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On photoexcitation of baryon antidecuplet

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Abstract. We show that the photoexcitation of the nonexotic members baryon antidecuplet, suggested by the soliton classification of low-lying baryons, is strongly suppressed on the proton target. The process occurs mostly on the neutron target. This qualitative prediction can be useful in identifying the nonexotic members of the antidecuplet in the known baryon spectrum. We also analyze the interrelation between photocouplings of various baryon multiplets in the soliton picture and in the nonrelativistic quark model.

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1. The soliton picture of baryons suggests a certain classification scheme for the low-lying baryons. In this scheme various baryons appear as rotational excitations of the same classical object —the soliton. In the case of three light flavours, the first two low-lying $SU_{\mathrm{fl}}(3)$ multiplets are the octet and the decuplet, just the same as in the quark model and in reality. The third rotational excitation is an *antidecuplet with spin* 1/2. Probably the existence of the antidecuplet as the next $SU_{\mathrm{fl}}(3)$ rotational excitation has been first pointed out at the ITEP Winter School (February, 1984), see ref. [1]. Other early references for the antidecuplet include refs. [2–4].

In fig. 1 we draw the $SU_{\mathrm{fl}}(3)$ diagram (from ref. [5]) for the suggested antidecuplet in the (T_3, Y) diagram, indicating its naive quark content as well as the (octet baryon + octet meson) content. In addition to the lightest Z^+, there is an exotic quadruplet of $S = -2$ baryons (we call them $\Xi_{3/2}$). In ref. [5] the following mass formula for the members of the antidecuplet was obtained:

$$M = \left[1890 - Y \times 180\right] \text{MeV}. \tag{1}$$

Note that this "soliton" mass formula is, to some extent, counterintuitive from the point of view of the naive quark model. For instance, the strange baryon (Z^+) appears to be lighter than the baryon with the nucleon quantum numbers. Up to now we were used to strange baryons being heavier than nonstrange ones in a given multiplet. Also Z^+ having 4 light + $\bar{s}$ quark content is about 540 MeV lighter than $\Xi_{3/2}^{--}$ with the quark content 3 light + 2 s quarks. In the naive quark model one would expect a mass difference of about ~ 150 MeV.

The essential assumption made in ref. [5] was the identification of the P_{11}-resonance, $N(1710)$, with the nucleon-like member of the antidecuplet. The calculated decay modes of $N(1710)$ were found to be in reasonable agreement with the existing data. Note, however, that the data

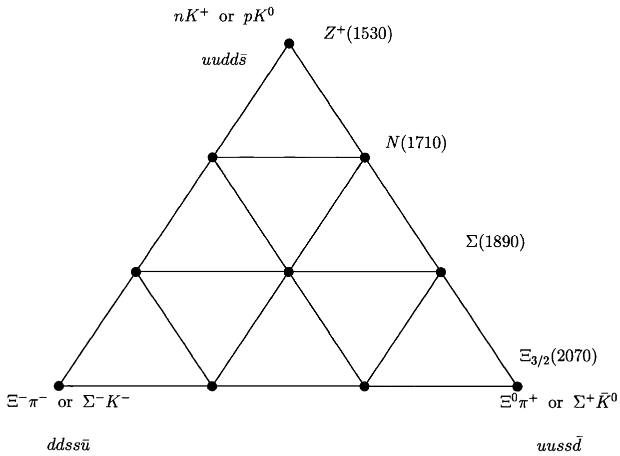

Fig. 1. The suggested antidecuplet of baryons [5]. The corners of this (T_3, Y) diagram are exotic. We show their quark content together with their (octet baryon + octet meson) content, as well as the predicted masses.

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were not good enough to make a decisive conclusion. At least it seems that the standard nonrelativistic $SU(6)$ description of this state as a member of an octet, is in trouble with the data: the antidecuplet idea fits better. With the identification made in ref. [5], the lightest exotic member of the antidecuplet is Z^+ ($S=+1, Q=+1, T=0$) predicted to have a mass around 1530 MeV and a total width of less than 15 MeV. As was discovered in ref. [5] the exotic Z^+ should be anomalously narrow due to the specific interplay of the soliton rotational correction to the meson-baryon couplings. In particular it was shown in ref. [5] that all these couplings tend to zero in the nonrelativistic quark limit of the soliton picture of baryons. The anomalous narrowness of Z^+ can explain why it escaped the thorough searches in the past in KN scattering processes. For references, see the latest PDG report on Z-baryons in the 1986 Review of Particle Properties [6] summarizing 20 years of experimental activity on $S=+1$ baryons. Also, see the latest partial-wave analysis for K^+N scattering in ref. [7].

