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Probing Subnuclear Physics in Heavy ion Collisions

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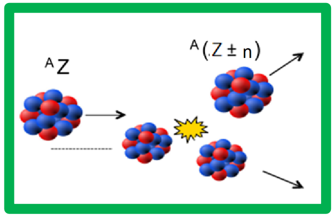
Agenda:

- Peripheral quasi-elastic and inelastic heavy ion reactions
- The excited nucleon in nuclear matter
- Reaction theory of peripheral heavy ion charge exchange reactions
- Nuclear response functions with resonances: N*RPA
- Applications to the recent FRS-data
- Perspectivies on decay spectroscopy at WASA@(Super)FRS
- Astrophysics: resonances in neutron stars

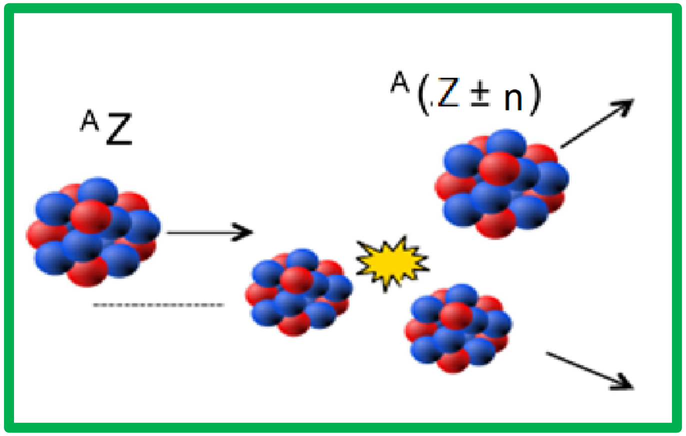
Experiment and Theory:
Rodriguez et al.,
Phys. Lett. B 807, 135565 (2020) & Physical Review C 106:014618 (2022)

Background Reading:
H. Lenske, M. Dhar, Th. Gaitanos, Xu Cao, Prog.Part.Nucl.Phys. 98: 119 (2018)



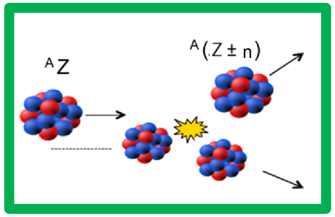
Peripheral
Charge Exchange
Heavy Ion Reactions

Characteristics of Peripheral Heavy Ion Charge Exchange Reactions



- **Grazing collisions and selective excitations leaving the reacting nuclei intact**
- **Quasi-elastic and (deep-)inelastic reactions under controlled conditions**
- **Nuclear spectroscopy at large momentum and energy transfers**
- **Probing N^*N^{-1} modes in n=1 single charge exchange (SCE) reactions**
- **Decay spectroscopy with WASA@(Super)FRS as an exciting new perspective**
- **Probing double-beta decay in n=2 double charge exchange (DCE) reactions**

(H. Lenske, F. Cappuzzello, M. Cavallaro, M. Colonna, Prog.Part.Nucl.Phys. 109 (2019) 103716)



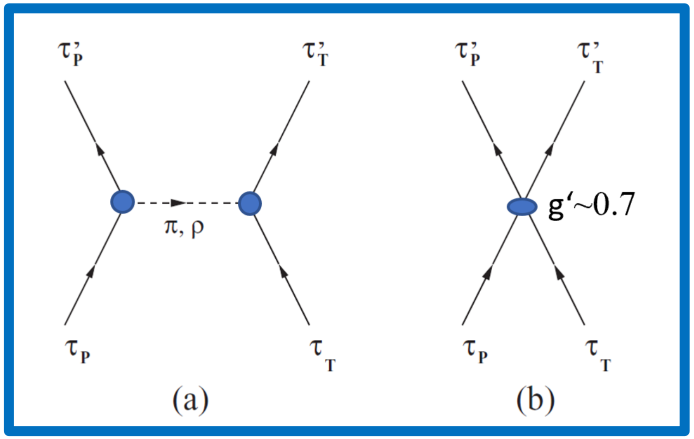
Theory of Peripheral Heavy Ion Charge Exchange Reactions: Cross Sections

Separability Hypothesis:
Quasi-Elastic and Inelastic Processes do not Interfere

$$\frac{d\sigma}{dE_b} = \frac{d\sigma}{dE_b}\Big|_{\rm qe} + \frac{d\sigma}{dE_b}\Big|_{\rm in}.$$

…implying the incoherent superposition of cross sections.

Quasi-elastic Cross Section – Target N´N^{-1} SCE transitions



- π,ρ → $\Delta S=1$ Gamow-Teller modes, $\pi_J=(-)^{J+1}$
- $\delta\sim[\pi\eta]_{I=1}$ → $\Delta S=0$ Fermi modes, $\pi_J=(-)^J$

„Collision Number"
→ Glauber Theory

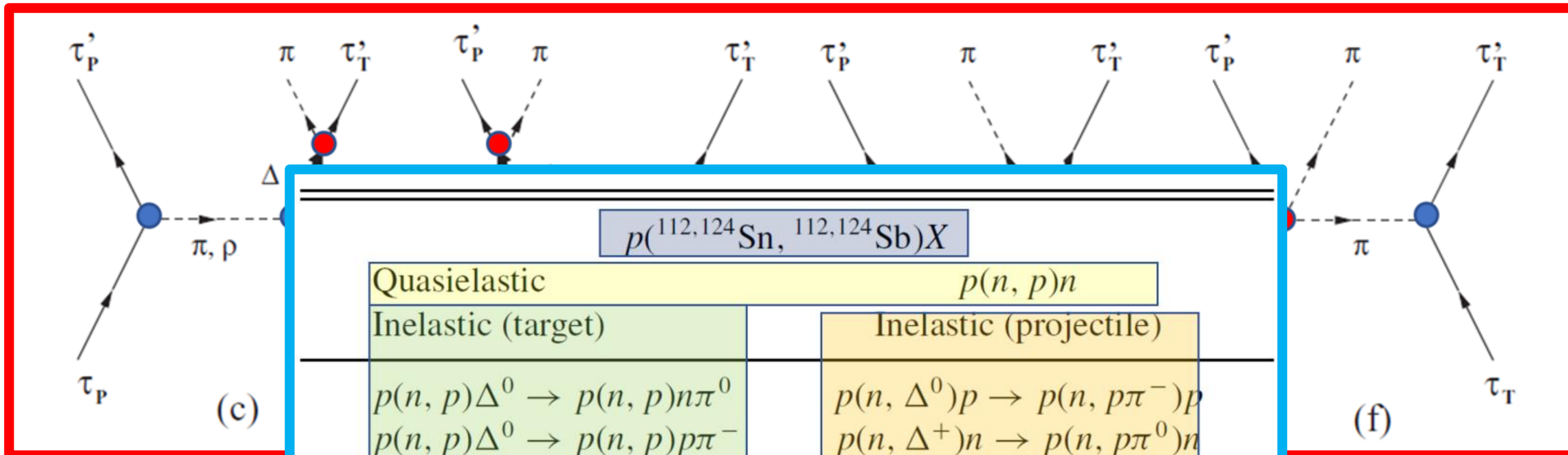
Target Response Function

NN isovector-SCE Amplitude

$$\left.\frac{d\sigma}{dE_b}\right|_{qe} = \langle N_{\tau_P\tau_T}\rangle |\mathcal{M}_{qe}|^2$$

$$|\mathcal{M}_{qe}|^2 = \frac{2|\vec{p}_b|}{(2\pi)^2}\frac{m^4}{\lambda^{1/2}(s,m^2,m^2)}\int\frac{d\vec{q}}{(2\pi)^3}\frac{d\Omega_b}{E_B} R_N^{(A)}(\sqrt{s}-E_b,\vec{q})\langle|M_{qe}(\vec{q})|^2\rangle$$

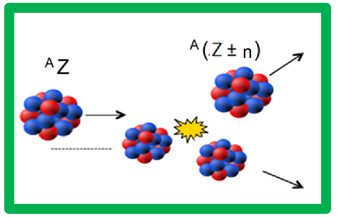
Inelastic Cross Section - N*N^{-1} SCE transitions



$p(^{112,124}\mathrm{Sn}, {}^{112,124}\mathrm{Sb})X$	
Quasielastic	$p(n,p)n$
Inelastic (target)	Inelastic (projectile)
$p(n,p)\Delta^0 \to p(n,p)n\pi^0$	$p(n,\Delta^0)p \to p(n,p\pi^-)p$
$p(n,p)\Delta^0 \to p(n,p)p\pi^-$	$p(n,\Delta^+)n \to p(n,p\pi^0)n$
$p(n,p)n\pi^0$ (s wave)	$p(n,p\pi^-)p$ (s wave)
$p(n,p)p\pi^-$ (s wave)	$p(n,p\pi^0)n$ (s wave)

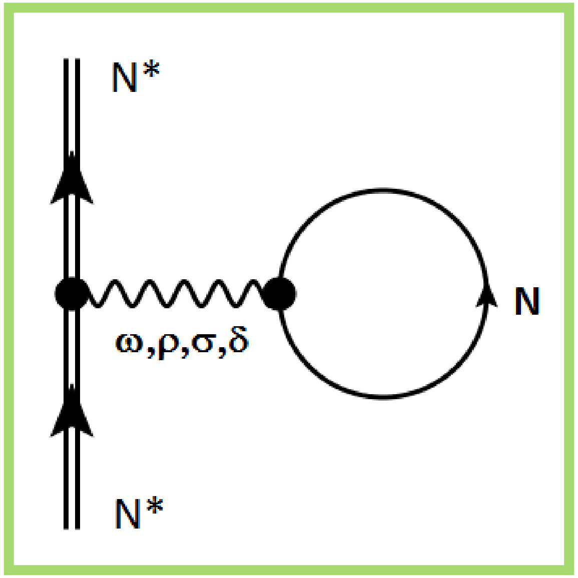
${}^AZ\,(^{112,124}\mathrm{Sn}, {}^{112,124}\mathrm{Sb})X$	
Quasielastic	$p(n,p)n$
Inelastic (target)	Inelastic (projectile)
$p(n,p)\Delta^0 \to p(n,p)n\pi^0$	$p(n,\Delta^0)p \to p(n,p\pi^-)p$
$p(n,p)\Delta^0 \to p(n,p)p\pi^-$	$p(n,\Delta^+)n \to p(n,p\pi^0)n$
$p(n,p)n\pi^0$ (s wave)	$p(n,p\pi^-)p$ (s wave)
$p(n,p)p\pi^-$ (s wave)	$p(n,p\pi^0)n$ (s wave)
$n(n,p)\Delta^- \to n(n,p)n\pi^-$	$n(n,\Delta^0)n \to n(n,p\pi^-)n$
$n(n,p)n\pi^-$ (s wave)	$n(n,p\pi^-)n$ (s wave)

Inelastic cross sections – see PRC 106:014618 (2022)



Theory of Peripheral Heavy Ion Charge Exchange Reactions: Spectral Distributions and Response Functions

N* Self-Energies in Nuclear Matter



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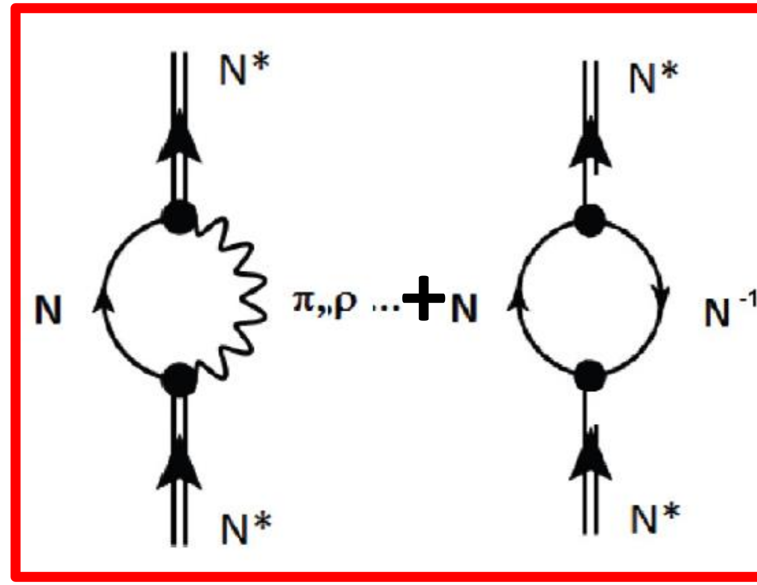


