Eur. Phys. J. A **25**, 325–327 (2005)
DOI 10.1140/epja/i2005-10139-6

THE EUROPEAN
PHYSICAL JOURNAL A

Letter

Extraction of radiative decay width for the non-strange partner of Θ$^+$

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Received: 13 July 2005 / Revised version: 15 August 2005 /

Communicated by V.V. Anisovich

Abstract. Using the results of the GRAAL Collaboration on the η photoproduction from the neutron target, we attempt to extract the partial radiative width of the possible new nucleon resonance $N^*(1675)$. The obtained estimates support this resonance to be a very attractive candidate for the non-strange member of the exotic antidecuplet of baryons —a partner of the Θ^+ pentaquark. Our phenomenological value for the transition magnetic moment $\mu(n^* n)$, appears to be in good agreement with the predictions of the Chiral Quark Soliton Model.

PACS. 13.30.-a Decays of baryons – 13.40.Hq Electromagnetic decays – 14.20.Gk Baryon resonances with $S=0$

The first independent evidences for the exotic baryon Θ^+, with strangeness +1, obtained in reactions γ^{12}C [1] and K^+Xe [2], were followed by important confirmations in more than ten experiments (see the recent experimental reviews [3]). We still know rather little about the properties of the exotic Θ^+, even its very existence has not yet been firmly established, see the discussion of the null experimental results in ref. [3].

However, if the Θ^+ does really exist, we have to deal from now on with a new type of baryonic multiplets in terms of the flavour $SU(3)$ group, most probably, the antidecuplet. This corresponds to predictions of the Chiral Quark Soliton Model (ChQSM) [4] (see also the recent theoretical reviews [5] and detailed references therein). In terms of quarks, the antidecuplet cannot be composed of three quarks, contrary to all previously known baryons. Its minimal quark configuration should be the 5-quark one (4 quarks and 1 antiquark). If so, it would be of great importance, in parallel to further studies of the Θ^+, to find and investigate other members of the antidecuplet. Also very interesting would be to understand the internal structure of the new baryons in terms of quarks.

Recently, the GRAAL Collaboration [6] provided an indication for a nucleon resonance $N^*(1675)$ in the process $\gamma n \to \eta n$. Its mass and seemingly narrow width correspond to the expected properties of the non-strange partner of the narrow Θ^+, see [7–9]. The fact that this nucleon state is excited by the photon preferably on the neutron target (not on the proton one) also favours its antidecuplet nature [10].

In this Letter we try to estimate the partial radiative width $\Gamma(n^* \to n\gamma)$ using the results of the GRAAL Collaboration [6, 11]. It is directly related to the corresponding transition multipole moment (magnetic dipole, according to ChQSM expectations). Though such a moment may be calculated theoretically in various approaches (ChQSM, sum rules, and so on), it is especially interesting for the quark description, where this moment is very sensitive to the hadron internal structure.

References [6, 11] reveal an irregular behaviour of the cross-section for the process $\gamma n \to \eta n$ near the invariant mass $W = 1675$ MeV. In ref. [11], the differential cross-section at scattering angle around 140° has been fitted by a smooth background plus a Gaussian peak. Assuming, for simplicity, incoherence of the resonance and background, the peak contribution has been fitted to the form

$$\frac{\mathrm{d}\sigma_{\text{visible peak}}}{\mathrm{d}\Omega}(W) = 0.19 e^{-(W-M_R)^2/(\Delta W)^2}\ \mu\mathrm{b}\cdot\mathrm{sr}^{-1}, \quad (1)$$

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where W is the invariant mass of the ηn (and/or γn) system, $M_R = 1675$ MeV and $\Delta W = 30$ MeV. The measured peak mass agrees with the candidate value $M = 1680$ MeV for the assumed partner of $\Theta^+(1540)$, as extracted from the Partial-Wave Analysis of the πN scattering [7]. The visible peak width is consistent with the expected smearing effects due to the Fermi motion and experimental resolution. Therefore, assuming that the peak corresponds to a nucleon resonance, we conclude that its true width should be considerably smaller. Then, we can write for the integrated cross-section:

$$\int \mathrm{d}W \frac{\mathrm{d}\sigma_{\mathrm{res}}}{\mathrm{d}\Omega}(W) = \frac{\pi}{4k_\gamma^2} \frac{\Gamma_{\gamma n}\Gamma_{\eta n}}{\Gamma_{\mathrm{tot}}}\,. \tag{2}$$

Here Γ_{tot} is the true total width of the resonance, while $\Gamma_{\gamma n}$ and $\Gamma_{\eta n}$ are its partial widths for the decay modes to γn and ηn, respectively; $k_\gamma = 574$ MeV is the c.m. relative momentum for the initial γn state at the resonance energy. We have also assumed that the nucleon resonance under discussion is of spin 1/2 (as suggested by the ChQSM for the flavour partners of the Θ^+), so its cross-section has a flat angular dependence. The area of integration over the invariant mass in eq. (2), which is effectively $\sim \Delta W$, should overlap the experimental resolution and Fermi motion smearing. It is assumed to be larger than Γ_{tot}. Such assumption is consistent with the Monte Carlo simulation (see fig. 3 of ref. [6]), which suggests $\Gamma_{\mathrm{tot}} \approx 10$ MeV. This agrees with the earlier theoretical estimate $\Gamma_{\mathrm{tot}} \leq 10$ MeV [7].