Recently the first evidence of a *narrow* $S=+1$ resonance in the mass region of 1530 MeV has been reported by the LEPS Collaboration at the SPring-8 photon gun [8] and by the DIANA Collaboration at ITEP [9]. If confirmed, this discovery may lead to a considerable revision of the quark model baryon spectroscopy as we have known it for the last forty years.

In the present paper we show that the photoproduction of the antidecuplet excitation of the chiral soliton possesses qualitative features which can be used as a clear signal for its identification. In particular, we show that the photoexcitation of the baryon antidecuplet, suggested by the soliton classification of low-lying baryons, is strongly suppressed on the proton target. It occurs mostly on the neutron target.

2. In order to estimate the photoexcitation of the antidecuplet of baryons, we shall exploit the idea that all low-lying baryons are rotational excitations of the same classical object —the soliton. We start with the magnetic dipole coupling of the soft photon with momentum $\mathbf{q}$ to the soliton in the chiral limit:

$$j_k^{\text{e.m.}}(\mathbf{q}) = \left[v_1\, D^{(8)}_{Qi}(R) + v_2 \sum_{\alpha,\beta=4}^{7} d_{i\alpha\beta} D^{(8)}_{Q\alpha}(R)\, J_\beta + \frac{v_3}{\sqrt{3}} \cdot D^{(8)}_{Q8}(R)\, J_i\right] i\varepsilon_{ijk}\, q_j\,. \quad (2)$$

This equation requires a detailed explanation. It is written in the space of collective rotational coordinates, $R \in SU(3)$, of the soliton. The corresponding operators of the infinitesimal $SU(3)$ rotation are denoted as J_A, while $D^{(\mu)}_{\nu\nu'}(R)$ stands for the Wigner $SU(3)$ finite-rotation matrices depending on the orientation matrix of the soliton. Eventually v_i are constants which are universal for all baryon multiplets. In order to obtain the physical coupling of the photon to baryons and various transitions using eq. (2), one has to sandwich it between the physical rotational states:

$$\int \mathrm{d}R\ \psi^*_{B_2}(R) \ldots \psi_{B_1}(R)\,, \quad (3)$$

where the rotation wave function of a particular baryon, $\psi_B(R)$, is expressed in terms of Wigner functions

$$\psi_B(R) = \sqrt{\dim\ r}(-1)^{J_3-1/2} D^{(\bar r)}_{Y,T,T_3;1,J,-J_3}\,, \quad (4)$$

where r is an irreducible representation of the $SU(3)$ group, $r = 8, 10, \overline{10}$, etc., B denotes a set of quantum numbers Y, T, T_3 (hypercharge, isospin and its projection) and J, J_3 (spin and its projection). It is a big advantage of the chiral soliton picture that all concrete numbers (for masses and couplings) do not rely upon a specific dynamical realization but follow from symmetry considerations only.

An example of the usage of eq. (2) is the calculation of the magnetic moments of the octet and decuplet baryons in the chiral limit, see *e.g.* refs. [10,11]:

Octet

$$\mu_N = -\frac{14T_3+1}{60}\left(v_1 - \frac{1}{2}v_2\right) + \frac{2T_3+3}{120}\, v_3, \quad (5)$$

$$\begin{aligned}
\mu_\Sigma &= -\frac{5T_3+3}{60}\left(v_1 - \frac{1}{2}v_2\right) + \frac{5T_3-1}{120}\, v_3,\\
\mu_{\Sigma^0\Lambda} &= -\frac{\sqrt{3}}{10}\left(v_1 - \frac{1}{2}v_2 + \frac{1}{6}v_3\right),\\
\mu_\Lambda &= \frac{1}{20}\left(v_1 - \frac{1}{2}v_2\right) + \frac{1}{120}\, v_3,\\
\mu_\Xi &= \frac{2T_3+2}{30}\left(v_1 - \frac{1}{2}v_2\right) + \frac{4T_3-1}{60}\, v_3\,. \quad (6)
\end{aligned}$$