Diffractive Self-Energy
→ Hartree-Potential

$$U^{(H)}_{N^*} = U_0 + U_1 \tau_{N^*} \cdot \tau_N$$

$$U^{(H)}_{N^*} \sim U_0 + U_1 t_z^{(N^*)} \cdot \frac{N-Z}{A}$$

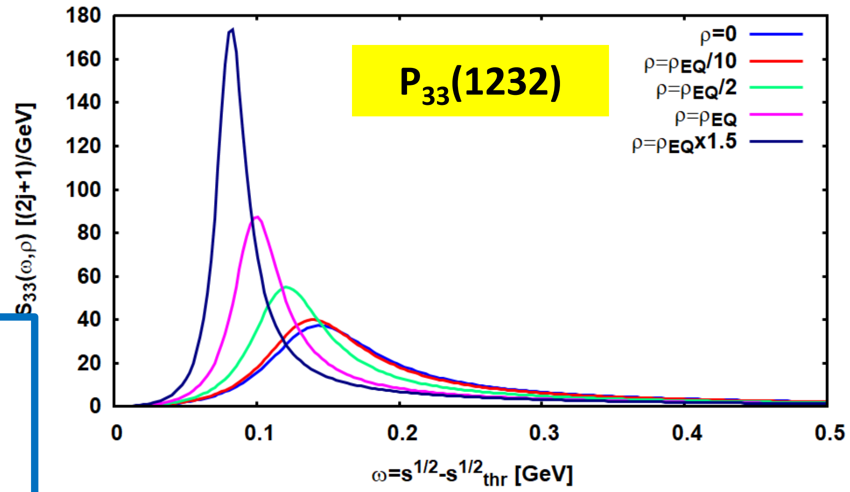
Polarization Self-Energy
→ dispersive (optical) potential

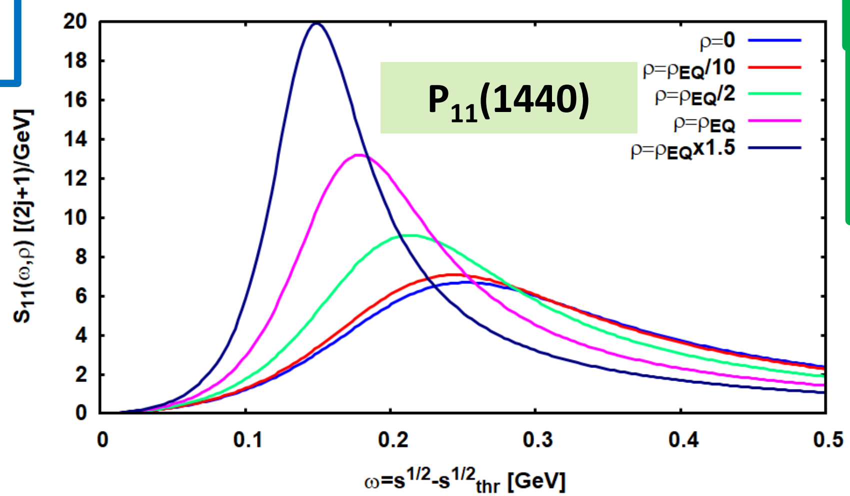
$$\Sigma^{(pol)}_{N^*} \sim \Sigma_0 + \Sigma_1 t_z^{(N^*)} \frac{N-Z}{A}$$

$$\Sigma_{0,1} = V_{0,1} - iW_{0,1} \;;\; W_{0,1} = \frac{1}{2}\Gamma_{0,1}$$

...for the dispersive part see e.g.:
E. Oset, L.L. Salcedo, NPA 468 (1987) 631; G.E. Brown, W. Weise, Phys. Rept. 22 (1975) 279

N* Spectral Distributions in Nuclear Matter





- **Mean-field potentials**
- **Effective Masses**
- **Pauli-Blocking**
- **Pion Absorption**
- **Coupling to NN^{-1} modes**

…with increasing density:

- **Downward mass shift**
- **Reduction of width**

…if a pre-formed N* resonance would be captured by a nucleus!

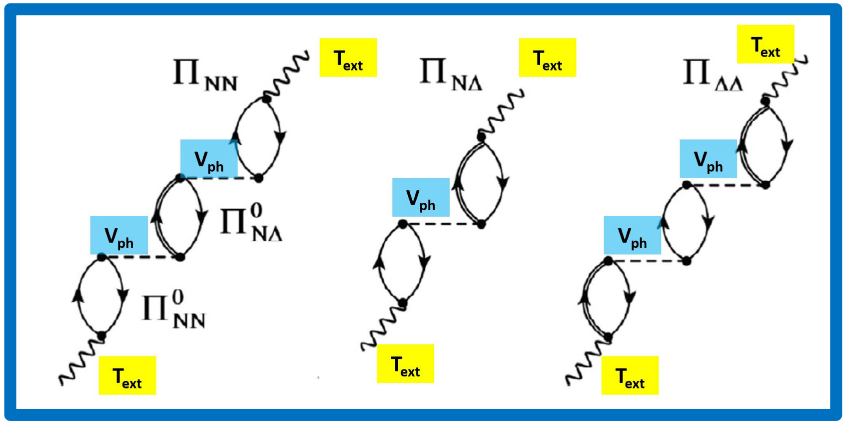
Theory of Spectral functions: Nucl.Phys.A 632 (1998) 109; *Nucl.Phys.A* 642 (1998) 506

Substitutional N^*N^{-1} Excitations in Nuclei - „N*RPA"

$$\Pi = \Pi^0 + \Pi^0 \hat{V} \Pi$$

$$\begin{pmatrix} \Pi_{NN} & \Pi_{N\Delta} \\ \Pi_{\Delta N} & \Pi_{\Delta\Delta} \end{pmatrix} = \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} + \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} \begin{pmatrix} V_{NN} & V_{N\Delta} \\ V_{\Delta N} & V_{\Delta\Delta} \end{pmatrix} \begin{pmatrix} \Pi_{NN} & \Pi_{N\Delta} \\ \Pi_{\Delta N} & \Pi_{\Delta\Delta} \end{pmatrix}$$

Coupled $N'N^{-1} \leftrightarrow \Delta N^{-1}$ Dyson Equation including N and N* self-energies



V_{ph} by pion, rho, delta/a_0 - meson exchange and „short range" g'

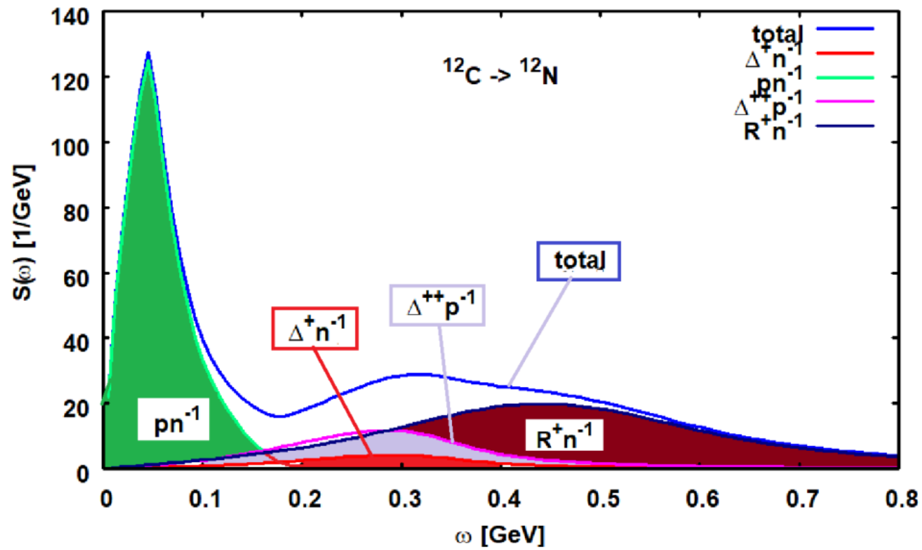
Polarization Tensor and Nuclear Response (H=N,Δ...)

$$R_H^{(X)\mu\nu}(\omega,\vec{q}) = -\frac{1}{\pi}\mathrm{Im}\left(\Pi_{HH}^{(X)\mu\nu}(\omega,\vec{q})\right) = -\frac{1}{\pi}\mathrm{Im}\left(\langle X | T_{ext}^{\dagger\mu}(\vec{q}) G_{HH}(\omega) T_{ext}^{\nu}(\vec{q}) | X \rangle\right)$$

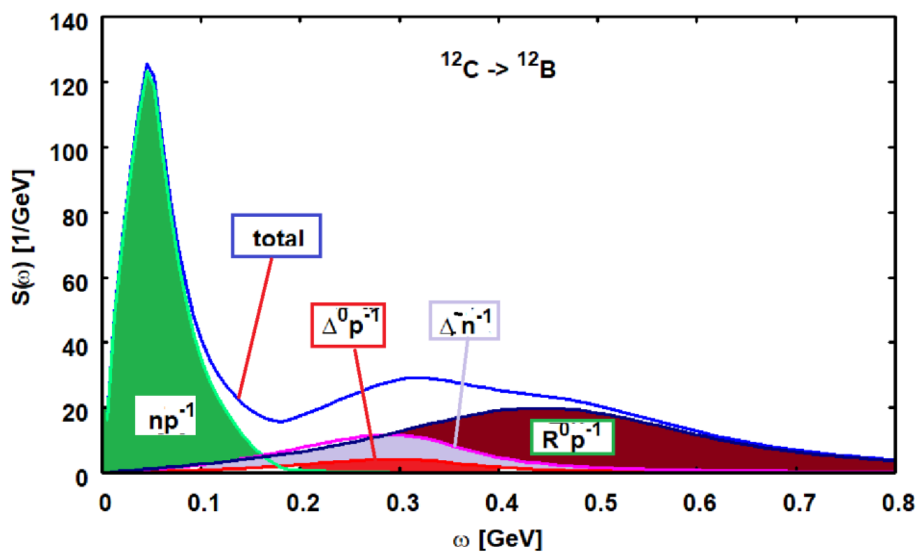
N^*N^{-1} Spectral Distributions for $^{12}C - P_{33}(1232)$ and $P_{11}(1440)$

Longitudinal Response@q=300 MeV/c

τ_+ operator : pn^{-1} – type
external probe: $\vec{\sigma} \bullet \vec{p}$



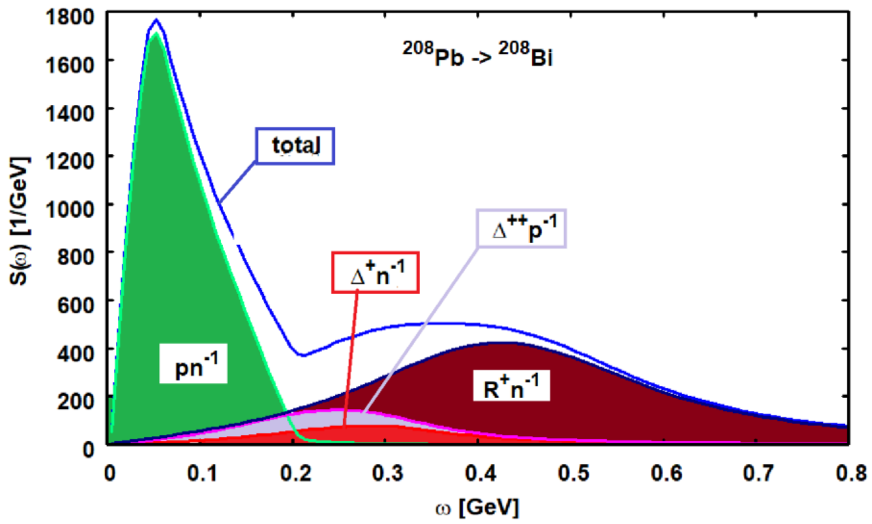
τ_- modes : np^{-1} – type
external probe: $\vec{\sigma} \bullet \vec{p}$



