Nucleon Resonances in Exotic Nuclear Matter

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Prelude: Excitations of the Nucleon
$\Delta_{33}(1232)$ resonance in $\pi + p$ scattering

S. Lourenco, H.L., S. Wycech
Resonances in $\pi+N$ scattering
Level Scheme: GiM coupled channel analysis vs. PDG
Agenda:

• Resonance excitation in nuclei
• **Nuclear structure and the excited nucleon:** \( \Delta N^{-1} \) modes
• **Nuclear response functions with resonances**
• **Astrophysical connections**
• **Resonance physics at the FRS and Super-FRS**
Delta Resonances in Nuclei
$\Delta_{33}(1232)$ resonance in $\pi^+{}^6\text{Li}$ scattering

S. Lourenco, H.L. S. Wycech
Incoherent, inclusive \((p,n)\) Reaction

\[ \text{Corresponding Experiments at SATURNE in the 1980ties} \]

Datta: LAMPF/Los Alamos

Theory:
Reaction Dynamics
Inelastic Hadronic Reactions:
Charge Conserving $\Delta Q=0$ Excitation of Quasi-elastic and Resonance States

Neutral Current (NC) Reactions

Charge Exchange Hadronic Reactions:
Charge Changing $\Delta Q=\pm 1$ Excitation of Quasi-elastic and Resonance States

Charged Current (CC) Reactions
Hadronic Tensor in NC/CC Ion-Ion Reactions:

\[ d^2\sigma \sim \sum_{bB} |M_{aA\rightarrow bB}(\omega, \bar{q})|^2 \sim \sum_{\mu\nu} \left| V_\mu(q^2) V_\nu(q^2) \right|^2 W_{a,\mu\nu}(\omega, \bar{q}) W_{A,\mu\nu}(\omega, \bar{q}) \]

Hadronic Tensor:

\[ W_{X,\mu\nu}(\omega, \bar{q}) = T_{X}^{\mu}(\omega, \bar{q}) T_{X}^{\nu}(\omega, \bar{q}) = -\frac{1}{\pi} \text{Im}(\langle X | T^{\dagger \mu} G_{X}(\omega, \bar{q}) T^{\nu} | X \rangle) \]

Factorization of the Hadronic Tensor:

\[ W_{X,\mu\nu}(\omega, \bar{q}) \sim N(\sqrt{s}) |F_{X}(\bar{q})|^2 R_{\mu\nu}(\omega, q) \]

\[ R_{\mu\nu}(\omega, q) = -\frac{1}{\pi} \text{Im}(\Pi_{\mu\nu}(\omega, q)) \]

The Cross Section:

\[ d^2\sigma \sim \sum_{\mu\nu} \left| F_{a\mu}(q^2) \right|^2 \left| F_{\nu\lambda}(q^2) \right|^2 R_{a,\mu\nu}(\omega, \bar{q}) R_{A,\mu\nu}(\omega, \bar{q}) \]
Nuclear Response Functions
Resonance Excitation in Nuclei: "\(\Delta N^{-1} \text{ RPA}\)"

\[
\Pi = \Pi^0 + \Pi^0 \hat{V} \Pi \\
\begin{pmatrix}
\Pi_{NN} & \Pi_{N\Delta} \\
\Pi_{\Delta N} & \Pi_{\Delta\Delta}
\end{pmatrix} = 
\begin{pmatrix}
\Pi^0_{NN} & 0 \\
0 & \Pi^0_{\Delta\Delta}
\end{pmatrix} + 
\begin{pmatrix}
\Pi^0_{NN} & 0 \\
0 & \Pi^0_{\Delta\Delta}
\end{pmatrix} 
\begin{pmatrix}
V_{NN} & V_{N\Delta} \\
V_{\Delta N} & V_{\Delta\Delta}
\end{pmatrix} 
\begin{pmatrix}
\Pi_{NN} & \Pi_{N\Delta} \\
\Pi_{\Delta N} & \Pi_{\Delta\Delta}
\end{pmatrix}
\]

- Full RPA includes \(\Delta\)-N mixing
- Non-perturbative problem
- QE-peak is influenced by intermediate \(\Delta\)-hole pairs
- Structure of the spin-isospin response can give a deeper understanding of the \(\Delta\)-N interaction

\[
\Pi_{NN} = \chi_{\Delta N} \chi_N \Pi^0_{NN}
\]
CC QRPA Spin-Multipole Response: L=J-1

Ni → Co ($p \to n$)

Ni → Cu ($n \to p$)
Nuclear beta-decay
Weak Charge Changing Currents

\[ M(GT^\pm) \propto \left| \left\langle f \left| \frac{\sigma}{2} \cdot \tau^\pm \right| i \right\rangle \right|^2 \]

GT sum rule (model independent)
K. Ikeda PL 3, 271 (1963)

\[ S_{\beta^-} - S_{\beta^+} = 3(N - Z) \]
The GT-Quenching Problem: 
\(~50\% \text{ of the Ikeda Sum Rule is missing}\)
Quasi-Free Nuclear Response
Response Functions (per nucleon) in $\beta$-stable Nuclei: RPA results for $T_a=\tau_-$ (pn$^{-1}$ & $\Delta n^{-1}$ transitions)

