The neutron anomaly in the $\gamma N \rightarrow \eta N$ cross section through the looking glass of the flavour SU(3) symmetry

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Abstract

We study the implications of the flavour SU(3) symmetry for various interpretations of the neutron anomaly in the $\gamma N \rightarrow \eta N$ cross section. We show that the explanation of the neutron anomaly due to interference of known N(1535) and N(1650) resonances implies that N(1650) resonance should have a huge coupling to $\phi$-meson – at least 5 times larger than the corresponding $\rho^0$ coupling. In terms of quark degrees of freedom this means that the well-known N(1650) resonance must be a “cryptoexotic pentaquark” – its wave function should contain predominantly an $s\bar{s}$ component.

It turns out that the “conventional” interpretation of the neutron anomaly by the interference of known resonances metamorphoses into unconventional physics picture of N(1650).

Introduction

The discovery of the neutron anomaly\textsuperscript{†} in the $\gamma N \rightarrow \eta N$ cross section was reported in Ref. [1], in this paper the GRAAL data on the photon scattering off the deuteron were analysed. Presently three other collaborations (LNS [2], CBELSA/TAPS[3], and A2 [4]) confirmed the neutron anomaly beyond any doubts. For an illustration of the neutron anomaly in $\gamma N \rightarrow \eta N$ we show on Fig. 1 the most recent results of the A2 collaboration [4]. Furthermore the neutron anomaly at the same invariant mass of $W \sim 1680$ MeV was also observed in the Compton scattering [5].

In our view the observation of the neutron anomaly is the most striking discovery in the field of the nucleon resonances spectroscopy during the last decade. It is important to figure out the physics nature of the phenomenon. In the present paper we study the implications of the flavour SU(3) symmetry for various explanations of the neutron anomaly.

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\textsuperscript{†}Existence of the narrow ($\Gamma \sim 10-40$ MeV) peak in the $\gamma n \rightarrow \eta n$ cross section around 1680 MeV and its absence in the $\gamma p \rightarrow \eta p$ process
Figure 1: Figure from Ref. [4]. Total cross sections as a function of the final-state invariant mass $m(\eta N)$: Blue triangles: proton data. Red circles: neutron data scaled by 3/2. Black stars: free proton data from MAMI-C [6]. Hatched areas: total systematic uncertainties of proton (blue) and neutron (red) data.

Flavour SU(3) decomposition of the $\gamma N \to \eta N$ amplitude

In the SU(3) symmetry limit the amplitudes $A(\gamma p \to \eta p)$ and $A(\gamma n \to \eta n)$ can be decomposed through the amplitudes corresponding to the irreducible representations of the SU(3) group in the s-channel. The photon and the nucleon belong to the octet representation of the SU(3) group. Therefore the possible representations in the s-channel are those which appear in the product $8 \times 8 = 1 + 8_F + 8_D + 10 + \overline{10} + 27$. Obviously, the 1 and 10 representations do not enter the decomposition of the $\gamma N \to \eta N$ amplitude. The SU(3) decomposition for the amplitudes has the following form:

$$A(\gamma p \to \eta p) = \frac{1}{3} A_D^{(8)} + A_F^{(8)} + A^{(27)},$$

$$A(\gamma n \to \eta n) = \frac{2}{3} A_D^{(8)} + A^{(10)} + \frac{1}{2} A^{(27)}. \quad (1)$$

One sees that the anti-decuplet amplitude $A^{(10)}$ do not enter the $\gamma p$ channel, whereas the antisymmetric octet amplitude $A_F^{(8)}$ do not enter the $\gamma n$ channel.

In order to describe the phenomenon of the neutron anomaly one needs that the amplitude $A(\gamma n \to \eta n)$ is very different (larger size and more rapid energy dependence) from $A(\gamma p \to \eta p)$ on a narrow invariant energy interval (several tens of MeV) around $W \sim 1680$ MeV. The decomposition (1) offers three possibilities to arrange such difference (ordered according to the *Prinzip der Denkökonomie*):

(I) the anti-decuplet amplitude $A^{(10)}$ has large size and rapid energy dependence on a narrow energy interval around 1680 MeV,

(II) there is a conspiracy and a fine tuning among the SU(3) amplitudes $A_F^{(8)}, A_D^{(8)}$ and $A^{(27)}$ on that narrow energy interval,
(III) an extraordinarily strong violation of the SU(3) symmetry on that narrow energy
interval.

We emphasise that the option (II) can explain the neutron anomaly only in the \( \eta \)-
photoproduction. In other channels, e.g. the Compton scattering [5], the assumed con-
spiracy and fine tuning are destroyed due to different from (1) SU(3) decomposition of
the Compton amplitude. The anti-decuplet amplitude \( A_{10}^{( \text{TM})} \) enters only the \( \gamma n \) channel
independently of the final state. Therefore the option (I) predicts the neutron anomaly
for the Compton scattering as well.

