Search for Narrow Resonances in Partial Wave Analyses

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_to the memory of Richard A. Arndt_

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Prehistory of the problem

Motivation:
strange resonances
\( \Sigma(1480) \) and \( \Xi(1620) \).
Still present in PDG Listings,
though status is low (*)

Question:
where is their non-strange partner?

Answer:
GMO \( \rightarrow \) N'(\( \Delta' \)) in the studied region,
near (or even below) \( \pi N \) threshold.

Various exp. data (chexch, photo-electroprod.) \( \rightarrow \) heavy restrictions
for production cross sections and decay widths, both strong and e.-m.;
if exists, the state should be narrow and have small production xsection:
"might be a consequence of the sharp difference
in inner quark structure of N' and N"

(many examples in atomic physics, but not in hadron physics ).
PWA of 1970 could only restrict \( (g_{NN'\pi})^2 < 0.1 (g_{NN\pi})^2 \) .
Since 90's - direct searches for light narrow baryonic states:

TRIUMF 94; Saclay 97, 03; INR, Moscow, 01; RCNP, Osaka, 02; JLab (Hall A), 03; MAMI, 03.

There are some evidences, but not decisive or convincing.

In 2003 I was invited to JLab in order to clarify, in collaboration with the GWU group, the status of light baryonic resonances.

The planned program was mainly:

1) to reconsider and tighten previous restrictions;
2) to find new restrictions, especially from PWA (much better quality in 2003, as compared to 1970).

Beginning of my collaboration with Dick Arndt and his group.
Light baryon resonances: Restrictions and perspectives

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The problem of nucleon resonances $N'$ with masses below the $\Delta$ is considered. We derive bounds for the properties of such states. Some of these are new, while others improve upon existing limits. We discuss the nature of $N'$ states, and their unitary partners, assuming that their existence can be verified.

Previous restrictions for states below $\pi N$ threshold became stronger, 1 – 2 orders (mainly due to new exp. data).

E.g., $(g_{NN'\pi})^2 < 0.01 (g_{NN\pi})^2$.

Better quality of PWA, reached to 2003, allowed to suggest a new approach.

It gave new restrictions: If there exists a state $N'$ ($\Delta'$) with any values of $J^P$ in the pure elastic region between $\Delta$ and $\pi N$ threshold, then its width $\Gamma < 50$ keV.
The next step: the problem of \( \Theta^+ \)-baryon

If the \( \Theta^+ \) exists, with mass about 1540 MeV, it should have \( J^P=1/2^+ \) (P01) and \( \Gamma < 1 \) MeV.

More detailed investigation gives here \( \Gamma < 0.7 \) MeV.

Present experim. value \( \Gamma = (0.36+/0.11) \) MeV [DIANA Coll., Ph.At.Nucl. 70, 35 (2007)]
Method of search for pure elastic narrow resonances is extended to inelastic region of an elastic amplitude. An evidence is obtained for the \( N'(P11) \) with \( J^P=1/2^+ \), with mass about 1680 MeV and very small elasticity \( \Gamma_{\pi N} < 0.5 \) MeV.

A decuplet member is predicted to have larger widths for \( \pi\Delta, \eta N, \) and \( K\Lambda \) decay modes. Check these channels.
Fit to photoproduction $\gamma + p \rightarrow K^+ + \Lambda$ gives some evidence for a narrow state with $M = 1650$ MeV and $J^p = 1/2^+$. Presumably, it is the same state as $N'(1680)$, which came from $\pi N$ PWA.
Narrow Nucleon Resonances:

Predictions, Evidences, Perspectives

Edinburgh, 8--11 June, 2009;  http://2009physicsevents.org

N(1680) ???

seen (?) in two processes now

- η-photoproduction off the neutron
- Compton scattering on the neutron
- no direct signal on the proton
  (as expected for antidecuplet)

all apparent widths are consistent with resolutions
From talk of V. Kuznetsov at Baryons' 10, Osaka, December 2010

At present, the only explanation that accommodates all experimental findings is the existence of a narrow N(1685) resonance.
Search for higher flavor multiplets in partial-wave analyses

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Abstract. The possible existence of higher multi-quark flavor multiplets of baryons is investigated. We argue that the $S$-matrix should have poles with any quantum numbers, including those which are exotic. This argument provides a novel justification for the existence of hadrons with arbitrary exotic structure. Though it does not constitute a proof, there are still no theoretical arguments against exotics. We then consider $KN$ and $\pi N$ scattering. Conventional and modified partial-wave analyses provide several sets of candidates for correlated pairs ($\Theta_1$, $\Delta$), each of which could label a related 27-plet. Properties of the pairs (masses, mass orderings, spin-parity quantum numbers) do not quite correspond to the current theoretical expectations. Decay widths of the candidates are either wider or narrower than expected. Possible reasons for such disagreements are briefly discussed.
HardWay to NR
PWA and Narrow Resonances: "Technology"

Two different kinds of PWA's

**Single-Energy PWA**
is made independently in narrow energy bins.

**Energy-Dependent PWA**
uses an energy-dependent parametrization to consider simultaneously data at various energies.

Both kinds miss narrow resonances (if they exist)

Resolution problems, gaps between data.

