$S_{11}$ resonances in meson baryon production

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Narrow Nucleon Resonances 2009:
Predictions, Evidences, Perspectives
Resonances in $\pi N$ scattering

The Jülich model of meson exchange.

| $N^*$ (1535) $S_{11}$ | Re $z_0$ [MeV] | -2 Im $z_0$ [MeV] | $|R|$ [MeV] | $\theta$ [deg] |
|----------------------|----------------|-------------------|----------|------------|
| ARN                  | 1519           | 129               | 31       | -3         |
| HOE                  | 1502           | 95                | 16       | -16        |
| CUT                  | 1510±50        | 260±80            | 120±40   | +15±45     |

| $N^*$ (1650) $S_{11}$ | Re $z_0$ [MeV] | -2 Im $z_0$ [MeV] | $|R|$ [MeV] | $\theta$ [deg] |
|----------------------|----------------|-------------------|----------|------------|
| ARN                  | 1669           | 136               | 54       | -44        |
| HOE                  | 1648           | 80                | 14       | -69        |
| CUT                  | 1640±20        | 150±30            | 60±10    | -75±25     |

| $N^*$ (1720) $P_{13}$ | Re $z_0$ [MeV] | -2 Im $z_0$ [MeV] | $|R|$ [MeV] | $\theta$ [deg] |
|----------------------|----------------|-------------------|----------|------------|
| ARN                  | 1663           | 212               | 14       | -82        |
| HOE                  | 1666           | 355               | 25       | -94        |
| CUT                  | 1680±30        | 120±40            | 8±12     | -160±30    |

| $\Delta (1232) P_{33}$ | Re $z_0$ [MeV] | -2 Im $z_0$ [MeV] | $|R|$ [MeV] | $\theta$ [deg] |
|-----------------------|----------------|-------------------|----------|------------|
| ARN                   | 1218           | 90                | 47       | -37        |
| HOE                   | 1211           | 99                | 52       | -47        |
| CUT                   | 1210±1         | 100±2             | 53±2     | -47±1      |

| $\Delta^*(1620) S_{31}$ | Re $z_0$ [MeV] | -2 Im $z_0$ [MeV] | $|R|$ [MeV] | $\theta$ [deg] |
|------------------------|----------------|-------------------|----------|------------|
| ARN                    | 1593           | 72                | 12       | -108       |
| HOE                    | 1595           | 135               | 15       | -92        |
| CUT                    | 1600±15        | 120±20            | 15±2     | -110±20    |

| $\Delta^*(1700) D_{33}$ | Re $z_0$ [MeV] | -2 Im $z_0$ [MeV] | $|R|$ [MeV] | $\theta$ [deg] |
|------------------------|----------------|-------------------|----------|------------|
| ARN                    | 1637           | 236               | 16       | -38        |
| HOE                    | 1632           | 253               | 18       | -40        |
| CUT                    | 1651           | 159               | 10       |            |

| $\Delta^*(1910) P_{31}$ | Re $z_0$ [MeV] | -2 Im $z_0$ [MeV] | $|R|$ [MeV] | $\theta$ [deg] |
|------------------------|----------------|-------------------|----------|------------|
| ARN                    | 1840           | 221               | 12       | -153       |
| HOE                    | 1771           | 479               | 45       | +172       |
| CUT                    | 1874           | 283               | 38       |            |


No pole term in the potential for the Roper; still a pole in the complex plane.
The $N^*(1535)$ as a dynamically generated resonance

- From the resonance picture to multiple rescattering:

- $(0^-)_M \otimes (1/2^+)_B$ in $SU(3)$: Coupled channels in $S = Q = 0$ are $\pi N, \eta N, K\Sigma, K\Lambda$.

- Interaction from the LO chiral Lagrangian: (Isovector) Weinberg-Tomozawa interaction.

- Unitarization through the Bethe-Salpeter equation

\[ T = (1 - VG)^{-1} V. \]

- $N^*(1535)$: Quasi-bound $K\Lambda, K\Sigma$ state
Photon coupling to the $N^*(1535)$
[Talk K. Nakayama on the ECT* PWA meeting, Trento June 2009]

Electromagnetic properties provide independent tests, because the couplings of the photon to the constituents of the resonances are well known. Parameter-free predictions are possible.
Additional degrees of freedom
Phase problem as explained in K. Nakayama's talk on the ECT* PWA Workshop Trento 06/2009.

- The $N^*(1650)$: Closeby resonance with the $N^*(1535)$’s quantum numbers → interfering resonances
- Could the $N^*(1535)$ be genuine? → put it as a resonance!
- → Include two genuine pole terms $\delta V_{ij} \sim \frac{g_i g_j}{\sqrt{s-M}}$ in the potential.
- Consider all available data on pion- and photon-induced reactions.
- Adjust the parameters: subtraction constants, couplings of the genuine resonances.
- With the following results:
Pole structure
Schematic picture; explained in greater detail in K. Nakayama’s talk, ECT*/Trento/06/2009.