Decuplet

$$\mu_B = -\frac{1}{8}\left(v_1 - \frac{1}{2}v_2 - \frac{1}{2}v_3\right)\, Q_B\,. \quad (7)$$

We give this example for two reasons. Firstly, it illustrates that the value of certain combinations of the universal constants v_i can be obtained from the data for the octet and decuplet baryons magnetic moments (see details in ref. [10]). Secondly, using eqs. (5)-(7) we can consider important limiting case of the nonrelativistic quark model, which, to some extent, can be used as a useful guiding line. In the nonrelativistic limit of the chiral quark soliton model[1] for the constants v_i, one obtains the following values[2]:

$$v_2^{\text{NR}}/v_1^{\text{NR}} = -4/5, \qquad v_3^{\text{NR}}/v_1^{\text{NR}} = -2/5. \quad (8)$$

Substituting these values into eqs. (5)-(6) and (7), one obtains the famous expressions for the magnetic moments of baryons in the nonrelativistic quark model. Calculations of v_i in the chiral quark soliton model [11] confirm the negative sign of $v_{2,3}/v_1$ and give the following values:

$$\begin{aligned}
\frac{v_2}{v_1 - \frac{1}{2}v_2} &= -0.3 \pm 0.08 \quad \left(-\frac{4}{7}\ \text{NRL}\right),\\
\frac{v_3}{v_1 - \frac{1}{2}v_2} &= -0.22 \pm 0.07 \quad \left(-\frac{2}{7}\ \text{NRL}\right), \quad (9)
\end{aligned}$$

[1] For reviews of this model see refs. [12–15] and for the review of the close in spirit NJL model see refs. [16,17].

[2] See refs. [5,18] for the discussion of the nonrelativistic quark model limit in the soliton picture.

which indicate a deviation from the nonrelativistic quark model results shown in the parentheses. We note that the second ratio is closer to the nonrelativistic quark model result. This ratio is related to the strange magnetic moment of the nucleon [11], the nonrelativistic limit corresponding to $\mu_N^s = 0$. Below for our numerical calculations we shall use for the second ratio in eq. (9) its nonrelativistic value of $-2/7$.

Due to its universality eq. (2) can be used for computing various phototransition amplitudes between different baryon multiplets. Let us first give, as an illustration, the corresponding expressions for the transition magnetic moments between the octet and decuplet baryons. For the octet-decuplet dipole magnetic transition we obtain

$$\mu_{N\Delta} = -2T_3\,\sqrt{\frac{2}{15}}\,\left(v_1 - \frac{1}{2}v_2\right), \tag{10}$$

$$\mu_{\Sigma\Sigma^*} = -(T_3+1)\,\frac{1}{\sqrt{30}}\,\left(v_1 - \frac{1}{2}v_2\right), \tag{11}$$

$$\mu_{\Lambda\Sigma^*} = -\frac{1}{\sqrt{10}}\,\left(v_1 - \frac{1}{2}v_2\right), \tag{12}$$

$$\mu_{\Xi\Xi^*} = \left(T_3 + \frac{1}{2}\right)\,\frac{1}{\sqrt{30}}\,\left(v_1 - \frac{1}{2}v_2\right). \tag{13}$$

We have seen previously that, using the values of the constants v_i (8) obtained by the nonrelativistic limit of the quark soliton model, we reproduce $SU(6)$ relations for the magnetic moments. This illustrates that the "soliton relations" reproduce successfully the results of the $SU(6)$ quark model for the baryon magnetic moments. However, if we now apply the nonrelativitic limit to the octet-decuplet magnetic transitions, we obtain a deviation of "soliton relations" from those of the $SU(6)$ quark model:

$$\mu_{N\Delta}^{\mathrm{NR}} = \frac{7}{\sqrt{30}}\,\mu_p^{\mathrm{NR}}, \tag{14}$$

which should be contrasted with the $SU(6)$ relation [19]:

$$\mu_{N\Delta}^{SU(6)} = \frac{2}{3}\sqrt{2}\,\mu_p^{SU(6)}. \tag{15}$$

Note that the "soliton relations" for the octet-decuplet transitions, even in the nonrelativistic limit, are in better agreement with the experimental value of $\mu_{N\Delta}/\mu_p = 1.24 \pm 0.01$ [20] than the corresponding $SU(6)$ relations.