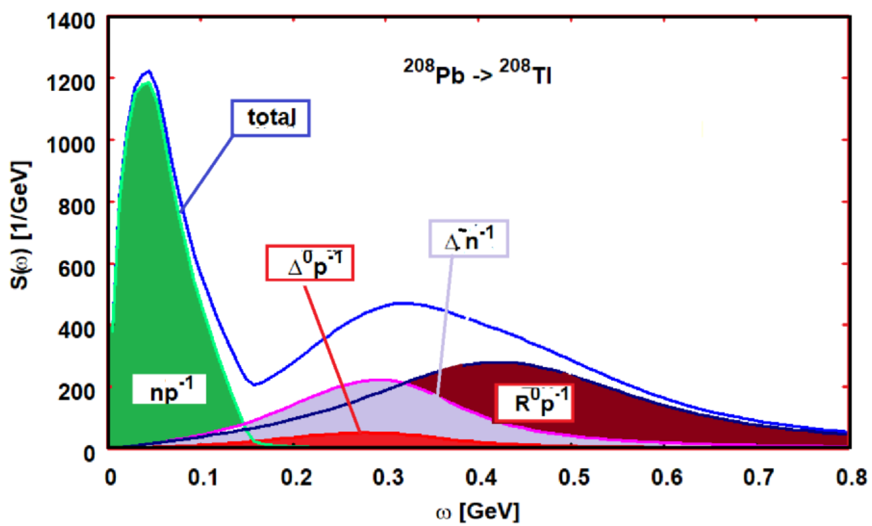
N^*N^{-1} Spectral Distributions for ^{208}Pb – $P_{33}(1232)$ and $P_{11}(1440)$

Longitudinal Response@q=300 MeV/c

τ_+ operator : pn^{-1} – type
external probe: $\vec{\sigma} \bullet \vec{p}$

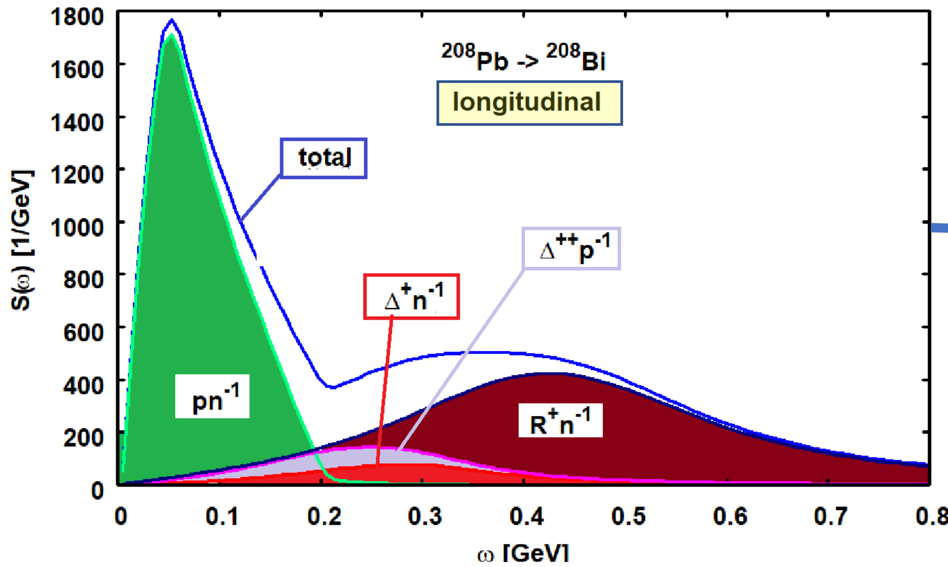


τ_- modes : np^{-1} – type
external probe: $\vec{\sigma} \bullet \vec{p}$



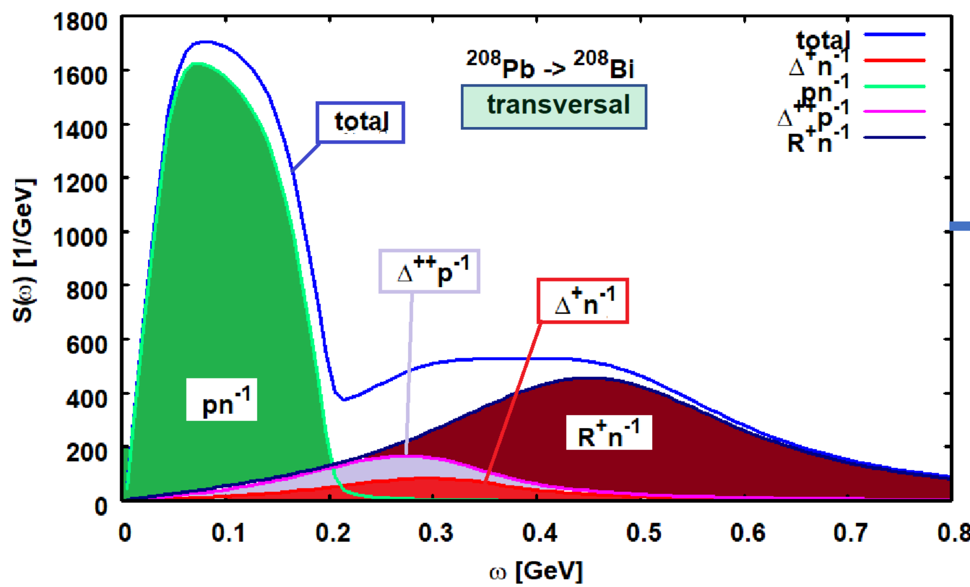
N^*N^{-1} Spectral Distributions for $^{208}Pb \rightarrow {}^{208}Bi$

Longitudinal and Transversal Response@q=300 MeV/c

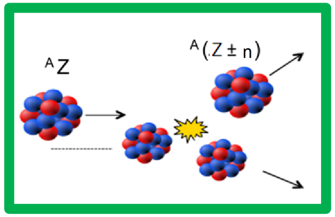


Operator:

$\sigma \bullet q$ (π-meson)



$\sigma \times q$ (ρ-meson)



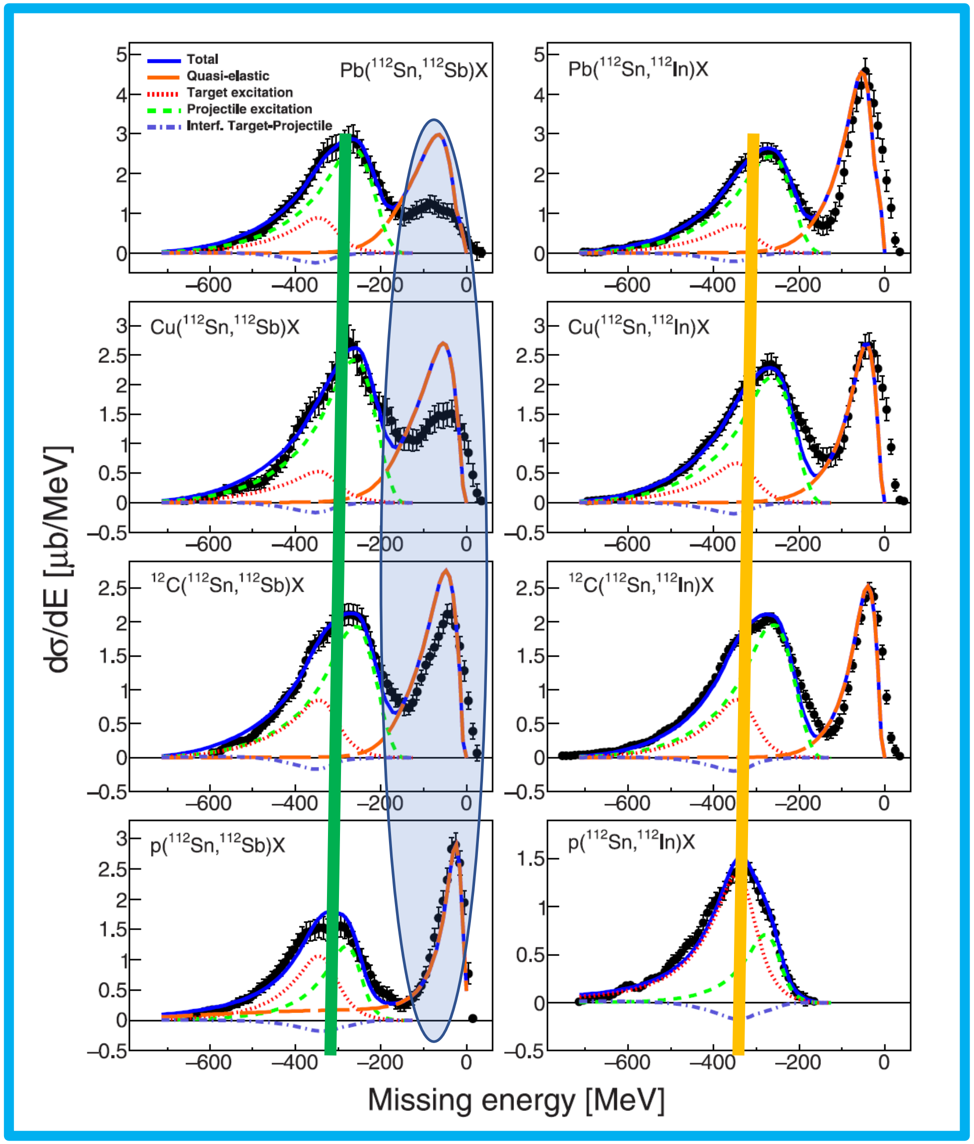
Comparison to the FRS-Data

Theoretical Results for ^{112}Sn on Pb, Cu, ^{12}C, and Proton Targets

Rodriguez et al., PHYSICAL REVIEW C 106, 014618 (2022)

$^{112}Sn(0+) \rightarrow {}^{112}Sb(3+)$
S(p)= 2.948 MeV
States E_x<S(p):
$1^+ \leq J^\pi \leq 12^-$

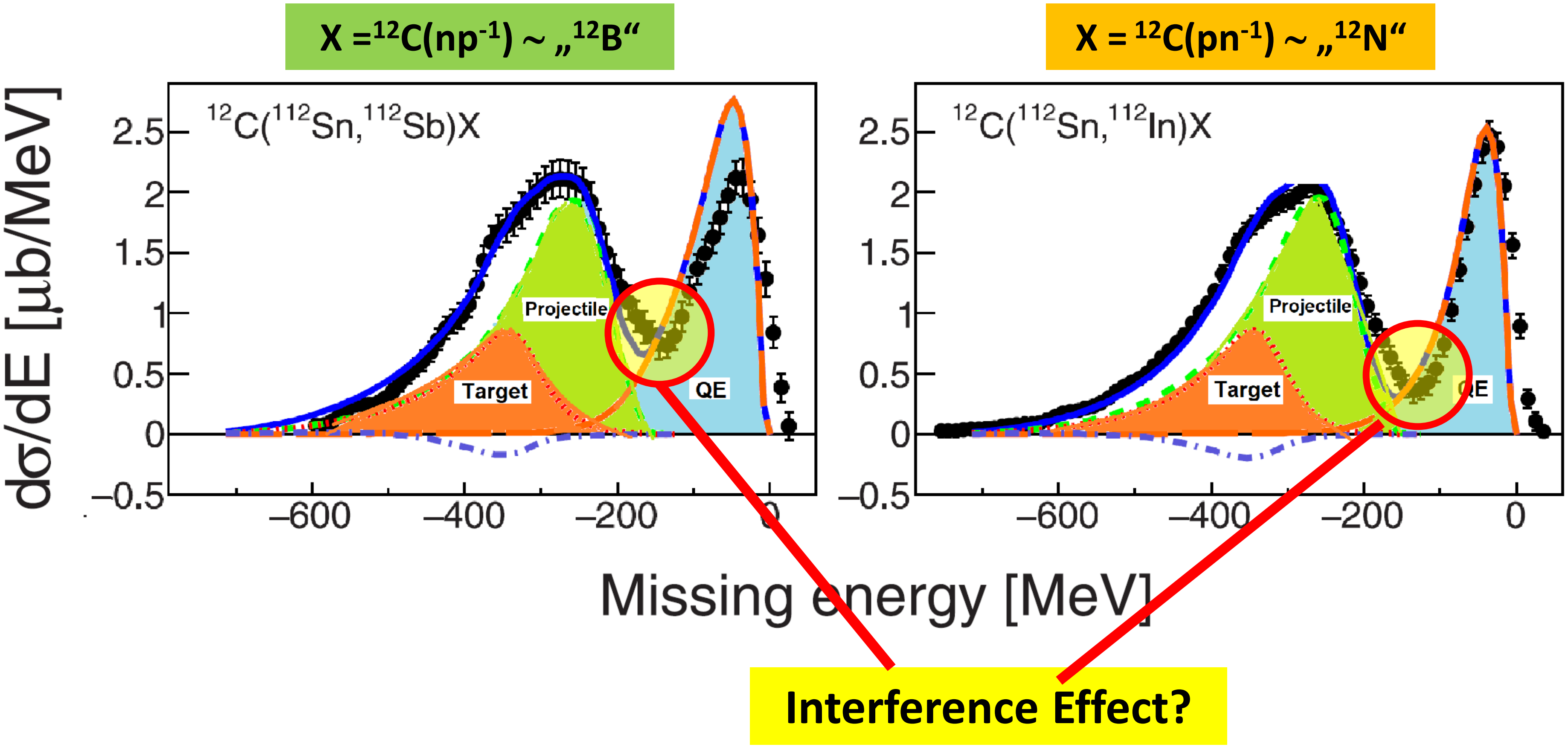
$[p_P n_P^{-1}]$
$Z_P \rightarrow Z_P+1$
$\leftrightarrow$
$Z_T \rightarrow Z_T-1$
$[n_T p_T^{-1}]$