Implications for fits using subthreshold resonances:
The $N^*(1535)$ may be gone!
$\pi N \rightarrow \pi N$

Real part and imaginary part of $S_{11}$ and $S_{31}$ as functions of $s^{1/2}$ in MeV.
\( \pi N \rightarrow \pi N \) at low energies

Refit; no genuine resonance terms.
\( \gamma p \rightarrow \pi^0 p \) at threshold

\[
E_{0^+} (\pi^0 p) \left(10^3 / m_{\pi^+}\right) \quad \text{vs.} \quad E_\gamma \ [\text{MeV}]
\]

- Re \( E_{0^+} \) shifted by -0.59
- corresponds to 10% change in Re phototransi. loop

Present model: Re \( E_{0^+} \) shifted by -0.59
corresponds to 10% change in Re phototransi. loop

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References:
- PRL 87, 232501 (2001)
- PRC 55, 2016 (1997) [Im: gray band]
- PRC 53, R1052 (1996)
- Maid 2007 [EPJA 34,69]
- ChPT [ZPhys C70, 483 (1996)]
- DR [PLB 399,13]
- Present model

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Edinburgh 06/10/2009

\( S_{11} \) resonances...
\( \gamma N \rightarrow \pi N \)

\[ S_{11} (p) \]

\[ S_{11} (n) \]

\[ S_{31} \]
\( \eta \) related quantities

\[ \gamma p \rightarrow \eta p \]

\[ \gamma n \rightarrow \eta n \]

\[ \pi^+ n \rightarrow \eta p \]

\[ \pi^- p \rightarrow \eta n \]

\[ \eta p \rightarrow \eta p \]

\[ \eta n \rightarrow \eta n \]

\[ \pi N \rightarrow \eta N \]

\[ E_{0+} \text{ amplitudes: ETA MAID, } S_{11} (\eta N): \text{ Arndt} \]
\( \eta \) related quantities

\[ \sigma [\text{mb}] \]

- \( \gamma p \rightarrow \eta p \)
- \( \gamma n \rightarrow \eta n \)
- \( \pi^+ n \rightarrow \eta p \)
- \( \pi^- p \rightarrow \eta n \)
- \( \pi N \rightarrow \eta N \)

\( E_{0+} \) amplitudes: ETA MAID, \( S_{11} (\eta N) \): Arndt

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The ratio \[ \frac{\sigma(\gamma n \rightarrow \eta n)}{\sigma(\gamma p \rightarrow \eta p)} \] Fermi motion not yet included.

Intermediate states in photon loops, \( Q = 0, 1 \):
- \( \pi^- p, \pi^0 n, \eta n, K^0 \Lambda, K^+ \Sigma^-, K^0 \Sigma^0 \)
- \( \pi^0 p, \pi^+ n, \eta p, K^+ \Lambda, K^+ \Sigma^0, K^0 \Sigma^+ \)

\[
a^-_1 = g^\gamma g_j, \quad g^\gamma = \sum_{i=1}^{6} \tilde{\Gamma}^i g_i, \\
i \tilde{M}_{PA} = \frac{a^-_1}{z - z_0}.
\]
The ratio \( \frac{\sigma(\gamma n \rightarrow \eta n)}{\sigma(\gamma p \rightarrow \eta p)} \) Fermi motion not yet included.

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- \( \pi^0 p, \pi^+ n, \eta p, K^+ \Lambda, K^+ \Sigma^0, K^0 \Sigma^+ \)

\( a_{-1} = g_\gamma g_j, \quad g_\gamma = \sum_{i=1}^{6} \tilde{\Gamma}^i g_i, \)

\( i \tilde{M}_{PA} = \frac{a_{-1}}{z - z_0}. \)
The ratio \( \frac{\sigma(\gamma n \rightarrow \eta n)}{\sigma(\gamma p \rightarrow \eta p)} \) Fermi motion not yet included.

- Intermediate states in photon loops, \( Q = 0, 1 \):
  - \( \pi^- p, \pi^0 n, \eta n, K^0 \Lambda, K^+ \Sigma^- , K^0 \Sigma^0 \)
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  - \( \pi^0 p, \pi^+ n, \eta p, K^+ \Lambda, K^+ \Sigma^0 , K^0 \Sigma^+ \)

\[
a_{-1}^\gamma = g_\gamma g_j, \quad g_\gamma = \sum_{i=1}^{6} \tilde{\Gamma}^i g_i,
\]

\[
i \tilde{M}_P^A = \frac{a_{-1}^\gamma}{z - z_0}.
\]
The ratio \( \frac{\sigma(\gamma n \rightarrow \eta n)}{\sigma(\gamma p \rightarrow \eta p)} \) Fermi motion not yet included.