Usually the approximate flavour SU(3) symmetry works pretty well. As a rule its
predictions are satisfied with an accuracy of about 30% or better, see e.g. a review [7]. A
very large violation of the SU(3) symmetry would be a serious challenge to our common
wisdom about hadron dynamics.

It is likely that a possible realisation of the option (III) is provided by Ref. [8]. In
this paper the neutron anomaly was explained by the threshold effect due to \( K \Lambda \) and
\( K \Sigma \) intermediate states. It was argued in Ref. [8] that the intermediate \( K^+ \Sigma^- \) state
in the \( \gamma n \) channel produces the cusp effect at \( W \sim 1685 \) MeV which can explain
the peak in that channel. In order to suppress the corresponding peak in the \( \gamma p \) channel the
authors of Ref. [8] fitted their model parameter in such a way that the cusp due to \( K^+ \Lambda \)
intermediate state cancels the cusp effect due to \( K^+ \Sigma^0 \) state (a kind of fine tuning). Such
fine cancellation may require a large violation of the SU(3) symmetry. We shall consider
this case in details elsewhere [9]. In any case, the explanation of the neutron neutron
anomaly of Ref. [8] is not universal, i.e. it works only for \( \eta \)-photoproduction and fails for
Compton scattering, the same as for the option (II).

In the following sections we analyse the physics realisations of the first two possibilities
discussed above.

(I) Dominance of the anti-decuplet amplitude

The simplest physics realisation of the option (I) is an existence of a narrow anti-decuplet
of baryons. The existence of such narrow exotic baryon multiplet was predicted in
Ref. [10]. Main properties of \( N^* \) from the anti-deculpet which were predicted theoretically
in years 1997-2004 (before the discovery of the neutron anomaly) are the following:

- quantum numbers are \( P_{11} (J^P = \frac{1}{2}^+, \text{isospin}=\frac{1}{2}) \) [10],
- narrow width of \( \Gamma \leq 40 \) MeV [10, 11, 12],
- mass of \( M \sim 1650 - 1720 \) MeV [11, 12, 13],
- strong suppression of the proton photocoupling relative to the neutron one [14],
- the \( \pi N \) coupling is suppressed, \( N^* \) prefers to decay into \( \eta N, K \Lambda \) and \( \pi \Delta \) [10, 11, 12].

The nucleon resonance with such properties can explain\(^\dagger\) concisely the neutron anomaly
in \( \eta \)-photoproduction, in the Compton scattering, in the \( \gamma N \rightarrow K \Lambda \) process, etc.

\(^\dagger\)Actually it was prediction of the phenomenon.
Table 1: Our estimate of properties of the putative narrow \( N^* \) extracted from the data under the assumption that \( N^* \) exists. \(^*\)In Ref. \cite{11} the elastic \( \pi N \) scattering data were analyzed and the tolerance limits for \( N^* \) parameters were obtained. The preferable quantum numbers in this analysis are \( P_{11} \).

Detailed account for predictions and evidences for narrow anti-decuplet nucleon was presented at length previously in the literature (see e.g. \cite{15, 20}). Not to dwell on this again, we just list the extracted properties of the putative anti-decuplet nucleon resonance (and relevant references) in Table 1.

(II) Conspiracy and fine tuning among non-exotic SU(3) amplitudes

A physics realisation of the option (II) was suggested in Refs. \cite{21, 22, 23} by the Bonn-Gatchina group (BnGa). In these papers the neutron anomaly was explained by the interference effect of well-known wide \( S_{11} \) resonances \( N(1535) \) and \( N(1650) \). In order to arrange a narrow structure in the neutron channel the photocouplings of these two resonances should be fine tuned. In particular, the proton and neutron photocouplings of \( N(1650) \) must have the same sign. To describe the most recent and the most precise data of the A2 collaboration on the neutron anomaly \cite{4} BnGa obtained the following ratio of the proton to neutron photocouplings \cite{23}:

\[
R_{pn} \equiv \frac{\mathcal{A}_p^{1/2}(1650)}{\mathcal{A}_n^{1/2}(1650)} = 1.74 \pm 0.66 \quad \text{[BnGa value].} \tag{2}
\]

Employing the flavour SU(3) symmetry one can express the ratio of the \( F_V \) and \( D_V \) octet vector couplings in terms of the ratio \( R_{pn} \):

\[
\frac{F_V}{D_V} = -\frac{1}{3} (2R_{pn} + 1) = -1.50 \pm 0.44 \quad \text{[BnGa value].} \tag{3}
\]

The resulting from the analysis \cite{23} \( F_V \) to \( D_V \) ratio is negative and larger than 1 in the absolute value. To our best knowledge such values of \( F_V/D_V \) have been never obtained in any model of baryon resonances (variants of quark model, MIT bag model, soliton models, etc). Let us see what are physics implications of such unusual values of the \( F_V/D_V \) ratio.