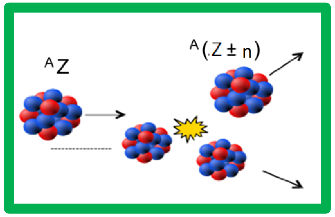


$^{112}Sn(0+) \rightarrow {}^{112}In(1+)$
S(p)= 6.027 MeV
States E_x<S(p):
$0^+ \leq J^\pi \leq 18^\pm$

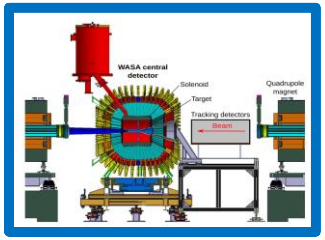
$[n_P p_P^{-1}]$
$Z_P \rightarrow Z_P-1$
$\leftrightarrow$
$Z_T \rightarrow Z_T+1$
$[p_T n_T^{-1}]$

^{112}Sn@1AGeV on ^{12}C
Quasi-elastic, Projectile, and Target Excitations



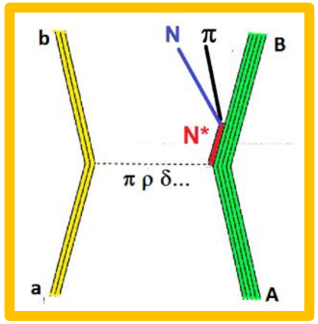


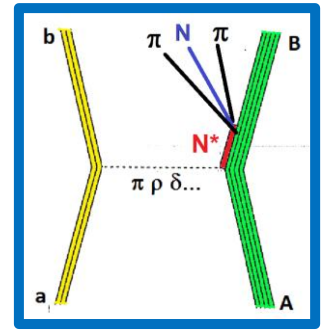
Perspectives of Resonance Studies at WASA@(Super)FRS

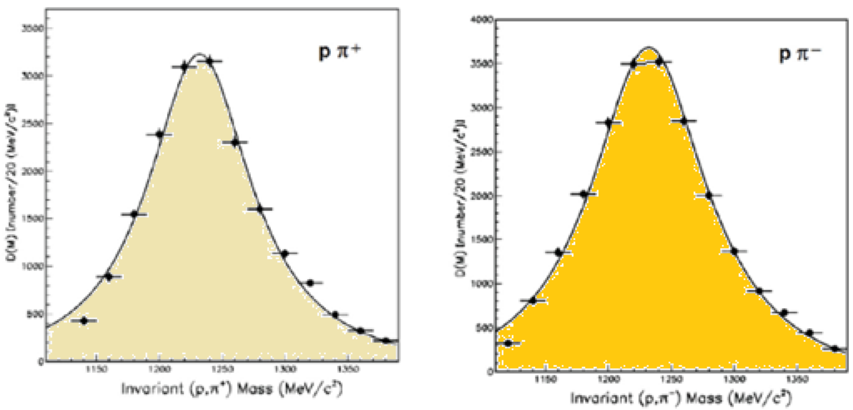


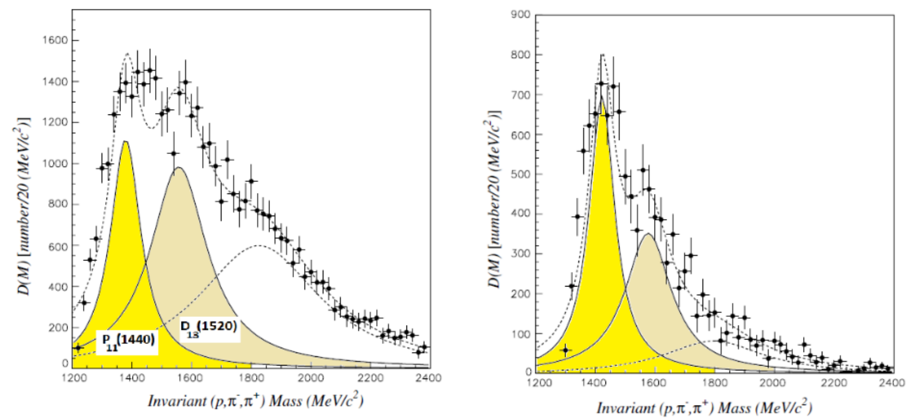
Invariant Nπ/Nππ Mass Spectroscopy at the SynchroPhasotron@DUBNA

$^{12}C + ^{12}C$ at $T_{lab} \sim 4$ AGeV)









($p\pi$) pairs to be in the Δ-resonance mass region

Reconstruction of the Delta-resonance from $\Delta^{++} \rightarrow p\pi^+$ (right) and $\Delta^0 \rightarrow p\pi-$ (left) mass spectroscopy

D. Krpic et al., Phys. Rev. C 65 (2002) 034909

N∗ → pπ+π− two-pion spectroscopy. Expected N* states are indicated (left).

D. Krpic et al.,, Eur. Phys. J. A 20 (2004) 351

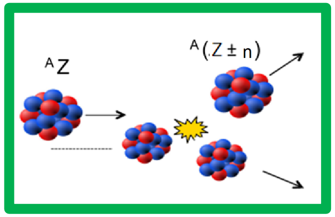
see: **H. Lenske et al. / PPNP 98 (2018) 119**

Summary and Outlook

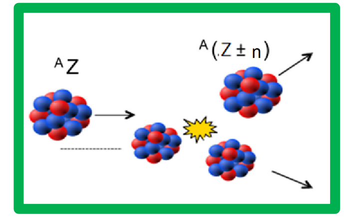
- **Resonance excitations in peripheral heavy ion collisions**
- **Resonance reaction dynamics and (semi-)quantal reaction theory**
- **Resonance spectral functions in nuclear matter**
- **Resonances in nuclei and N^*N^{-1} response functions**
- **Resonances for astrophysics: N* in neutron stars**
- **Next steps:**
  - **Resonance tagging on WASA@FRS – experiment and theory**
  - **Resonances beyond $\Delta(1232)$ and $P_{11}(1440)$ – coupled channel schemes**

Credits to
Jose Luis Rodriguez and the experiment team
and
Isaac Vidana for modelling the reaction

Supported by DFG, AvH, and HFHF



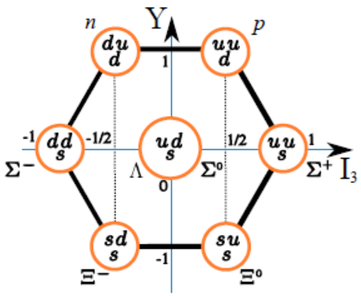
Backups

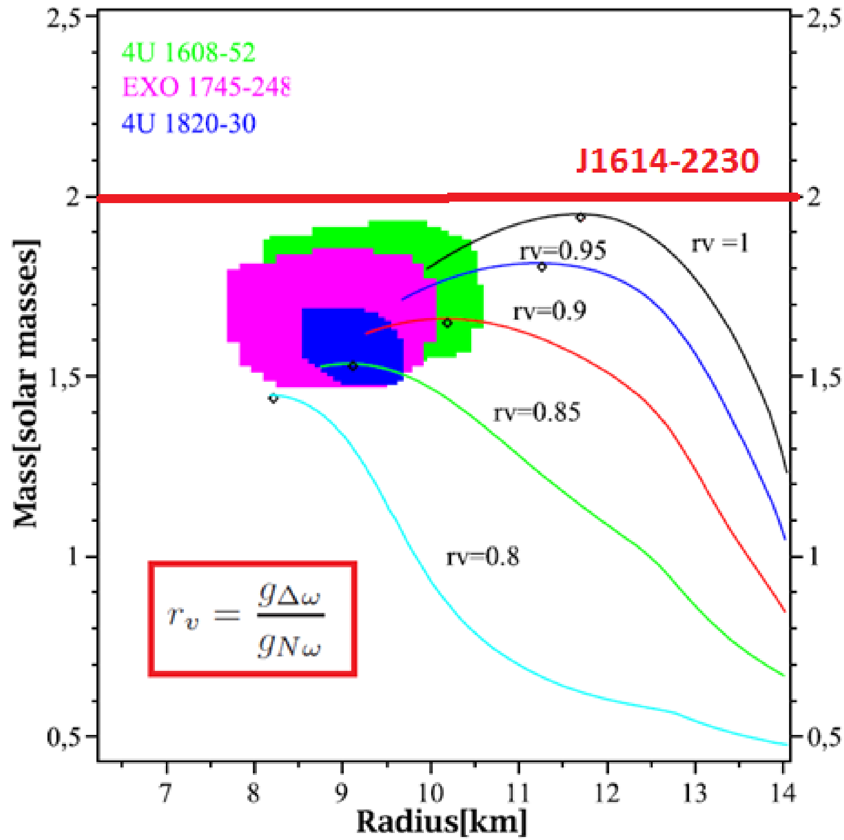


N* Resonances
in
Neutron Stars

Δ's in Neutron Stars

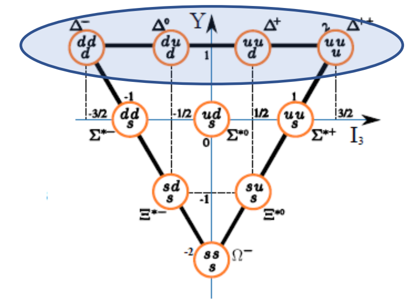
Baryon Octet:





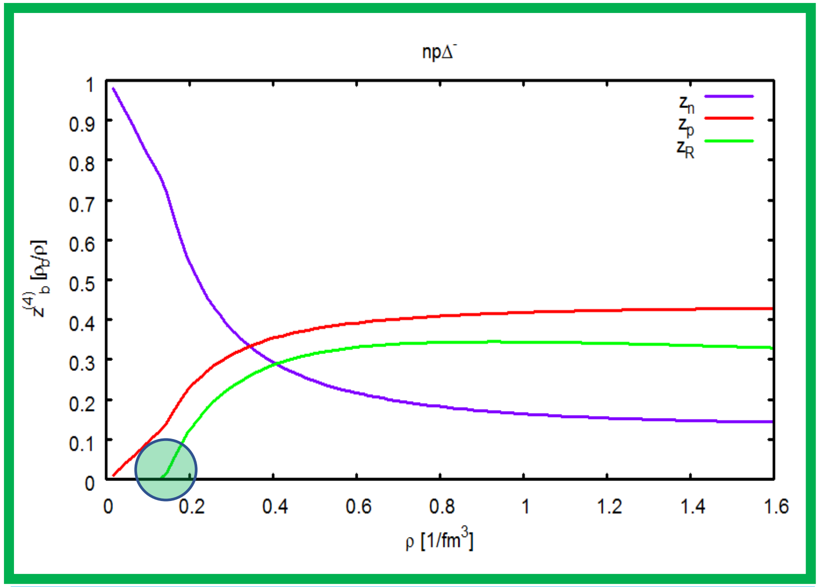
Mass-Radius-relationship of Neutron stars for various couplings of the Δ resonances, starting from $r_v = 1$ (upper line) to 0.8 (lowest line). Also included are the 1-σ errorbars for measured neutron stars . The black diamond on each curve represents the maximum stable configuration

Baryon Decuplet:



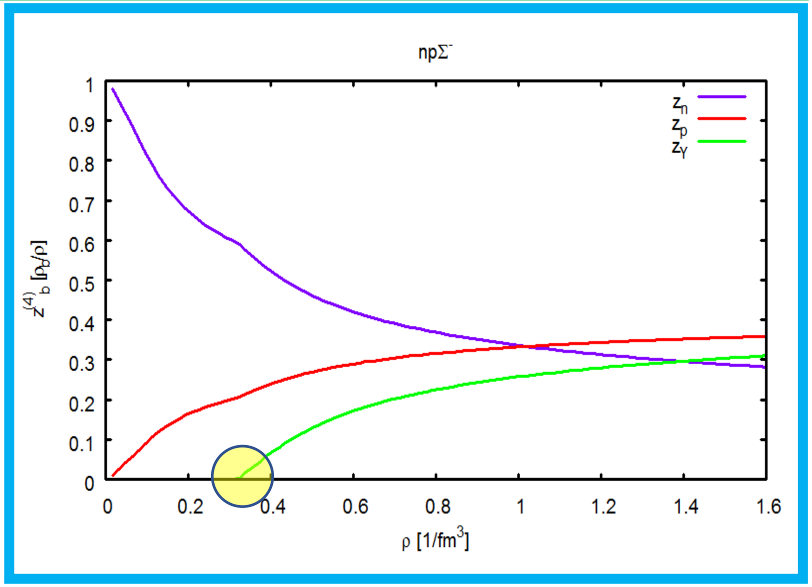
Schürhoff, Schramm,Dexheimer, *Astrophys.J.Lett.* 724 (2010) L74

Δ^- and Σ^- in Neutron Star Matter



npe$\mu\Delta^-$ matter in beta-equilibrium: onset at $\rho \sim \rho_{SAT}$

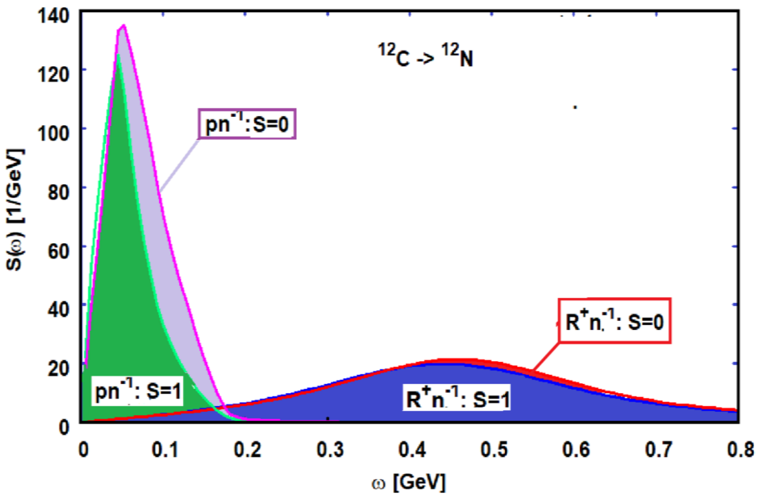
npe$\mu\Sigma^-$ matter in beta-equilibrium: onset at $\rho \sim 2\rho_{SAT}$

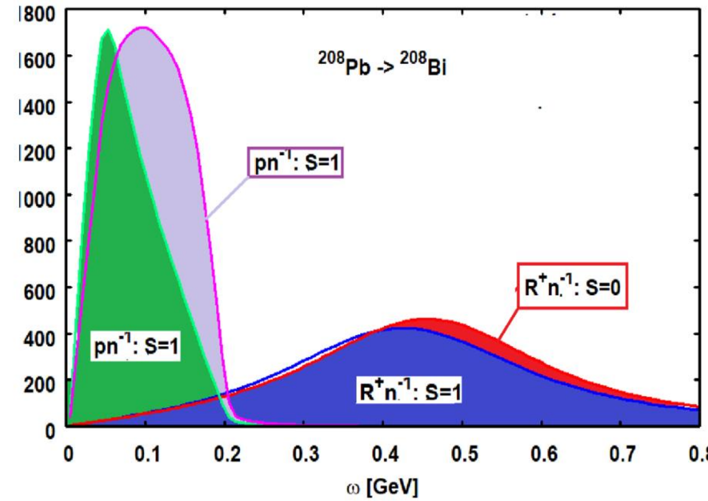


Spin-Scalar S=0 vs. Spin-Vector S=1 Response Functions

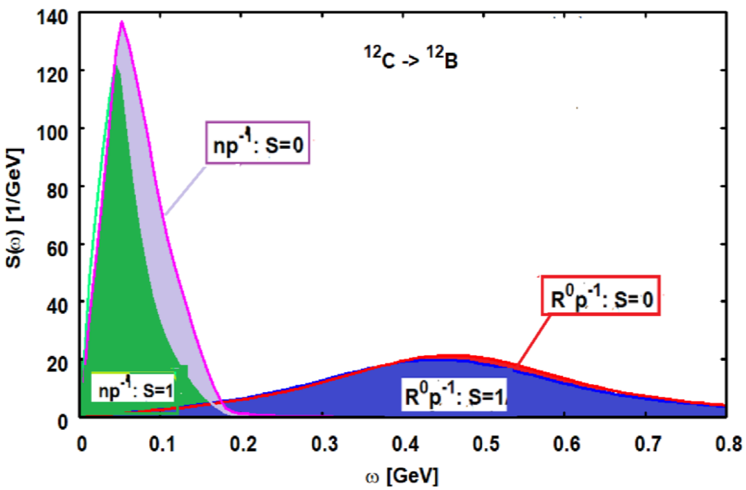
Longitudinal Response@q=300 MeV/c

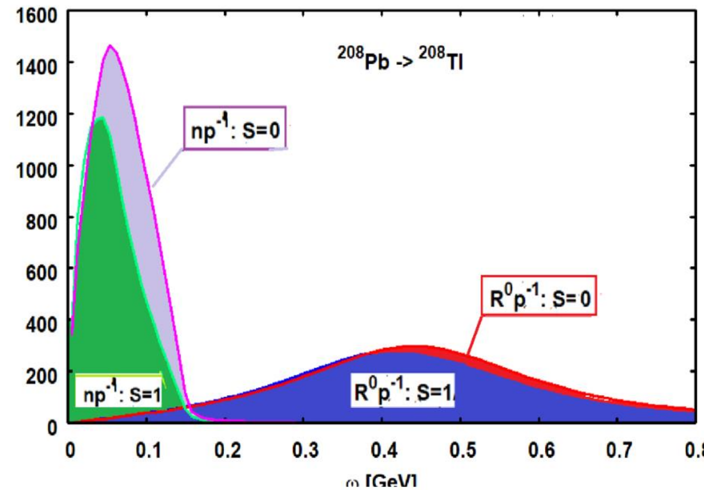
^{12}C | **^{208}Pb**





τ_+ operator : pn^{-1} – type
external probes: $\vec{\sigma}\bullet\vec{p}$ and 1





τ_- modes : np^{-1} – type
external probes: $\vec{\sigma}\bullet\vec{p}$ and 1

Structure of the Inelastic Cross Sections

$$\frac{d\sigma}{dE_b}\bigg|_{\text{in}} = \begin{cases} \langle N_{nn}\rangle \left|\mathcal{M}_{\text{in}}^{(nn\to pn\pi^-)}\right|^2 + \langle N_{np}\rangle \left|\mathcal{M}_{\text{in}}^{(np\to pp\pi^-)}\right|^2 + \langle N_{np}\rangle \left|\mathcal{M}_{\text{in}}^{(np\to pn\pi^0)}\right|^2 & (n,p)\text{-type} \\ \langle N_{pp}\rangle \left|\mathcal{M}_{\text{in}}^{(pp\to np\pi^+)}\right|^2 + \langle N_{pn}\rangle \left|\mathcal{M}_{\text{in}}^{(pn\to nn\pi^+)}\right|^2 + \langle N_{pn}\rangle \left|\mathcal{M}_{\text{in}}^{(pn\to np\pi^0)}\right|^2 & (p,n)\text{-type} \end{cases}$$

$$\left|\mathcal{M}_{\text{in}}^{(\tau_P\tau_T\to\tau_P'\tau_T'\pi)}\right|^2 = \frac{1}{S}\frac{|\vec{p}_b|}{(2\pi)^5}\frac{m^4}{\lambda^{1/2}(s,m^2,m^2)}$$

$$\times \int \frac{d\vec{q}}{(2\pi)^3}\frac{d\vec{p}_\pi d\Omega_b}{E_B E_\pi} R_\Delta^{(A)}(\sqrt{s}-E_b-E_\pi, \vec{q}-\vec{p}_\pi)\left\langle \left|M_{\text{in}}^{(\tau_P\tau_T\to\tau_P'\tau_T'\pi)}(\vec{q}-\vec{p}_\pi)\right|^2\right\rangle$$

„Collision Numbers" by Glauber-Model

$$\langle N_{np}\rangle = (A_P - Z_P)\frac{\sigma_T}{\sigma_{PT}},$$

$$\langle N_{pp}\rangle = Z_P\frac{\sigma_T}{\sigma_{PT}},$$

$$\langle N_{nT}\rangle = (A_T - Z_T)\frac{\sigma_P}{\sigma_{PT}},$$

$$\langle N_{pT}\rangle = Z_T\frac{\sigma_P}{\sigma_{PT}},$$

$$\sigma_{P(T)} = \int d\vec{b}(1-[1-T_{P(T)}(b)\sigma_{NN}]^{A_{P(T)}}),$$

$$T_{P(T)}(b) = \int dz\rho_{P(T)}(b,z),$$

$$\sigma_{PT} = \int d\vec{b}(1-[1-T_{PT}(b)\sigma_{NN}]^{A_PA_T}),$$

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

„Collision Numbers“ by Glauber-Theory

$$\langle N_{\tau_P \tau_T} \rangle = \langle N_{\tau_P} \rangle \times \langle N_{\tau_T} \rangle, \quad \tau_P = n, p, \ \tau_T = n, p,$$

$$\langle N_{n_P} \rangle = (A_P - Z_P) \frac{\sigma_T}{\sigma_{PT}},$$

$$\langle N_{p_P} \rangle = Z_P \frac{\sigma_T}{\sigma_{PT}},$$

$$\langle N_{n_T} \rangle = (A_T - Z_T) \frac{\sigma_P}{\sigma_{PT}},$$

$$\langle N_{p_T} \rangle = Z_T \frac{\sigma_P}{\sigma_{PT}},$$

$$\sigma_{P(T)} = \int d\vec{b} (1 - [1 - T_{P(T)}(b) \sigma_{NN}]^{A_{P(T)}}),$$

$$T_{P(T)}(b) = \int dz \rho_{P(T)}(b, z),$$

$$\sigma_{PT} = \int d\vec{b} (1 - [1 - T_{PT}(b) \sigma_{NN}]^{A_P A_T}),$$

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

→ Nuclear form factors and elementary NN-cross sections

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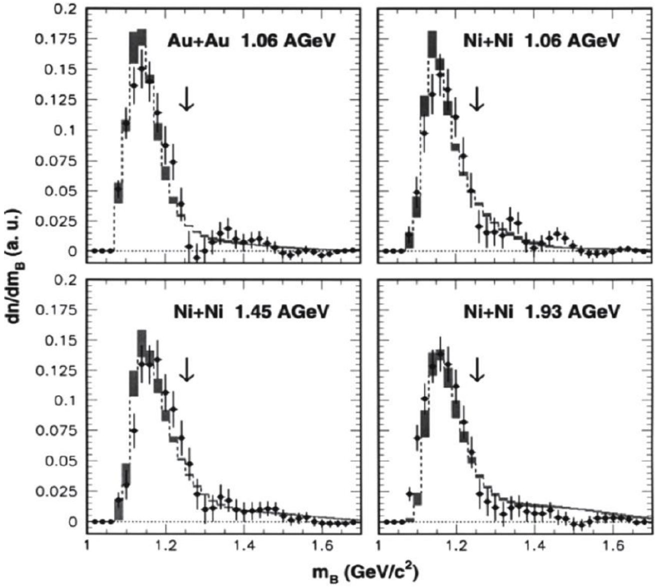
→ Nuclear form factors and elementary NN-cross sections