Now it is easy to derive the expressions for the dipole magnetic transitions between the octet and antidecuplet baryons. The result is

$$\mu_{NN^*} = -(2T_3 - 1)\,\frac{1}{12\sqrt{5}}\left(v_1 + v_2 + \frac{1}{2}v_3\right), \tag{16}$$

$$\mu_{\Sigma\Sigma^*} = -(T_3 - 1)\,\frac{1}{12\sqrt{5}}\,\left(v_1 + v_2 + \frac{1}{2}v_3\right). \tag{17}$$

We see immediately the important qualitative feature of the octet-antidecuplet electromagnetic transitions: in the chiral limit the photoexcitation of the antidecuplet from the proton ($T_3 = 1/2$ in eq. (16)) or Σ^+ ($T_3 = 1$ in eq. (17)) targets *does not occur*. In our scheme the excitation of the anti-10 from the proton and from Σ^+ can occur only due to the $SU_{\mathrm{fl}}(3)$ symmetry-breaking effects. Hence, the corresponding couplings should be relatively suppressed. This qualitative feature can be used experimentally as a test whether a given P_{11} nucleon resonance is a member of the antidecuplet. Another important feature of eq. (16) is that in the nonrelativistic limit (see (8)), the combination of constants $\left(v_1 + v_2 + \frac{1}{2}v_3\right)$ is exactly zero. It means that the photoexcitation of the antidecuplet (even if allowed) is a purely relativistic effect from the point of view of the quark model. This is also true for the meson decays of the antidecuplet. In particular this feature explains why the exotic member Z^+ should be anomalously narrow, see discussion in [5].

3. In ref. [5] the nucleon-like member of the antidecuplet has been identified with the nucleon resonance $P_{11}(1710)$. Now using the results of eq. (16), we can make a prediction for the photon dipole magnetic couplings for this resonance. To this end, we have to fix the values of the dynamical constants v_i. We fix the ratio $v_2/(v_1 - v_2/2)$ to the value obtained in the chiral quark soliton model, see the first equation in (9), whereas the ratio $v_3/(v_1 - v_2/2)$ we fix by its nonrelativistic value of $-2/7$. The later corresponds to the vanishing strange magnetic moment of the nucleon. With this all constants but $(v_1 - v_2/2)$ are fixed. The constant $(v_1 - v_2/2)$ is adjusted in order to reproduce the magnetic moment of the proton. To estimate the $SU_{\mathrm{fl}}(3)$ breaking effects (expected at the level of 15–20%) due to the nonzero strange-quark mass we use the method and the results of refs. [10,11].

With such fixing of the constants v_i we obtain the following range for dipole magnetic transition between the octet and antidecuplet nucleons (in nuclear magneton):

$$\mu_{pp^*} = -0.15 \div 0.15, \qquad \mu_{nn^*} = -1 \div -0.3. \tag{18}$$

We should note here that the obtained numerical values are very sensitive to the values of the constants v_i: it is reflected in a rather wide spread of our numerical predictions. These spreads were obtained varying the value of v_2 and the values of the symmetry-breaking effects. The most important conclusion we can make from the above values is that the photoexcitation of $P_{11}(1710)$ as a member of antidecuplet is favoured from the neutron target, since for ratio of the *octet-antidecuplet* dipole magnetic transition one expects that $\left|\frac{\mu_{nn^*}}{\mu_{pp^*}}\right| > 2$. The corresponding ratio for the *octet-octet* transition is estimated as $\sim -2/3$. The magnetic couplings of the antidecuplet are rather small because these couplings are nonzero owing to the relativistic effects only. In the nonrelativistic quark model limit they would be exactly zero.

