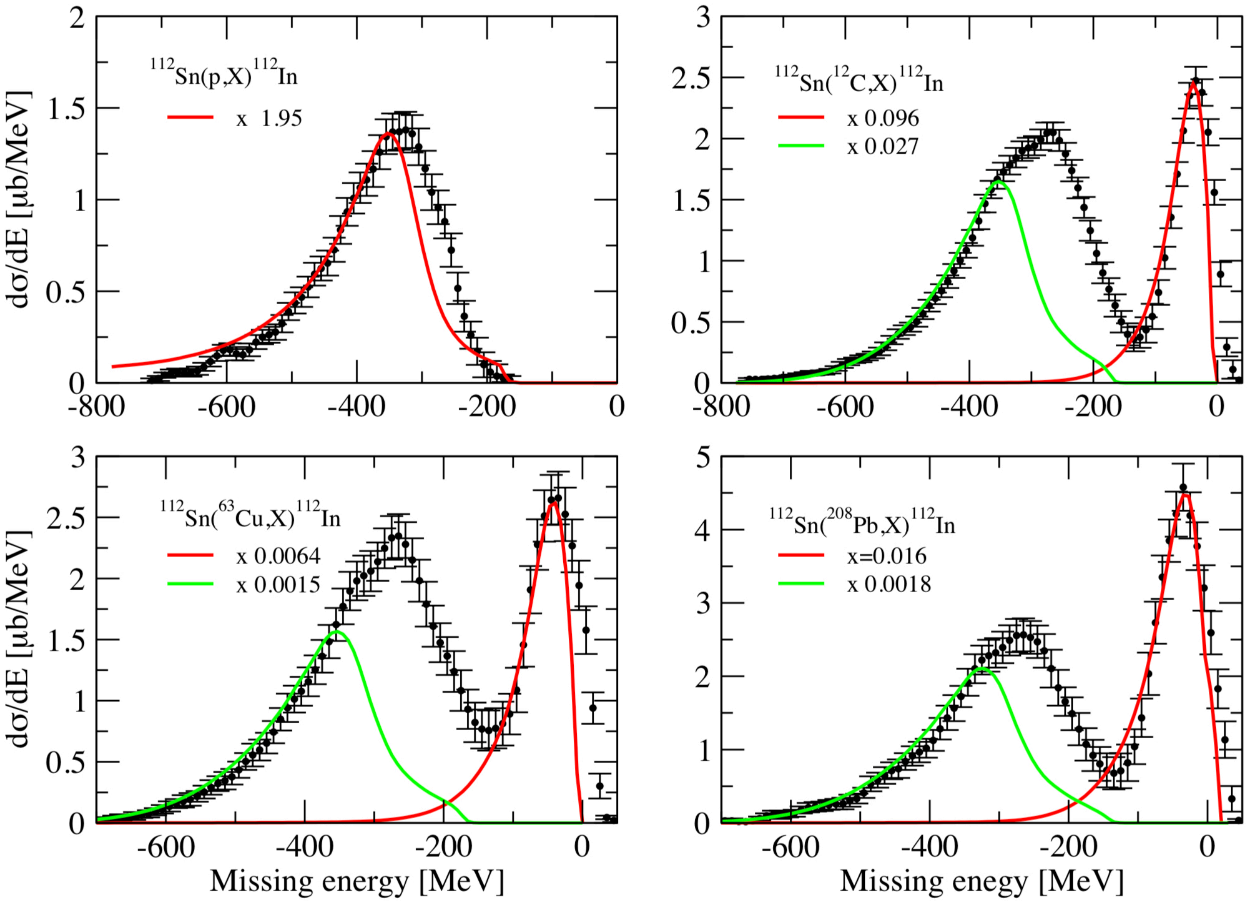
✧ Δ^{++} excitation in Target

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

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

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

Comparison with data: (p,n) channel



<u>QE</u>:

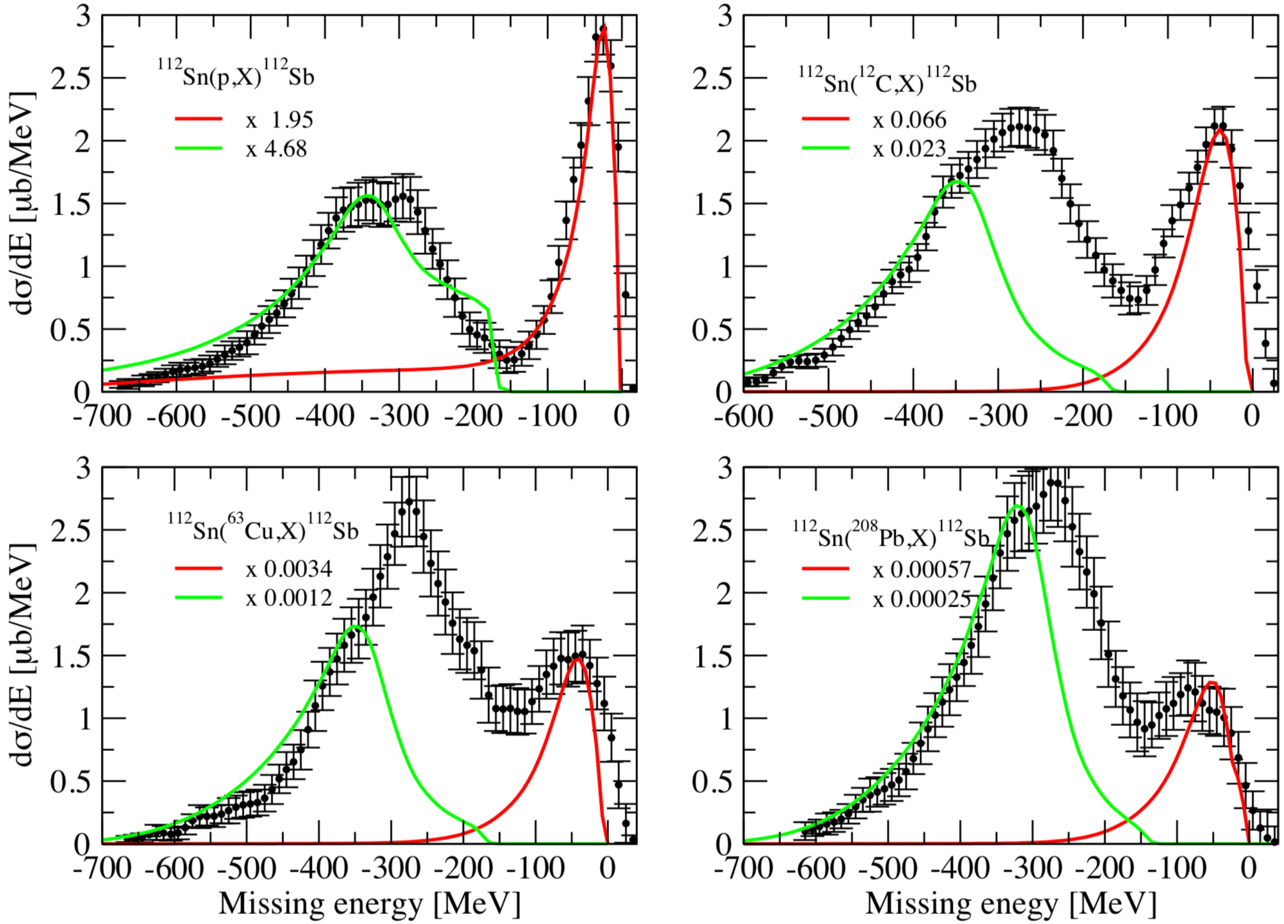
Rather good agreement once rescaled

<u>Inelastic</u>:

Little shoulder at the left of big peak due to the excitation of resonances in target nuclei. Model once rescaled described reasonably well

Big peak due to the excitation of resonances in projectile nuclei. Model cannot reproduce it (need to be solved)

Comparison with data: (n,p) channel



QE:

Rather good agreement once rescaled

Inelastic:

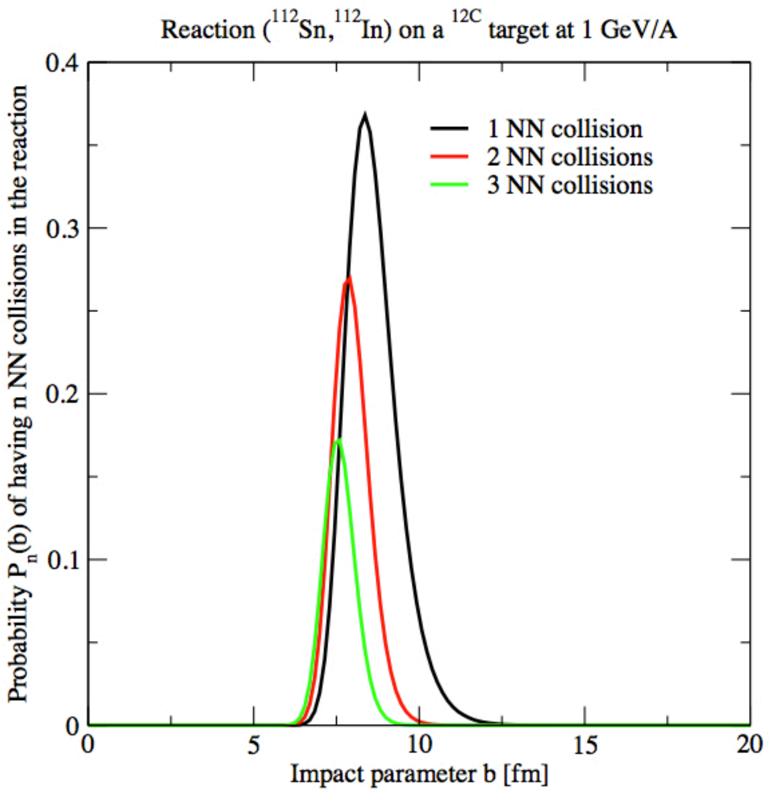
Little shoulder at the left of big peak due to the excitation of resonances in target nuclei. Model once rescaled described reasonably well

Big peak due to the excitation of resonances in projectile nuclei. Model cannot reproduce it (need to be solved)

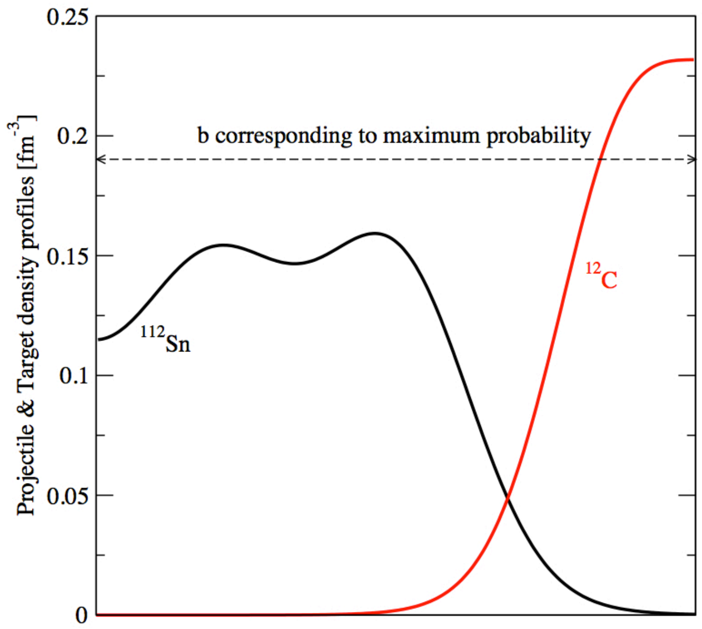
Isospin content of the projectile tail: peripheral character of the reaction

Probability of having n NN collisions in the reaction

$$P_n(b) = \binom{A_P A_T}{n} \left(T_{PT}(b)\sigma_{NN}\right)^n \left(1 - T_{PT}(b)\sigma_{NN}\right)^{A_P A_T - n}$$



(^{112}Sn,^{112}In) reaction on a ^{12}C target at 1GeV/A



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

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

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

(p,n) 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

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

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

Seems as entangled as before !!