$R(\omega,q) \sim \text{Im} \Pi(\omega,q)$

$|q|=300$

quasi-elastic

$\Delta(1232)$
Response Functions (per nucleon!) along the Ni-chain: RPA results for $T_\alpha=\tau_-$ (pn$^{-1}$ & $\Delta n^{-1}$ transitions)
Delta's in the Nuclear Medium
Delta Self-Energy in Nuclear Matter

Direct Self-energy $\rightarrow$ Hartree(Fock)-Potential

$$U_\Delta^{(H)} = U_0 + U_1 \tau_\Delta \cdot \tau_N$$
$$U_\Delta^{(H)} \sim U_0 - U_1 t_z^{(\Delta)} \cdot \frac{N-Z}{A}$$

Polarization Self-Energy $\rightarrow$ dispersive (optical) potential

$$\Sigma^{(\Delta)}_{pol} \sim \Sigma_0 - \Sigma_1 t_z^{(\Delta)} \frac{N-Z}{A}$$
$$\Sigma_\alpha = V_\alpha - iW_\alpha$$

...see e.g.:
In-Medium $\Delta(1232)$ Width

\[
\Gamma_{\Delta}(p_\Delta^2, \rho) = -2 \text{Im} \Sigma(p_\Delta^2, \rho) \sim \Gamma_{\text{free}}(p_\Delta^2) + \Gamma_{\text{Pauli}}(p_\Delta^2, \rho) + \Gamma_{\text{abs}}(p_\Delta^2, \rho)
\]

\[
\text{Re}\left(\Sigma(\omega, q)\right) = -\frac{2\omega}{\pi} P \int d\omega' \frac{\text{Im}\left(\Sigma(\omega', q)\right)}{\omega' - \omega}
\]
QCD Aspects of Resonances:

- hadronic (*soft scale*) molecular-type components \( |N_s\rangle \)
- QCD (*hard scale*) confined components \( |N_h\rangle \)

\[
|N^*\rangle = |N_s^*\rangle + |N_h^*\rangle = x_1 |mB\rangle + x_2 |qqq\rangle + x_3 |qqq\rangle \otimes |q\bar{q}\rangle + ...
\]

Strong Medium Dependence

Weak Medium Dependence
A Test Case:
Quasi-free Inclusive \((e,e')\) Scattering

\[ {^{40}\text{Ca}, E_i=500 \text{ MeV}, \theta=60} \]

\[ \frac{d^2\sigma}{dQd\omega} \text{ sr}^{-1}\text{MeV}^{-1} \]

\[ \omega \text{ [MeV]} \]
Connection to Astrophysics: Neutrino-Nucleus Interactions
Neutrino-Nucleus Cross Sections and $N\Delta$-Response Functions:
$\nu_\ell + N \rightarrow \Delta \rightarrow N + \pi$ Reactions
Inclusive CC cross section

J. Nieves, I. Ruiz Simo, M. J. Vicente Vacas
PRC 83, 045501 (2011)

Gießen „N-Δ RPA“
Connection to Astrophysics: Resonances in Neutron Stars?
Baryon Resonances in Neutron Stars?

(NN, NY, YY DBHF Interactions)

\[ \Delta \text{ and } N^* \text{ at } \rho \geq 6...7 \rho_0 \]
Challenges
Excitation of Higher Resonances in A+A Collisions

$^{12}$C+$^{12}$C @ 4.2 AGeV

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

<table>
<thead>
<tr>
<th></th>
<th>$M$ (MeV/$c^2$)</th>
<th>$\Gamma$ (MeV/$c^2$)</th>
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</thead>
<tbody>
<tr>
<td>$N(1440)$</td>
<td>1380 ± 10</td>
<td>130 ± 20</td>
</tr>
<tr>
<td>$N(1520)$</td>
<td>1550 ± 20</td>
<td>230 ± 30</td>
</tr>
<tr>
<td>The 3rd peak</td>
<td>1810 ± 30</td>
<td>510 ± 40</td>
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</tbody>
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<td>$N(1440)$</td>
<td>1420 ± 10</td>
<td>105 ± 15</td>
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<tr>
<td>$N(1520)$</td>
<td>1570 ± 20</td>
<td>190 ± 60</td>
</tr>
<tr>
<td>The 3rd peak</td>
<td>1790 ± 120</td>
<td>410 ± 90</td>
</tr>
</tbody>
</table>

Exclusive Reactions: Resonance Excitation and Meson Production in Ion-Ion Collisions
Exclusive reaction studies:

- $(p,n)$ reaction at KEK@$T_{lab}=830$MeV on $^{12}$C
- $(^3$He,$t)$ reaction at Saturne@$T_{lab}=2$GeV on $^{12}$C


FANCY@KEK 88% of $4\pi$

DIOGENE@SATURNE ~100% of $4\pi$
Summary and Outlook

- Resonances in cold, equilibrated nuclear matter
- Resonances as probes for nuclear isospin dynamics
- Resonances and Nuclear Response Functions
- Resonances beyond $\Delta(1232)$: $P_{11}(1440), D_{13}(1520)\ldots$
- Resonances and in-medium self-energies
- Resonance excitation and reaction dynamics
- Resonance tagging by pion production
- Resonances and astrophysics

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