Let us note that we should keep in mind important caveats in the above estimates. Firstly, the magnetic transitions were computed in the soft-photon limit. The actual energy of the photon in the Breit frame is rather large, about 740 MeV, which can be hardly considered as soft. This can lead to rather sizable corrections to the numerical estimates (18). However, these corrections will not change the ratio of the proton-to-neutron transition, meaning that these corrections do not change the qualitative feature of dominance of photoexcitation from the neutron target.

Secondly, we have made our estimates assuming that $P_{11}(1710)$ is a purely antidecuplet state. However, quantum numbers of this state do not preclude its mixing with the corresponding states from the octet family. The mixing can be strong if the nucleon excitation belonging to the octet is close in mass to $P_{11}(1710)$. A pattern of such a mixing has been considered in ref. [21] in the framework of a particular variant of the Skyrme model [22]. The model of ref. [21] gives a strong mixing pattern between almost degenerate nucleon states from antidecuplet and from the octet. It should be possible to verify this experimentally by accurate measurements of the properties of the nucleon resonances in the mass region around 1700 MeV. Unfortunately, the present information about nucleon resonances in this mass region is rather incomplete and controversial, see the examples of recent analyses [23–26]. For instance, in a recent analysis of the pion photoproduction data of ref. [23] the resonance $P_{11}(1710)$ is very elusive, a similar feature has been found in ref. [25] in the analysis of $\gamma p \to K+\Lambda$ data. Hopefully modern electron facilities like SPring-8 [27], JLab [28], ELSA [29], MAMI [30], GRAAL [31] will bring us more detailed information on the nucleon resonances in the 1700 MeV region.

4. In this paper we argued that the photoexcitation amplitudes are good tools to probe the antidecuplet component of the nucleon resonances. Probably special attention should be paid to the *antidecuplet "friendly" photoreactions* such as, for example,

$$\gamma n \to K^+\Sigma^-, \qquad \gamma n \to \eta n, \qquad \gamma n \to (\pi\pi)_{I=1} N\,. \quad (19)$$

In these channels the antidecuplet part of the nucleon resonances should be especially enhanced, whereas in the analogous channels with the proton target the anti-10 component is relatively suppressed. The anti-10 component can be also filtered out in *octet "friendly" photoreactions* such as

$$\gamma p \to \gamma p, \qquad \gamma p \to \pi\Delta, \qquad \gamma p \to (\pi\pi)_{I=0}\, p. \quad (20)$$

Virtual photons provide us with an additional possibility to filter out the anti-10 component of the nucleon resonances. For instance, excitation of the anti-10 component of a given nucleon resonance by a longitudinally polarized virtual photon is strongly suppressed. Also high-energy experiments can be effectively used to search baryons from the anti-10 family (pentaquarks), see a detailed review on this in [32].

In the nonrelativistic limit of the "soliton relations" for photo- and meson[3] couplings of anti-10 baryons to the ground-state baryon octet we have found that they would be zero in the nonrelativistic quark model. This important qualitative feature makes anti-10 baryons (especially purely exotic Z^+) some kind of benchmark for relativistic quark interactions in baryons.

[3] See a detailed discussion of meson couplings in ref. [5].