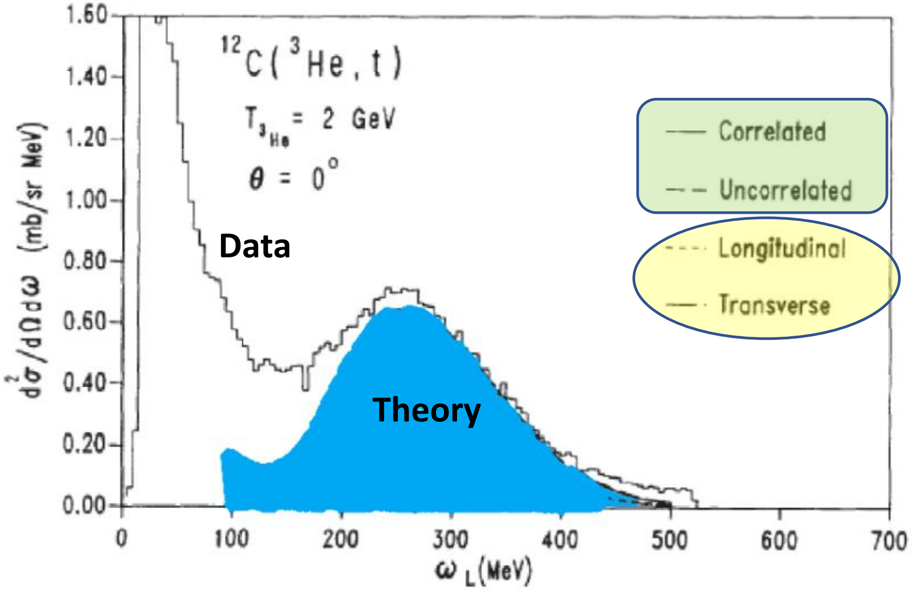
Discussion

Prelude: Early Resonance Studies with Heavy Ions

Central Heavy Ion Collisions
FOPI@GSI



Peripheral Charge Exchange Collisions
DIOGENE@SATURNE

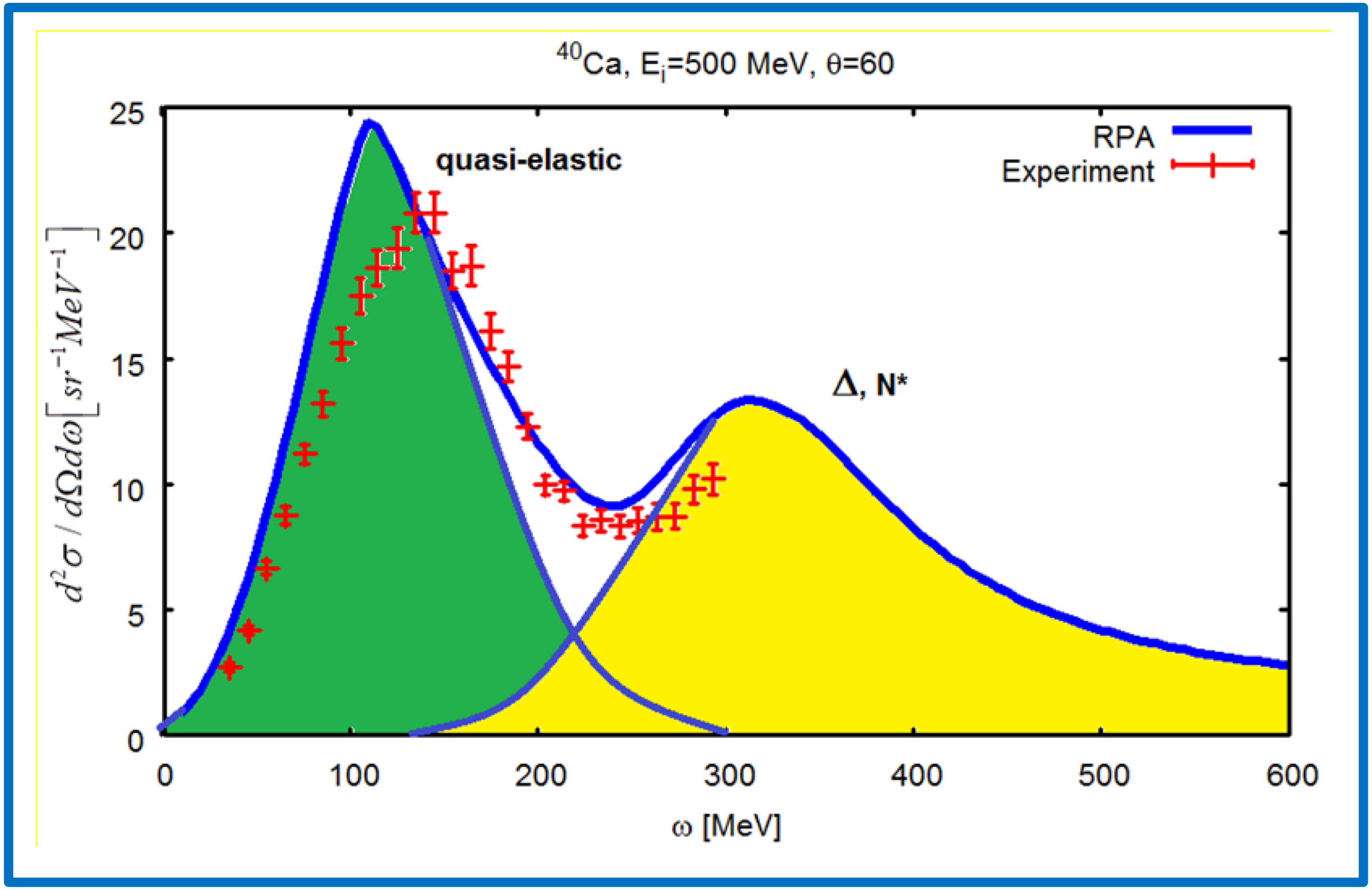


Filled symbols: transverse momentum spectra of $\pi^{\pm}$.
Filled circles: measured $p\pi^{\pm}$ pairs.
Arrows: Centroid of the free Δ(1232) mass distribution
M. Eskef, et al., Eur. Phys. J. A 3 (1998) 335

Theory: T. Udagawa et al., Phys. Rev. C 49 (1994) 3162
Data: D. Contardo, et al., Phys. Lett. B 168 (1986) 331

See also: **EOS@BEVALAC:** E.L. Hjort, et al., PRL. 79 (1997) 4345 ; **E814@AGS**, J. Barrette *et al.*, PLB **351**, 93 (1995) ; **Synchro-Phasotron@Dubna:** D. Krpic et al., PRC 65 (2002) 034909…

Photo-Excitation of Resonances in Inclusive (e,e‘) Scattering



Theory (GiEDF): NN^{-1} & N^*N^{-1} Longitudinal Response Functions by „N*-RPA“
***Data (Bates): Williamson et al., Phys.Rev.C* 56 (1997) 3152**

Cross Section for SCE Reactions at Relativistic Energies

$$d^2\sigma_{aA\to bB} \sim \sum_{\mu\nu} D_{aA,bB}(\sqrt{s},\vec{q}) R^{\dagger}_{ab,\mu\nu}\left(\omega-\omega_A,\vec{q}-\vec{q}_A\right) R^{\mu\nu}_{AB}\left(\omega_A,\vec{q}_A\right) d\omega d\Omega$$

Distortion Coefficient ↔ Ion-Ion Kinematics and elastic ISI/FSI:

$$\mathrm{D}_{aA,bB}\left(\sqrt{s},q\right) = \left\langle \chi^{(-)}_{bB} \middle| e^{iq\bullet r} \middle| \chi^{(+)}_{aA} \right\rangle$$

…at AGeV properly treated by Eikonal or Glauber Theory

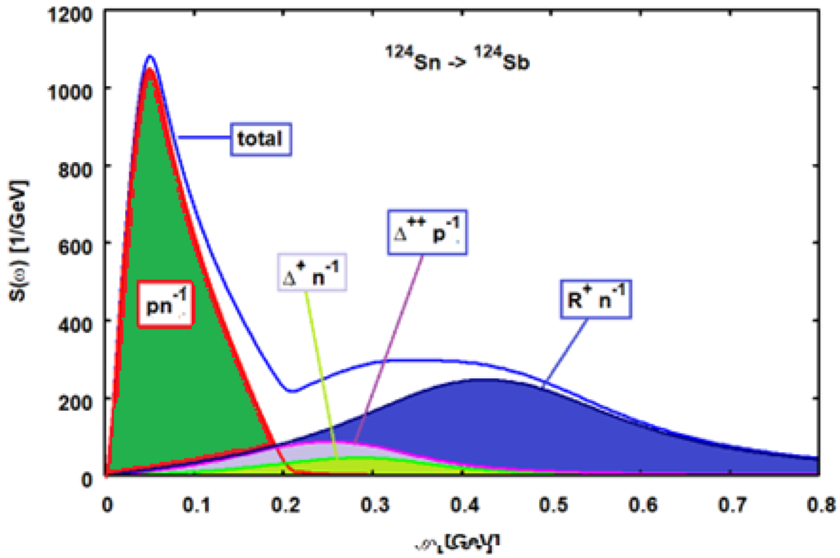
Hadronic Tensor ↔ Nuclear Response and Interactions:

$$R^{\mu\nu}_{X}\left(\omega,\vec{q}\right) = -\frac{1}{\pi}\mathrm{Im}\left(\sum_{\alpha=L,T} F_{\alpha}\left(\sqrt{s},\vec{q}\right)\Pi^{\mu\nu}_{\alpha X}\left(\omega,\vec{q}\right)\right)$$

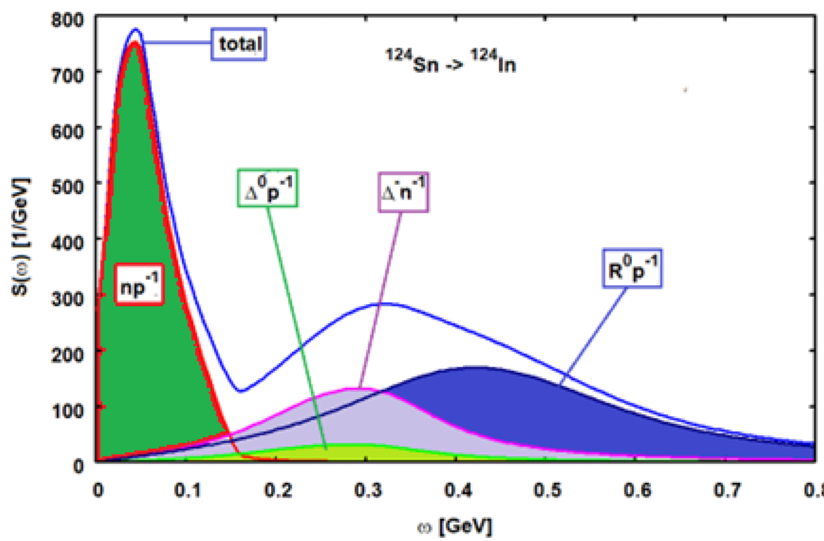
(X=ab;AB)

Composition of N^*N^{-1} Spectral Distributions – $P_{33}(1232)$ and $P_{11}(1440)$
Longitudinal@q=300 MeV/c

τ_+ operator : pn^{-1} – type
external probe: □ $\vec{\sigma} \bullet \vec{p}$



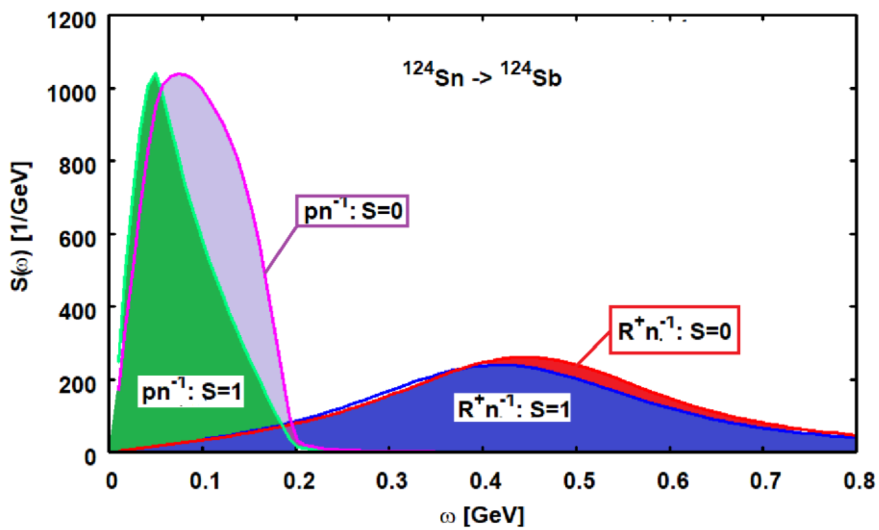
τ_- modes : np^{-1} – type
external probe: □ $\vec{\sigma} \bullet \vec{p}$