Parametrizations assume mild energy dependence, may strongly smear a narrow peak.

For $\pi N$ PWA the boundary is about 25 – 30 MeV. A new approach is necessary for smaller widths!
Consider an elastic scattering.  
Let us take a ED PWA (without narrow resonances),  
that fit data with some $\chi^2$.  
Add a narrow resonance with given parameters $(J^P, M, \Gamma)$.  

If new $\chi^2$ becomes larger, the resonance is absent.  
If new $\chi^2$ becomes smaller, we have a possible candidate.  

**WARNING:**  
Procedure of appending a narrow resonance should not violate UNITARITY.
Narrow Resonances: Modification of PWA

Unitary modification of PWA for an elastic transition $a \rightarrow a$

**Elastic energy region:**
\[
\langle a|S|a \rangle = \exp(2i\delta_a); \quad \delta_a = \delta^B_a + \delta_R;
\]
we may rewrite \[
\langle a|S|a \rangle = S^B_a + \exp(2i\delta^B_a)[\exp(2i\delta_R)-1];
\]
as background we take the ED PWA;
\[
\exp(2i\delta_R) = (M_R - W + i\Gamma_R/2)/(M_R - W - i\Gamma_R/2).
\]

**Inelastic energy region:**
If $\Gamma_R$ is smaller than the scale of characteristic changes,
\[
\langle a|S|a \rangle = S^B_a + r_a \exp(2i\delta_0)[\exp(2i\delta_R)-1],
\]
$r_a$ – branching ratio; $\delta_0$ – some eigenphase of the $S$-matrix;
of course, should be $|\langle a|S|a \rangle| \leq 1$. 
Narrow Resonances: Modification of PWA

Unitary modification of PWA for a general transition \( a \to b \):

\[
\langle b | S | a \rangle = S^B_{ba} + r_{ba} \exp(2i \delta_0)[\exp(2i \delta_R)-1], \quad |\langle b | S | a \rangle| \leq 1.
\]

What is the background?

\( \pi N \) analyses in PR C\textbf{68}(2003), PR C\textbf{69}(2004), and EPJ A\textbf{26}(2004) use the SAID \( \pi N \) PWA.

\( KN \) analyses in PR C\textbf{68}(2003) and NP A\textbf{754}(2005) use VPI KN PWA.

Analysis of \( K \Lambda \) photoproduction by T.Mart uses two models that fit experimental data.
What have we learned from work with modified PWA?

♦ The negative effect is quite good to reject a narrow resonance with given parameters.

♦ The positive effect does not necessarily mean existence of the resonance.
Similar change of $\chi^2$ for different partial amplitudes in $\pi N$ scattering.

It is related here to the nearby $\pi\pi N$ threshold at about 1220 MeV.

The inserted resonance may imitate (correction to) some other singularity. Typical property of such a case is the similar effect in different partial waves. Check them!

FIG. 2. Change of overall $\chi^2$ due to insertion of a resonance into (a) $P_{33}$ and (b) $P_{11}$ for $M=1100–1295$ MeV and $\Gamma=100$ and 150 keV, using $\pi N$ PWA [22]. The curves are given to guide the eye.
[AAPSW, PR C69 (2004)]

The possible effect in $\pi N$ at 1680 MeV is present in one partial amplitude, but absent in adjacent amplitudes.
Another case may be related to a gap in experimental data.

[AASW, PR C68 (2003)]

Effect of possible resonance at $M=1145$ MeV ($E=79.5$ MeV) may be negligible even at the nearest measured energy.
The suggested position of the resonance may be used to choose energy for additional measurements, where presence/absence of the resonance might be clearly discriminated.

[AASW, PR C68 (2003)]
What have we learned from work with modified PWA?

- In the inelastic region, the method have much better sensitivity to the partial width $\Gamma_a$, than to the total width $\Gamma_R$.

- Mass of the suggested narrow resonance may slightly depend on the energy interval used in the fit.
Indeed, $\Gamma_R$ appears only in the denominator and may be neglected at the tails, where $|M_R - W| \gg \Gamma_R$. On the other side, $\Gamma_a$ appears in the nominator and cannot be neglected without rejecting the Res.

The used interval of mass (energy) influences the length of the “active part” of the BW tail.
Final Conclusions

- Canonical PWA tends to miss Narrow Resonances (NR’s).
- Modification of PWA may be a good instrument to work with possible NR’s.
- If insertion of a NR gives negative result, \( \Delta \chi^2 > 0 \), the NR is definitely rejected.
- Positive result, \( \Delta \chi^2 < 0 \), does not prove existence of the NR and needs further checks.
- The case of N(1680) demonstrates that the modified PWA may be reasonably used for targeting and planning further studies to confirm the suggested Narrow Resonance.
- The method may also be used to check the quality of description of known singularities in the particular PWA.
Thank you for attention