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References

1. D. Diakonov, V. Petrov, *Baryons as solitons*, preprint LNPI-967 (1984), published in *Elementary Particles*, Vol. **2** (Energoatomizdat, Moscow, 1985) p. 50 (in Russian).
2. M. Chemtob, Nucl. Phys. B **256**, 600 (1985).
3. M. Praszalowicz, in *Skyrmions and Anomalies*, edited by M. Jezabek, M. Praszalowicz (World Scientific, Singapore, 1987) p. 112.
4. H. Walliser, in *Baryon as Skyrme Soliton*, edited by G. Holzwarth (World Scientific, Singapore, 1992) p. 247; H. Walliser, Nucl. Phys. A **548**, 649 (1992).
5. D. Diakonov, V. Petrov, M.V. Polyakov, Z. Phys. A **359**, 305 (1997), arXiv:hep-ph/9703373.
6. Particle Data Group (M. Aguilar-Benitez *et al.*), *The Review of Particle Properties*, Phys. Lett. B **170**, 1 (1986).
7. J.S. Hyslop, R.A. Arndt, L.D. Roper, R.L. Workman, Phys. Rev. D **46**, 961 (1992).
8. T. Nakano (for the LEPS Collaboration), talk at PaNic02, XVI International Conference on Particles and Nuclei, Osaka, Japan, 30 September-4 October, 2002, see `http://www.rcnp.osaka-u.ac.jp/~panic02/`; LEPS Collaboration (T. Nakano *et al.*), Phys. Rev. Lett. **91**, 012002 (2003), arXiv:hep-ex/0301020.
9. A.G. Dolgolenko, private communication and talk at ITEP seminar; DIANA Collaboration (V.V. Barmin *et al.*), talk at Session of the Nuclear Division of the Russian Academy of Sciences, December 3, 2002, in Yad. Fiz. **66**, 1763 (2003) (Phys. At. Nucl. **66**, 1715 (2003)).
10. M. Wakamatsu, N. Kaya, Prog. Theor. Phys. **95**, 767 (1996); H.C. Kim, M. Praszalowicz, K. Goeke, Phys. Rev. D **57**, 2859 (1998), arXiv:hep-ph/9706531.
11. H.C. Kim, A. Blotz, M.V. Polyakov, K. Goeke, Phys. Rev. D **53**, 4013 (1996), arXiv:hep-ph/9504363.
12. D. Diakonov, V.Y. Petrov, P.V. Pobylitsa, Nucl. Phys. B **306**, 809 (1988).
13. M. Wakamatsu, H. Yoshiki, Nucl. Phys. A **524**, 561 (1991).
14. C.V. Christov *et al.*, Prog. Part. Nucl. Phys. **37**, 91 (1996), arXiv:hep-ph/9604441.
15. D. Diakonov, V.Y. Petrov, *Nucleons as chiral solitons*, arXiv:hep-ph/0009006.
16. R. Alkofer, H. Reinhardt, H. Weigel, Phys. Rep. **265**, 139 (1996), arXiv:hep-ph/9501213.
17. H. Weigel, Int. J. Mod. Phys. A **11**, 2419 (1996), arXiv:hep-ph/9509398.
18. M. Praszalowicz, A. Blotz, K. Goeke, Phys. Lett. B **354**, 415 (1995), arXiv:hep-ph/9505328.
19. H.R. Rubinstein, F. Scheck, R.H. Socolow, Phys. Rev. **154**, 1608 (1967).
20. L. Tiator, D. Drechsel, O. Hanstein, S.S. Kamalov, S.N. Yang, Nucl. Phys. A **689**, 205 (2001), arXiv:nucl-th/0012046.

21. H. Weigel, Eur. Phys. J. A **2**, 391 (1998), arXiv:hep-ph/9804260.
22. J. Schechter, H. Weigel, Phys. Rev. D **44**, 2916 (1991).
23. R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, R.L. Workman, Phys. Rev. C **66**, 055213 (2002), arXiv:nucl-th/0205067.
24. G. Penner, U. Mosel, Phys. Rev. C **66**, 055212 (2002), arXiv:nucl-th/0207069.
25. S. Janssen, D.G. Ireland, J. Ryckebusch, Phys. Lett. B **562**, 51 (2003), arXiv:nucl-th/0302047.
26. W.T. Chiang, F. Tabakin, T.S. Lee, B. Saghai, Phys. Lett. B **517**, 101 (2001), arXiv:nucl-th/0104052.
27. T. Nakano *et al.*, Nucl. Phys. A **684**, 71 (2001).
28. V.D. Burkert, Eur. Phys. J. A **17**, 303 (2003), arXiv:hep-ph/0210321.
29. CB-ELSA Collaboration (J. Junkersfeld), Acta Phys. Pol. B **33**, 941 (2002).
30. T. Walcher, Prog. Part. Nucl. Phys. **34**, 1 (1995).
31. GRAAL Collaboration (O. Bartalini *et al.*), Nucl. Phys. A **699**, 218 (2002).
32. L.G. Landsberg, Phys. Usp. **42**, 871 (1999) (Usp. Fiz. Nauk **169**, 961 (1999)).