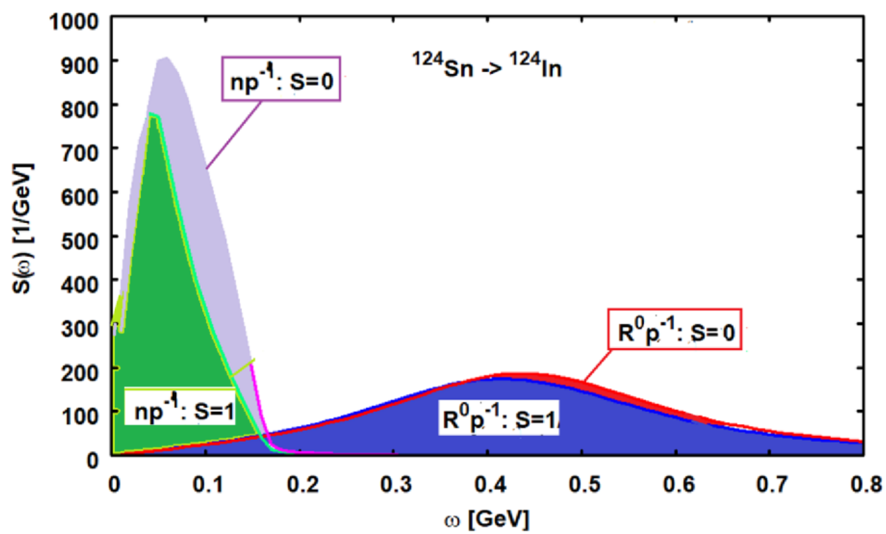
Spin-Scalar S=0 vs. Spin-Vector S=1 Modes

Longitudinal@q=300 MeV/c

τ_+ operator : pn^{-1} – type
external probes: □ $\vec{\sigma}\bullet\vec{p}$ and 1



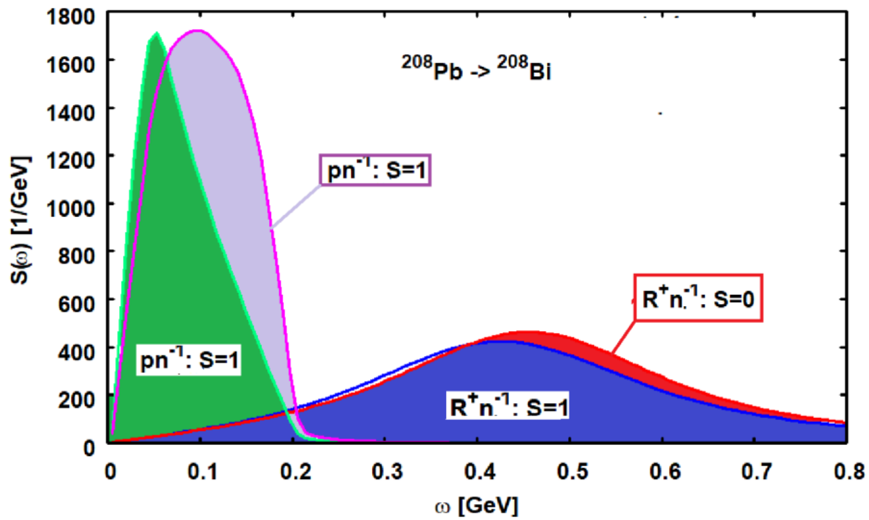
τ_- modes : np^{-1} – type
external probes: □ $\vec{\sigma}\bullet\vec{p}$ and 1



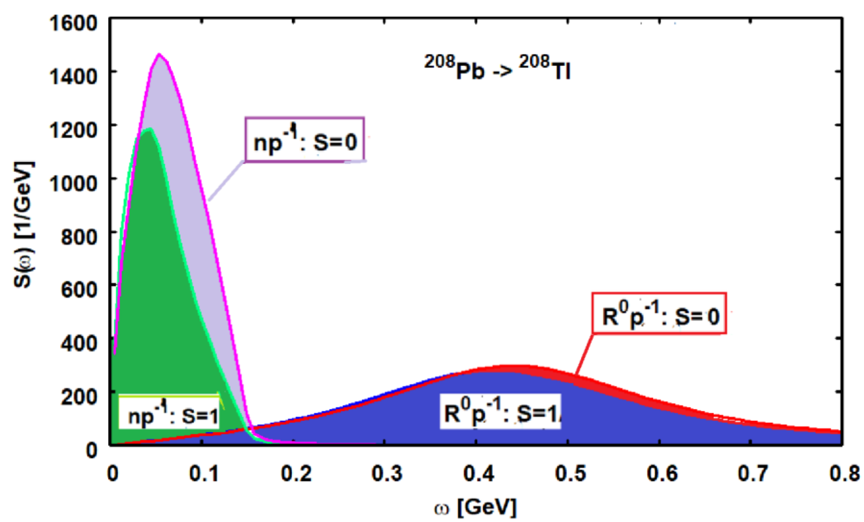
Spin-Scalar S=0 vs. Spin-Vector S=1 Modes

Longitudinal@q=300 MeV/c

τ_+ operator : pn^{-1} – type
external probes: $\square\ \vec{\sigma} \bullet \vec{\mathrm{p}}$ and 1



τ_- modes : np^{-1} – type
external probes: $\square\ \vec{\sigma} \bullet \vec{\mathrm{p}}$ and 1



Spin-Scalar S=0 vs. Spin-Vector S=1 Modes

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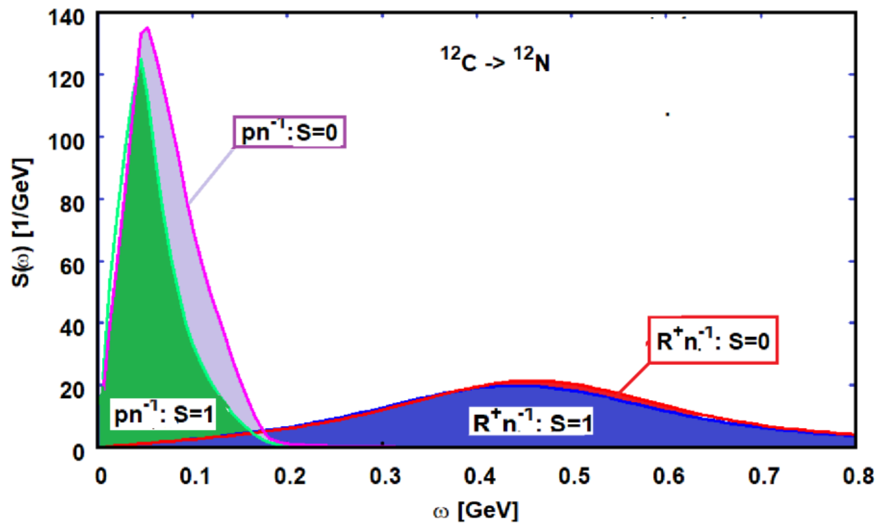

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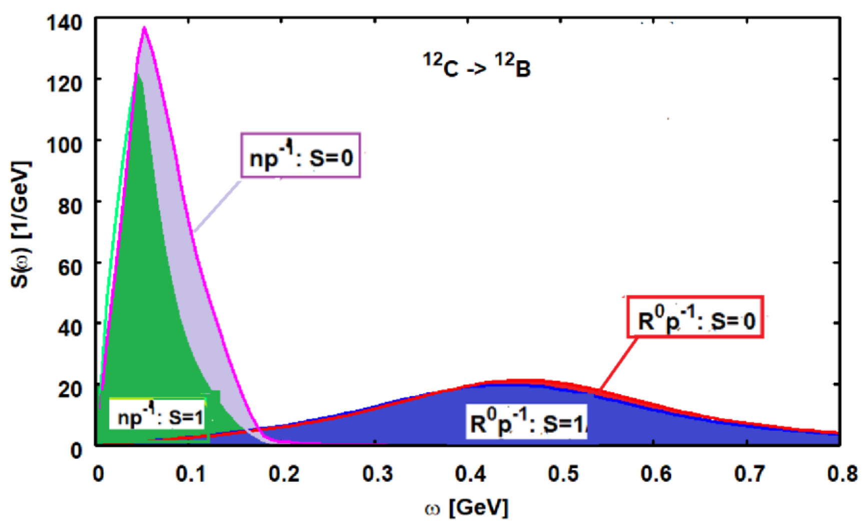
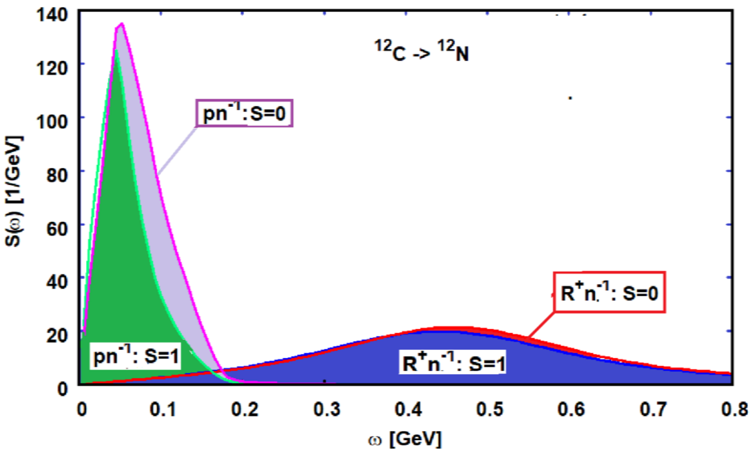
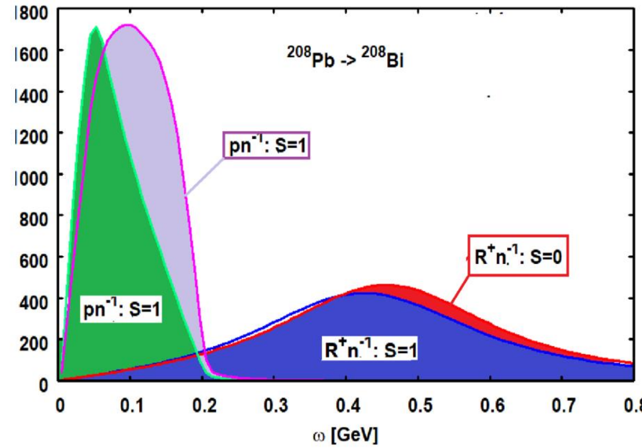


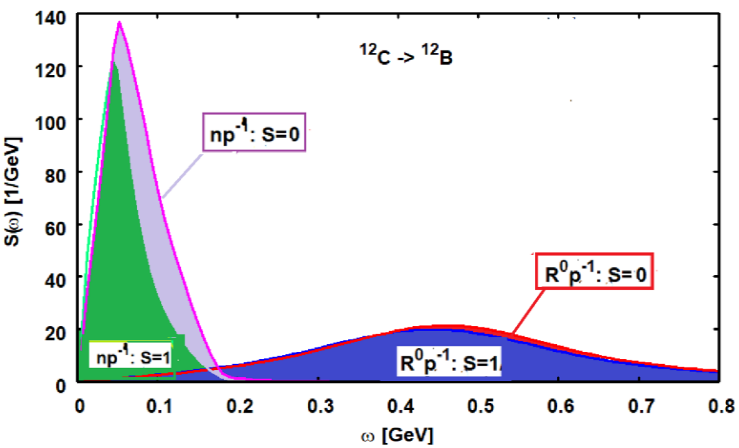
Spin-Scalar S=0 vs. Spin-Vector S=1 Modes

Longitudinal@q=300 MeV/c

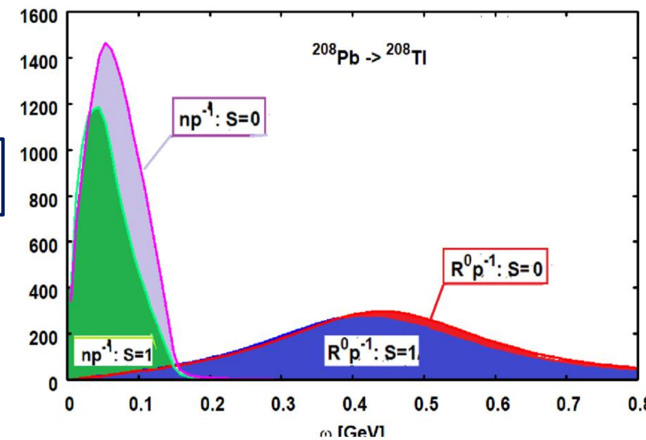


τ_+ operator : pn^{-1} – type
external probes: $\vec{\sigma}\bullet\vec{p}$ and 1



