PARITY DOUBLETS FROM A RELATIVISTIC QUARK MODEL

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The $N$– and the $Λ$–excitation spectrum exhibit parity doublets, i.e. states of the same spin but with opposite parity being almost degenerate in mass. It is shown that in a relativistic quark model with instantaneous interaction kernels, where confinement is implemented by a linearly rising potential and the major mass splittings are generated from an interaction based on instanton effects, this degeneracy occurs quite naturally: Once the parameters of the instanton induced interaction are fixed to reproduce the ground state octet-decuplet splittings, some states are selectively lowered to a position which is degenerate with states of opposite parity. Some observable consequences are briefly discussed.

A glance at the nucleon– and $Λ$–excitation spectrum reveals a conspicuous degeneracy of some states with the same spin and opposite parity. Prominent examples are $N_2^+(1680)–N_2^-(1675)$, $N_2^+(2220)–N_2^-(2250)$, $Λ_2^+(1820)–Λ_2^-(1830)$. Although one might also regard $Δ_2^+(1905)–Δ_2^-(1930)$ and $Δ_2^+(2300)–Δ_2^-(2400)$ as parity partners, the situation seems less clear: for the first because of the nearby $Δ_2^+(2000)$-resonance and for the second because of the relatively large splitting. In the $Σ$–spectrum no clear indications of parity doublets is found. In the literature these observations have been related to a phase transition from the Nambu–Goldstone mode of chiral symmetry to the Wigner–Weyl mode in the upper part of the baryon spectrum. In the present contribution we will show how this feature can be understood in the context of a (relativistic) constituent quark model on the basis of the quark dynamics, where the major spin-dependent mass splittings are induced by instanton effects (‘t Hooft’s force).

Our relativistically covariant constituent quark model is based on the Bethe-Salpeter equation for three-quark bound states with instantaneous interaction kernels. The details of the model are described elsewhere. Quarks are assumed to possess an effective constituent mass and confinement is implemented by a linearly rising 3-body string potential with a Dirac structure, which is a combination of scalar and time-like vector structures chosen such that unwanted spin-orbit effects are minimized. The major spin-dependent mass splittings are generated by a flavor dependent 2-particle in-
interaction, which is motivated by instanton effects. This force affects flavor-antisymmetric $qq$-pairs only, and consequently this interaction does not act on flavor symmetric states, such as the $\Delta$-resonances, which are thus determined by the dynamics of the confinement potential alone. Accordingly, the constituent quark masses and the confinement parameters were determined by a fit to the spectrum in this sector.

The residual instanton induced interaction does act on particular flavor octet states. Once the strengths of this interaction have been adjusted to account for the ground state nucleon and $\Lambda$-mass we find that in fact one can describe the major spin-dependent mass splittings in the nucleon spectrum quite well, see Fig. 1. In particular one finds that in this manner the Roper resonance can be accounted for quite naturally. Moreover one finds a selective lowering of those substates of a major oscillator shell (which in spite of the linear confinement adopted here still provides an adequate classification of states with confinement alone) which contain so called scalar diquarks, i.e. quark pairs with trivial spin and angular momentum. This is found in particular for the highest spin states in a given oscillator shell $N$, see Fig. 2. For given $N\hbar\omega$ the maximum total angular momentum for a state containing such a scalar diquark is $J = (L_{\text{max}} = N) + \frac{1}{2}$. 't Hooft’s force lowers this

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state enough to become almost degenerate with the unaffected spin-quartet state of the oscillator shell with \(N - 1\), which has opposite parity but the same total angular momentum: \(J = (L_{\text{max}} = N - 1) + \frac{1}{2}\). In this way patterns of approximate parity doublets for all lowest excitations in the sectors \(J = \frac{5}{2}\) to \(J = \frac{13}{2}\) are formed systematically. In the \(N^\frac{5}{2}^+\) and \(N^\frac{9}{2}^\pm\) sectors this scenario is nicely confirmed experimentally by the well-established parity doublets \(N^\frac{5}{2}^+ (1680) - N^\frac{5}{2}^- (1675)\) and \(N^\frac{9}{2}^+ (2220) - N^\frac{9}{2}^- (2250)\). In the \(N^\frac{7}{2}\) sector, however, the present experimental findings seem to deviate from such a parity doubling structure due to the rather highly determined resonance position of the \(N^\frac{7}{2}^- (2190)\). Although this state is given a four-star rating, an investigation of this sector with new experimental facilities such as the CLAS detector at CEBAF (JLab) or the Crystal Barrel detector at ELSA (Bonn) would be highly desirable. The same mechanism explains approximate parity doublet structures also for states with lower angular momentum as e.g. the \(N^*_\pi^\pm\) doublets in the second resonance region around \(\sim 1700\) MeV with spins \(J^\pi = \frac{1}{2}^\pm, \frac{3}{2}^\pm,\) and \(\frac{5}{2}^\pm\) (see fig. 1).

Observable consequences of this parity doubling scenario should manifest in a different shape of electromagnetic \(p^* \gamma \to N^*\) transition form factors of both members of a doublet due to their significantly different internal structures. Fig. 3 shows as an example the magnetic multipole \(\gamma p \to N^\frac{3}{2}^+ (1680)\) and \(\gamma^* p \to N^\frac{3}{2}^- (1675)\) transition form factors: That member of the doublet, which is affected by 't Hooft’s force (\(N^\frac{3}{2}^+\)), exhibits a rather strong scalar diquark correlation and thus its structure should be more compact compared to its unaffected doublet partner (\(N^\frac{3}{2}^-\)) whose structure is expected to be
Figure 3. The $\gamma^* p \to N_{\frac{3}{2}}^+(1680)$ (dotted line) and $\gamma^* p \to N_{\frac{3}{2}}^-(1675)$ (short dashed line) transition form factors $G_{\star M}^\star(Q^2)$ divided by the dipole form $G_D(Q^2)$ and normalized to their threshold values $G_{\star M}^\star(0)$. For comparison also the $\gamma^* p \to N_{\frac{1}{2}}^-(1535)$ (solid line) and $\gamma^* p \to \Delta_{\frac{3}{2}}^+(1232)$ (dashed line) are shown.

rather soft. Consequently, the transition form factor to the latter resonance decreases faster than that to its doublet partner with the scalar diquark contribution.

In the strange sector, 't Hooft's force accounts in a similar way for the prominent doublets of the $\Lambda$-spectrum. At the same time instanton-induced effects are found to be significantly weaker in the $\Sigma$-spectrum, thus explaining the fact that no clear experimental indications of parity doublets are observed in this sector.

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