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

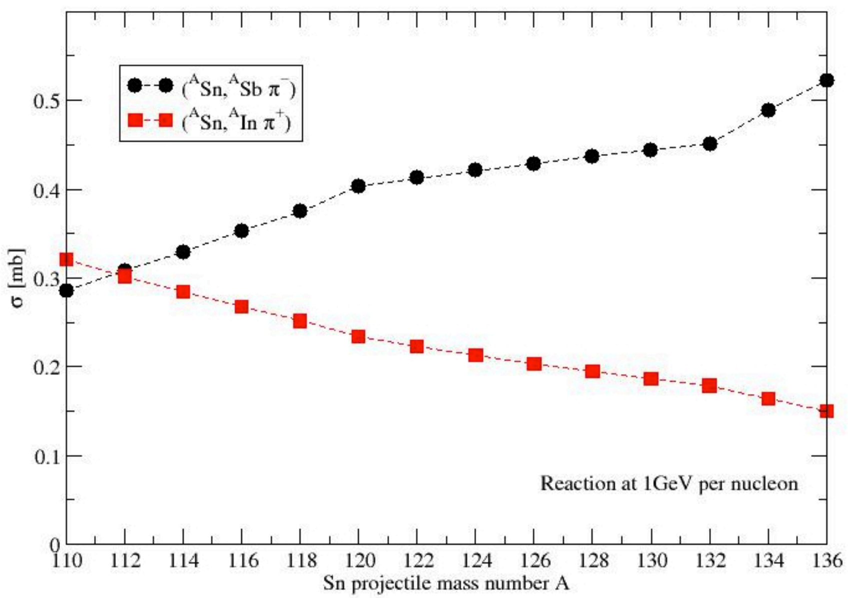
The cleanest case: measurements with a proton target

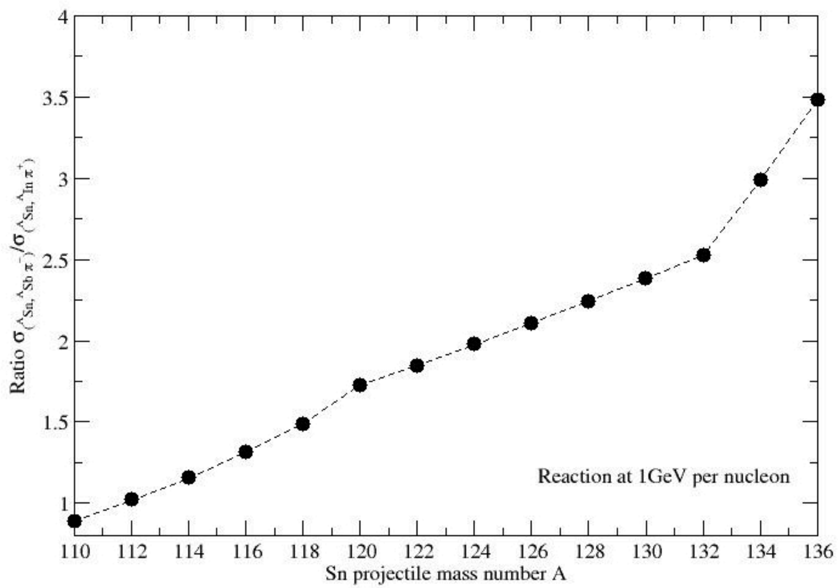
In this case we can consider just one ratio