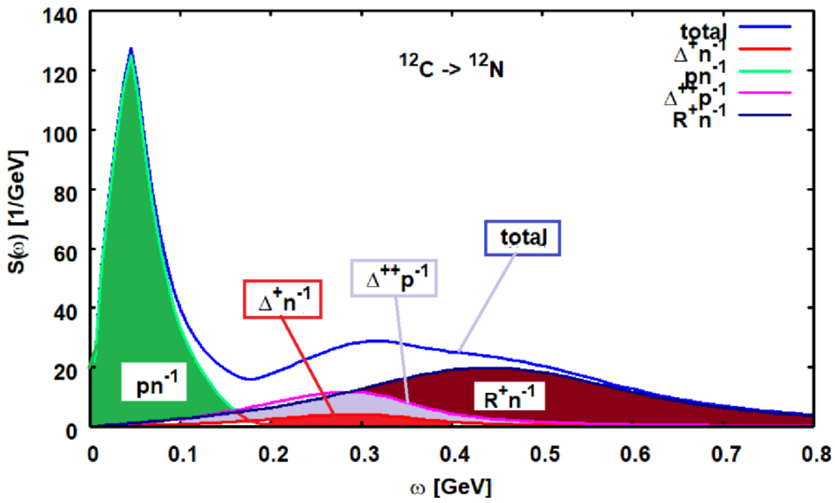


τ_- modes : np^{-1} – type
external probes: $\vec{\sigma}\bullet\vec{p}$ and 1

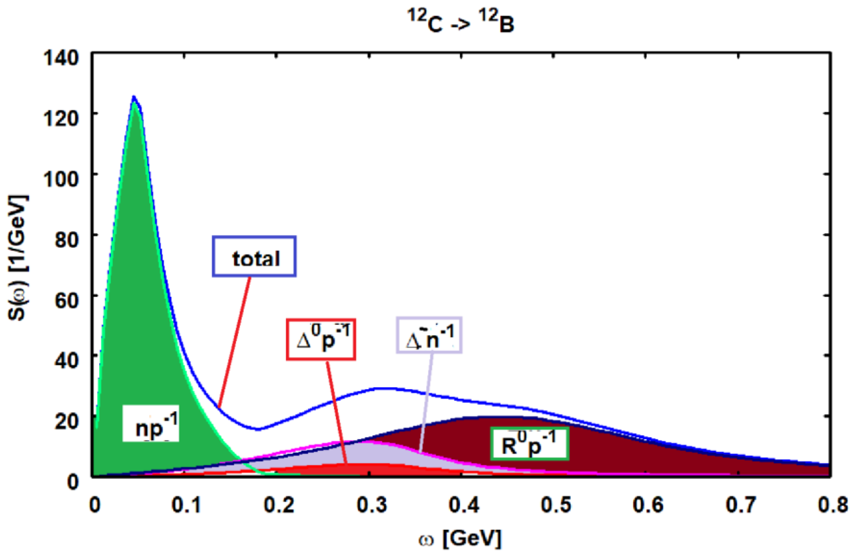


N*N^{-1} Spectral Distributions – $P_{33}(1232)$ and $P_{11}(1440)$
Longitudinal@q=300 MeV/c

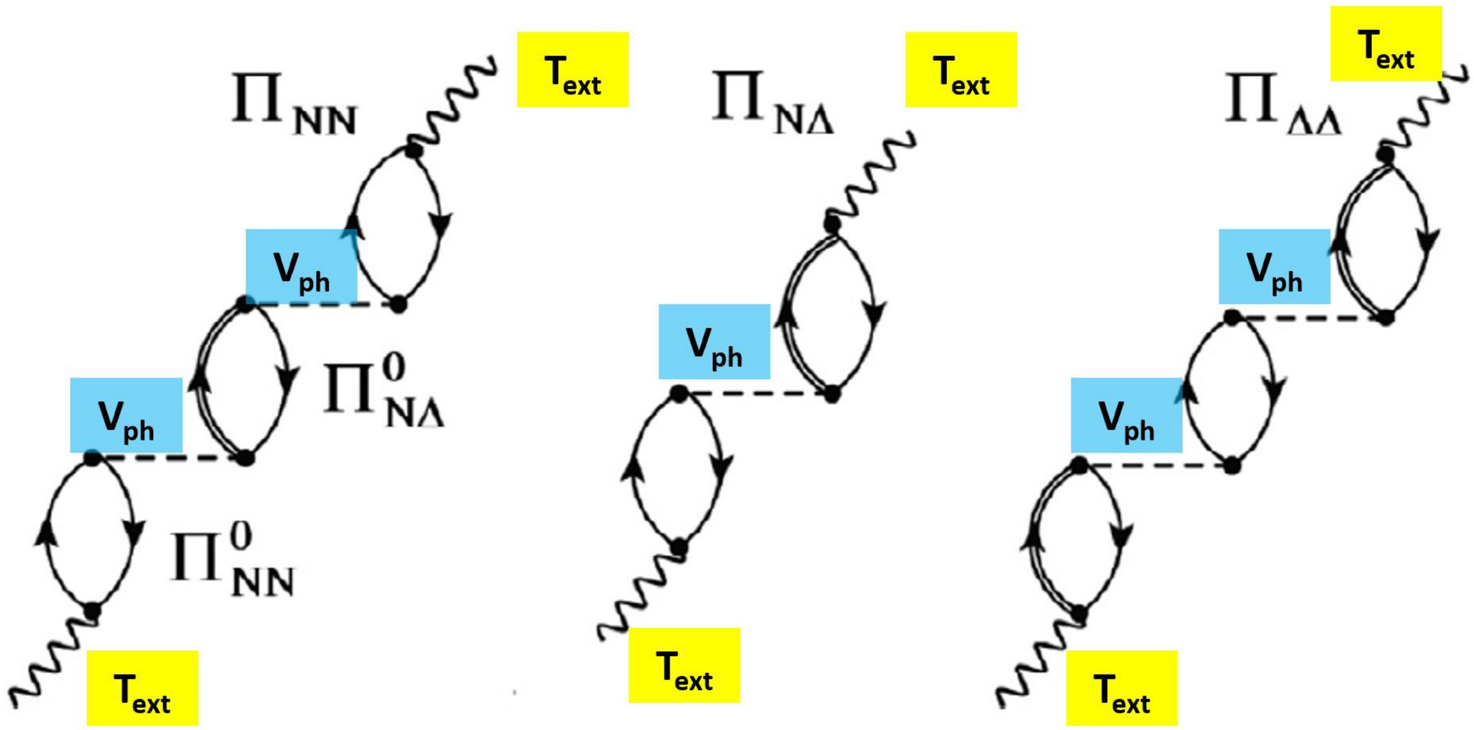
τ_{-} modes : np^{-1} – type
external probes: □ $\vec{\sigma}\bullet\vec{p}$ and 1



τ_{+} operator : pn^{-1} – type
external probes: □ $\vec{\sigma}\bullet\vec{p}$ and 1



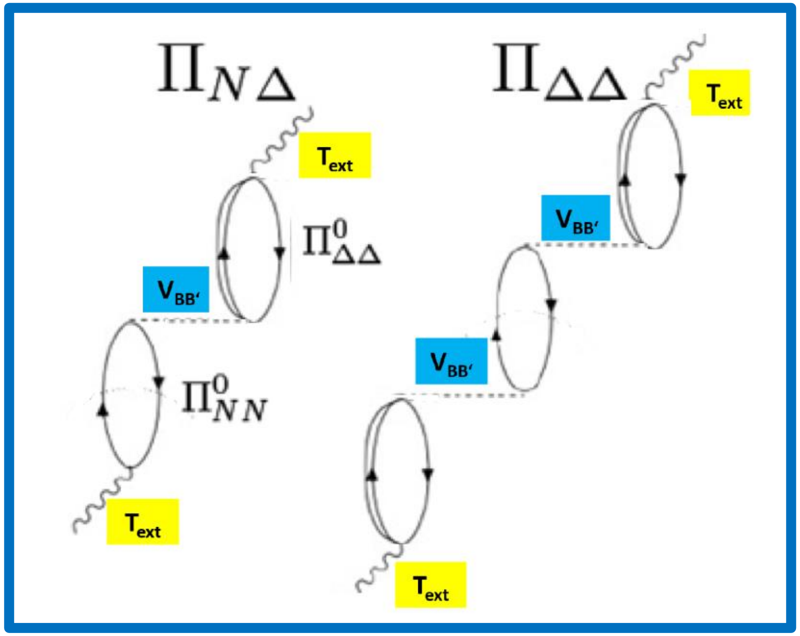
Polarization Tensor and Nuclear Response



V_{ph} ~ π, ρ, δ exchange and „short-range“ g‘

$$R_X^{\mu\nu}(\omega,\vec{q}) = -\frac{1}{\pi}\mathrm{Im}\left(\Pi_X^{\mu\nu}(\omega,\vec{q})\right) = -\frac{1}{\pi}\mathrm{Im}\left(\langle X | T_{ext}^{\dagger\mu}(\vec{q}) G_X(\omega) T_{ext}^{\nu}(\vec{q}) | X \rangle\right)$$

Polarization Tensor and Nuclear Response



$$V_{N\Delta} = \left(V_\pi \sigma_N \bullet q S_{N\Delta} \bullet q + V_\rho \sigma_N \times q \bullet S_{N\Delta} \times q + g'_{N\Delta} \sigma_N \bullet S_{N\Delta}\right) \tau_N \bullet T_{N\Delta}$$

$$V_{NR} = \left(V_\pi \sigma_N \bullet q \sigma_R \bullet q + V_\rho \sigma_N \times q \bullet \sigma_R \times q + g'_{NR} \sigma_N \bullet \sigma_{NR} + U_\rho + U_\delta\right) \tau_N \bullet \tau_R$$

$$R_X^{\mu\nu}(\omega, \vec{q}) = -\frac{1}{\pi} \mathrm{Im}\left(\Pi_X^{\mu\nu}(\omega, \vec{q})\right) = -\frac{1}{\pi} \mathrm{Im}\left(\langle X | T_{ext}^{\dagger\mu}(\vec{q}) G_X(\omega) T_{ext}^{\nu}(\vec{q}) | X \rangle\right)$$

Example: Elementary Modes in pn^{-1}-type (^{A}Sn,^{A}Sb) Reactions

$p(^{112,124}\mathrm{Sn},\ ^{112,124}\mathrm{Sb})X$	
Quasielastic	$p(n,p)n$
Inelastic (target)	Inelastic (projectile)
$p(n,p)\Delta^0 \rightarrow p(n,p)n\pi^0$	$p(n,\Delta^0)p \rightarrow p(n,p\pi^-)p$
$p(n,p)\Delta^0 \rightarrow p(n,p)p\pi^-$	$p(n,\Delta^+)n \rightarrow p(n,p\pi^0)n$
$p(n,p)n\pi^0$ (s wave)	$p(n,p\pi^-)p$ (s wave)
$p(n,p)p\pi^-$ (s wave)	$p(n,p\pi^0)n$ (s wave)
$^{A}Z\ (^{112,124}\mathrm{Sn},\ ^{112,124}\mathrm{Sb})X$	
Quasielastic	$p(n,p)n$
Inelastic (target)	Inelastic (projectile)
$p(n,p)\Delta^0 \rightarrow p(n,p)n\pi^0$	$p(n,\Delta^0)p \rightarrow p(n,p\pi^-)p$
$p(n,p)\Delta^0 \rightarrow p(n,p)p\pi^-$	$p(n,\Delta^+)n \rightarrow p(n,p\pi^0)n$
$p(n,p)n\pi^0$ (s wave)	$p(n,p\pi^-)p$ (s wave)
$p(n,p)p\pi^-$ (s wave)	$p(n,p\pi^0)n$ (s wave)
$n(n,p)\Delta^- \rightarrow n(n,p)n\pi^-$	$n(n,\Delta^0)n \rightarrow n(n,p\pi^-)n$
$n(n,p)n\pi^-$ (s wave)	$n(n,p\pi^-)n$ (s wave)