The flavour SU(3) symmetry allows to express various flavour combinations of the vector current couplings in terms of \( F_V/D_V \)-ratio (and hence in terms of \( R_{pn} \) (2) owing
Eq. (3)). One can easily derive the following relations for various vector couplings of N(1650) (valid also for any octet nucleon resonance N′):

\[ R_\omega \equiv \frac{g_{\omega NN'}}{g_{\phi NN'}} = \frac{R_{pn} + 1}{R_{pn} - 1} + \sqrt{\frac{2}{3}} \frac{r_0}{1}, \quad (4) \]

\[ R_\phi \equiv \frac{g_{\phi NN'}}{g_{\rho NN'}} = -\sqrt{2} \frac{R_{pn} + 1}{R_{pn} - 1} + \sqrt{\frac{1}{3}} \frac{r_0}{1}. \quad (5) \]

Here \( r_0 \) is the ratio of the flavour singlet \( ((\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d + \bar{s}\gamma_\mu s)/\sqrt{3}) \) vector current coupling to the isovector \( ((\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d)/\sqrt{2}) \) that. The value of \( r_0 \) is not fixed by the SU(3) symmetry, however with help of Eqs. (4,5) we can express \( \phi \)-meson coupling \( R_\phi \) in terms of the \( \omega \)-meson coupling \( R_\omega \) and the proton to neutron ratio of the photocoupling \( R_{pn} \):

\[ R_\phi = \frac{1}{\sqrt{2}} \left( R_\omega - 3 \frac{R_{pn} + 1}{R_{pn} - 1} \right). \quad (6) \]

Additionally, from Eqs. (4,5) one can easily derive the following inequality (kind of Cauchy-Bunyakovsky-Schwarz inequality):

\[ R_\omega^2 + R_\phi^2 \geq 3 \left( \frac{R_{pn} + 1}{R_{pn} - 1} \right)^2. \quad (7) \]

If we take the BnGa value (2) for \( R_{pn} \) we obtain from (7):

\[ R_\omega^2 + R_\phi^2 \geq 27. \quad (8) \]

One sees that in the scenario of Refs. [21, 22, 23] the \( \omega \)- and \( \phi \)-meson couplings of N(1650) can not be small simultaneously\(^\S\).

Experimentally [25] the decay N(1650) → \( \rho N \) is seen and sizable, however the decay N(1650) → \( \omega N \) is not seen. If we conservatively assume that the yield of \( \omega \) mesons does not exceed factor of four relative to the yield of \( \rho \) mesons, i.e \( R_\omega^2 \leq 4 \) then from Eq. (6) with BnGa value for the p/n ratio of N(1650) photocouplings (2) we obtain:

\[ |R_\phi| \geq 6. \quad (9) \]

We see that the explanation of the neutron anomaly by the interference of known N(1535) and N(1650) resonances advocated in [21, 22, 23] suggests that the \( \phi \)-meson (almost pure \( s\bar{s} \) state) coupling to N(1650)→N transition should be huge. In terms of quark degrees of freedom it means that N(1650) has a large admixture of \( s\bar{s} \) component, i.e. in the scenario of Refs. [21, 22, 23] N(1650) is dominantly “cryptoexotic pentaquark”. It turns out that the “conventional” interpretation of the neutron anomaly by the interference of known resonances [21, 22, 23] metamorphoses into unconventional physics picture of N(1650).

\(^\S\)Note that if we take N(1650) photocouplings from the SAID analysis [24], than \( F_V/D_V = 0.6 \pm 0.6 \) (range of values typical for all models of baryon resonances) and \( R_\omega^2 + R_\phi^2 \geq 0.2 \) (small values of \( \omega \) and \( \phi \) couplings are not excluded).
Conclusions

In summary, we analysed the implication of the flavour SU(3) symmetry for explanations of the neutron anomaly in the $\gamma N \rightarrow \eta N$ cross section. The SU(3) symmetry suggests two class of scenarios: (I) dominance of the anti-decuplet channel at narrow energy interval (II) fine tuning of parameters of known wide resonances to arrange very specific interference pattern, see Refs. [21, 22, 23].

Both scenarios need exotic nucleon resonances – this can be either (I) a narrow anti-decuplet of baryons, or (II) well know N(1650) resonance with very large $s\bar{s}$ component, i.e. the well-known N(1650) resonance must be a “cryptoexotic pentaquark”.

We stressed that the option (II) (in contrast to the first scenario) can explain the neutron anomaly only in the $\gamma N \rightarrow \eta N$ process and it fails to explain the neutron anomaly in the Compton scattering. It seems that the simplest, universal (for both $\eta$-photoproduction and the Compton scattering) and concise way to explain the neutron anomaly is the existence of a narrow anti-decuplet of baryons.

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