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

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

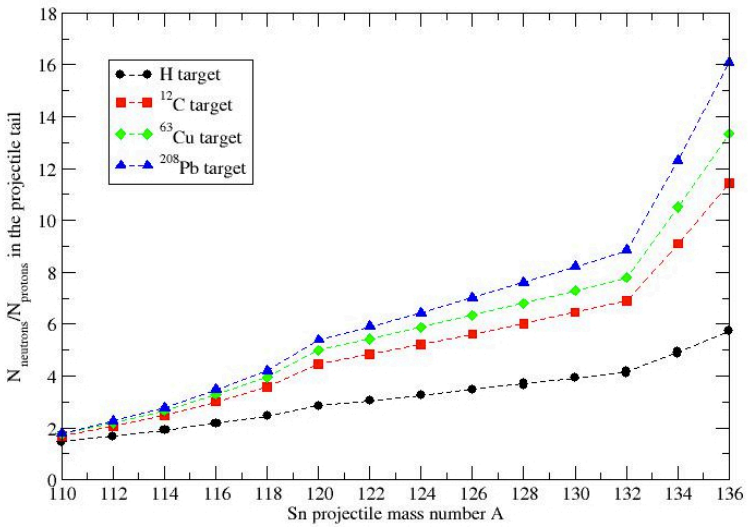
in this case $\longrightarrow$ $\frac{N_n^{(P)}}{N_p^{(P)}} \propto R_1$

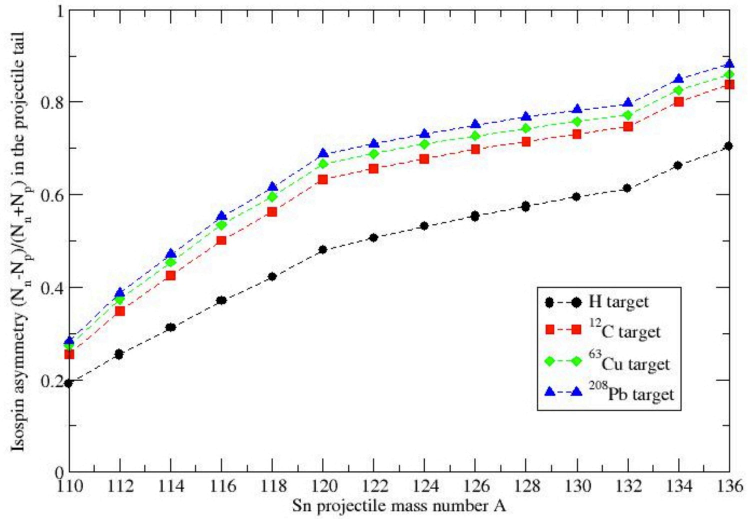




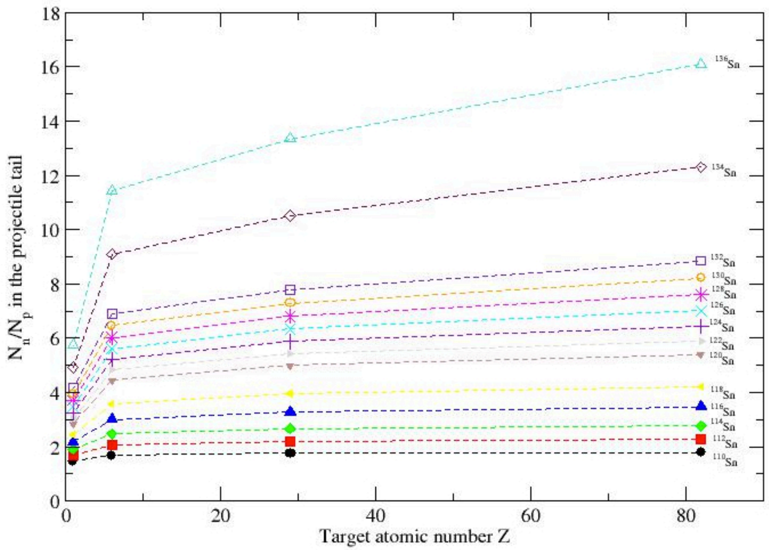
Isospin content of the projectile: model estimations