- Intermediate states in photon loops, \( Q = 0, 1 \):
  - \( \pi^- p, \pi^0 n, \eta n, K^0 \Lambda, K^+ \Sigma^-, K^0 \Sigma^0 \)
  - \( \pi^0 p, \pi^+ n, \eta p, K^+ \Lambda, K^+ \Sigma^0, K^0 \Sigma^+ \)

\[
\begin{align*}
a_{-1}^\gamma &= g_{\gamma} g_{j}, & g_{\gamma} &= \sum_{i=1}^{6} \tilde{\Gamma}^i g_i, \\
i \tilde{M}^{PA} &= \frac{a_{-1}^\gamma}{z - z_0}.
\end{align*}
\]

- \( SU(3) \) loop structure explains naturally the excess in \( \sigma_n \).
The ratio \( \frac{\sigma(\gamma n \rightarrow \eta n)}{\sigma(\gamma p \rightarrow \eta p)} \) Fermi motion not yet included.

- Intermediate states in photon loops, \( Q = 0, 1 \):
  - \( \pi^- p, \pi^0 n, \eta n, K^0 \Lambda, K^+ \Sigma^-, K^0 \Sigma^0 \)
  - \( \pi^0 p, \pi^+ n, \eta p, K^+ \Lambda, K^+ \Sigma^0, K^0 \Sigma^+ \)

\[ a_{-1}^\gamma = g_\gamma g_j, \quad g_\gamma = \sum_{i=1}^{6} \tilde{\Gamma}^i g_i, \]

\[ i\tilde{M}^{PA} = \frac{a_{-1}^\gamma}{z - z_0}. \]

- \( SU(3) \) loop structure explains naturally the excess in \( \sigma_n \).
Remarks on $\sigma_n/\sigma_p$

- Full $SU(3)$ structure appears in intermediate photon loops of the $U\chi PT$ model (not considered in many phenomenological models).
- Structure in $\sigma_n/\sigma_p$ appears from coupling of the $\gamma$ to the $K\Lambda$ intermediate state (in interference with all other SU(3) allowed states).
- This is connected to:
  - Strong coupling of the $S_{11}$ partial wave to $K\Lambda$, $K\Sigma$, $\eta N$...
  - One of the consequences being a dynamically generated $N^*(1535)$, but rather think of an energy dependent amplitude.
- The excess in $\sigma_n \equiv \sigma(\gamma n \rightarrow \eta n)$ appears as a pure interference effect in $S_{11}$, from 1535 and 1650, but – more important – intermediate photon loops with full $SU(3)$ structure. Signs of this have always been there.
- The excess in $\sigma_n$ appears qualitatively in different coupled channel models that comprise SU(3) structure plus unitarization. It appears in fits where $\sigma_n/\sigma_p$ is not included (the rest is fine tuning). $\pi\pi N$ in $\eta N$ production.
- Full rise and fall in $\sigma_n/\sigma_p$ appears after including the $N^*(1650)$.
- Isospin limit, no genuine states, only $\pi N$ photon loop: $\sigma_n/\sigma_p \equiv 1$.
\( \gamma N \rightarrow KY \) 

\[ \pi N \rightarrow KY \text{ of similar quality} \]

- \( \gamma p \rightarrow K^+ \Lambda \)
- \( \gamma p \rightarrow K^+ \Sigma^0 \)
- \( \gamma p \rightarrow K^0 \Sigma^+ \)

Data: SPAHIR, \( E_{0^+} \): KAON-MAID, brown dotted lines: Background diagrams (real)
Properties of the present solution

- Combined analysis of reactions in $S_{11}$ and $S_{31}$, for
  - $\pi N$ and $\gamma N$ initial state.
  - $\pi N$, $\eta N$, $K\Lambda$, $K\Sigma$ final state.

- Features of the solution (decided by the fit):
  - Dynamically generated $N^*(1535)$.
  - Genuine pole term for the $N^*(1650)$ (resonance interference with $N^*(1535)$).
  - Second genuine pole far in complex plane produces small background instead of replacing the $N^*(1535)$. Mostly needed for missing $t$ channel meson exchange with anomalous photon couplings.
  - Dynamical generation of virtual state close to threshold. May be genuine or “mock up” of subthreshold cuts.
  - Some need for higher chiral interactions at low energies is seen (too much strengths below the $\eta N$ threshold); $\pi\pi N$ channel could be included.

- Simultaneous description of different $\eta N$ cusps (forms, strengths) and $N^*(1535)$ phases in $S_{11}(\pi N \rightarrow \pi N)$, $E_{0+}(\gamma p)$, $E_{0+}(\gamma n)$.

- Photon coupling to intermediate $\pi N$, $K\Lambda$, $K\Sigma$ can explain $\sigma_n/\sigma_p$ in $\gamma N \rightarrow \eta N$. 
Previous results
The rise in $\sigma_n/\sigma_p$ observed in different models.

The rise has been observed in previous models that comprise the full space of SU(3) allowed channels. No Fermi motion included.
Necessary inelasticity from $\pi\pi N$ to bring the cross section in $\pi N \rightarrow \eta N$ down from $3.5 \mu b$; consequence of unitarity and inelasticity [Argument by C. Hanhart].
\[ \pi N \rightarrow KY \]
### Pole positions and coupling strengths

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<tr>
<td>( z_0 ) [MeV]</td>
<td>( 1537 - 37 i )</td>
<td>( 1537 - 139 i )</td>
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<td>( g_{\pi^- p} )</td>
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<td>( g_{\eta n} )</td>
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