Now, using eq. (2) and taking the l.h.s. integral of the visible peak cross-section (1), we obtain expression for the radiative partial width of n^*:

$$\begin{aligned}\Gamma\,(n^* \to \gamma n) &= \frac{4k_\gamma^2\,\Delta W}{\sqrt{\pi}\,\mathrm{Br}(\eta n)}\,\frac{\mathrm{d}\sigma_{\text{visible peak}}}{\mathrm{d}\Omega}\bigg|_{W=M_R}\\ &\approx \frac{1.08\cdot 10^{-2}}{\mathrm{Br}(\eta n)}\ \mathrm{MeV}.\end{aligned} \tag{3}$$

The radiative partial width is simply related with the transition magnetic moment $\mu(n^* \to n)$:

$$\Gamma(n^* \to \gamma n) = \left(\frac{\mu}{\mu_N}\right)^2 \frac{\alpha}{M_N^2}\,k_\gamma^3\,, \tag{4}$$

where μ_N is the nuclear magneton, $\alpha = 1/137$, and k_γ is the photon momentum in the rest frame of the decaying resonance (*i.e.*, the same as above). Now, at last, we arrive at an estimate:

$$|\mu(n^* \to n)| = \frac{0.083}{\sqrt{\mathrm{Br}(\eta n)}}\,\mu_N\,. \tag{5}$$

Surely, this estimate is rather rough, but corresponds to the present quality of experimental data. In particular, the data do not allow to separate different partial-wave contributions. Therefore, we do not model in detail the non-resonant background for the N^*, and even have not explicitly accounted for a possible effect of nearby wide resonances (according to RPP [12], they could be $S_{11}(1650)$, $D_{15}(1675)$, $F_{15}(1680)$, $D_{13}(1700)$, $P_{11}(1710)$, and $P_{13}(1720)$, all with widths $\sim$ 100–200 MeV). Moreover, we have assumed in our estimates that the peak seen by the GRAAL Collaboration corresponds to a narrow resonance with definite quantum numbers $J^P = 1/2^+$, as is expected in the ChQSM (the case of $1/2^-$ would look similar, but with $\mu(n^* \to n)$ being the transition electric dipole moment). Nevertheless, we believe that our estimate (5) may be reasonable and close to reality, say, within a factor of two.

Equation (5) still depends on the branching ratio of the decay $n^* \to \eta n$. For its value we employ estimates obtained in the framework of the ChQSM [4,7,13], as well as the phenomenological analysis of ref. [9]. It is expected that the possible range of the ηn branching is 0.05–0.4. Using this range, we obtain, as the final result, that the transition magnetic moment $\mu(n^* \to n)$ lies in the interval

$$|\mu(n^* \to n)| = (0.13\text{–}0.37)\,\mu_N\,,$$

which corresponds to $\Gamma_{\gamma n} = (27\text{–}216)$ keV.

Even keeping in mind all uncertainties of the above theoretical estimates, of the present phenomenological analysis, and of the experimental errors in the fit (1), the obtained numbers are self-consistent and agree quite well with the ChQSM expectations for this transition magnetic moment to be (0.10–0.56) μ_N [14]. It is important also to note that the extracted moment is numerically small (for comparison, $\mu(\Delta \to N) \approx 3$). This qualitative feature is in agreement with the prediction of the ChQSM that in the non-relativistic limit the corresponding transition moment vanishes [10].

This smallness correlates with the ChQSM expectation of an anomalously small width of the Θ^+ [4]; the reason for smallness, in both cases, is the formal cancellation of various coupling constants, which becomes exact in the non-relativistic limit. It was suggested years ago [15] that since hadrons are systems with an internal structure, some of them may have the structure essentially different from that of conventional hadrons. Such structure inconsistency could suppress their couplings with the conventional hadrons, leading to small production cross-sections and decay widths, despite the strong interaction nature of the processes. A recent calculation of the Θ^+ width [16], in terms of quark configurations in effective mean field, seems to explain its smallness by the essential difference between quark structures for the initial (mainly 5-quark Θ) and final (mainly 3-quark nucleon) baryons, thus supporting the assumed possibility.

Let us emphasize once more the absence of the corresponding resonance-like structure in the $\gamma p \to \eta p$ process [6,11]. It implies that the ratio of magnetic transitions $\mu(p^*p)/\mu(n^*n)$ should be less than $\sim 1/3$, otherwise the corresponding peak would be visible in data on η photoproduction off the proton target, having higher statistics and better quality. This supports the (mainly) antidecuplet nature of the discussed resonance.

To summarize, we have tried to extract the radiative decay parameters for a new nucleon resonance which could be a partner of the Θ^+. Even with existing preliminary data, our results seem to be self-consistent in the framework of the Chiral Quark Soliton Model.

The work was partly supported by the Russian State Grant RSGSS-1124.2003.2, by the Russian-German Collaboration Treaty (RFBR, DFG), by the COSY-Project Jülich, by the Sofja Kowalewskaja Programme of the Alexander von Humboldt Foundation, BMBF, DFG, by the U.S. Department of Energy Grant DE-FG02-99ER41110, by the Jefferson Laboratory, and by the Southeastern Universities Research Association under DOE Contract DE-AC05-84ER40150.

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