✧ Projectile mass number dependence





✧ Target atomic number dependence



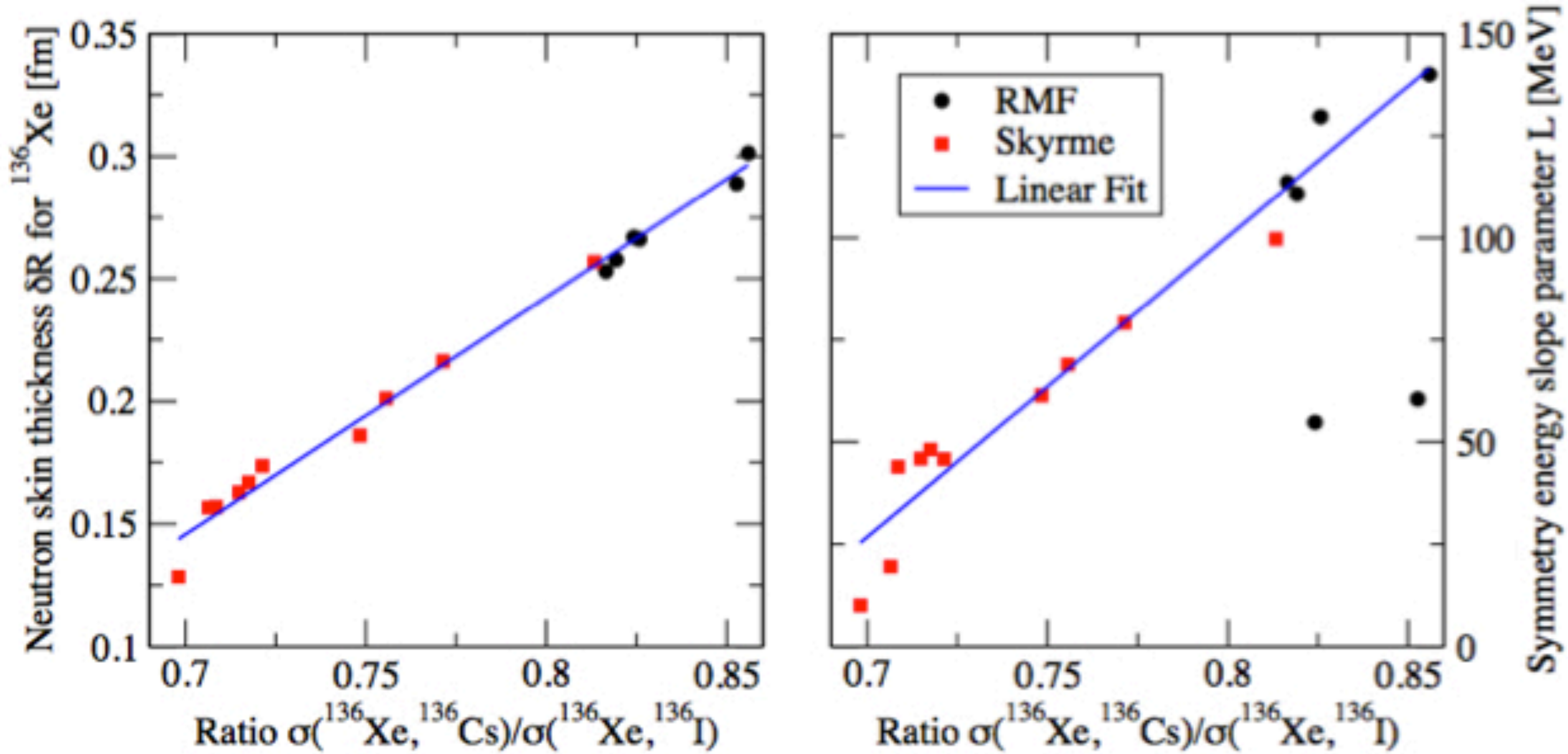
Neutron Skin Thickness & Symmetry Energy

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 & L

^{136}Xe on a proton target at 1GeV/A



Take home message

- ✧ Results are still very preliminar
- ✧ The spectrum structure is rather well understood
- ✧ Quasi-elastic peak at low missing energies
- ✧ Inelastic channel:
  - Data: little shoulder at approx. -334 MeV, about 60 MeV at the left of the big peak due to, according to the model, the **excitation of the nucleon resonances in the target nuclei**
  - Data: big peak at about -274 MeV, due to , according to the model, the **excitation of the nucleon resonances in the projectile nuclei** (model, however, must be improved in this case)
- ✧ Sensitivity to the isospin content of the projectile tale
- ✧ Neutron skin thickness & Symmetry Energy from ICER ?

- You for your time & attention

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