Linear sigma model for N, and $\Delta(1232)$ and its chiral partners

Keitaro Nagata[1,2], V. Dmitrašinović[3], Atsushi Hosaka[2]
[1] Department of Physics, Chung-Yuan Christian University, Chung-Li 320, Taiwan
[2] *Research Center for Nuclear Physics, Osaka University, Ibaraki 567–0047, Japan*
[3] *Vinča Institute of Nuclear Sciences, lab 010, P.O.Box 522, 11001 Beograd, Serbia*

When chiral symmetry breaks down spontaneously, $SU(2)_R \times SU(2)_L \to SU(2)_V$, the broken symmetry plays a dynamical role in the low energy theorems among the Nambu-Goldstone bosons, i.e. the pions. Hadrons are then classified according to the residual symmetry $SU(2)_V$. If chiral symmetry is restored at high temperature or density, hadrons should form degenerate multiplets of the full chiral group representations (I_R, I_L), where $I_R(I_L)$ is the isospin for the $SU(2)_R(SU(2)_L)$. Even in the broken phase, we may expect that hadrons are expressed as one or a simple superposition of chiral multiplets [1]. Familiar examples are the chiral mesons $(\sigma, \vec{\pi})$ and the vector mesons $(\vec{\rho}, \vec{a}_1)$. However, the role of chiral symmetry in the classification of the baryons has been less explored. It is in this regard that we can shed some new light.

The linear realization of chiral symmetry offers two advantages. First, the properties of different hadrons in the same chiral multiplet are related by the larger symmetry $SU(2)_R \times SU(2)_L$ than $SU(2)_V$, which reduces the number of free parameters. Second it is easy to investigate the property changes towards the chiral restoration as functions of the chiral condensate. Having these advantages, the purpose of this work is to investigate the properties of baryons in a manner that respects chiral symmetry.

Recently, we clarified the relation between the baryon fields' chiral multiplets and their quark structures [4]. For instance, we find a set of interpolating fields that belong to a chiral multiplet $(1, \frac{1}{2}) \oplus (\frac{1}{2}, 1)$. We assume that a set of two spin-$\frac{3}{2}$ baryons form the multiplet of $(1, \frac{1}{2}) \oplus (\frac{1}{2}, 1)$ as chiral partners. We extend this idea to include two more baryons by introducing the mirror representations [5]. The mirror baryons carry an axial charge which is opposite in sign as compared with the ordinary (called naive in the literature) baryons. Thus we have altogether four baryons; two with positive parity and two with negative parity. This is a quartet model proposed by Jido et. al. [3]. The four baryons are then identified with $N^+_{P_{13}}(1720)$, $N^-_{D_{13}}(1520)$, $\Delta^+_{P_{33}}(1232)$ and $\Delta^-_{D_{33}}(1700)$.

In order to construct an effective Lagrangian, we write the baryon fields explicitly in terms of three quarks. By making the two quark fields into a suitable diquark combinations, the chiral transformation properties of the baryon fields becomes manifest and the construction of the chiral invariant combination is rather straightforward. The resulting combination contains, in general, several different baryon components with different isospins, which can be explicitly separated into their terms by using the novel technique of the projection method. The details of this method is explained in Ref. [5].

By exploring this technique, we can write down interaction Lagrangians for the four baryons belonging to $(1, \frac{1}{2}) \oplus (\frac{1}{2}, 1)$ and its mirror representations. This is also extended to the construction of the new type of interaction for transitions from the four baryons to the ground state nucleon, assuming that the latter belongs to the fundamental representation $(\frac{1}{2}, 0) \oplus (0, \frac{1}{2})$. The resulting interaction Lagrangians are composed of (1) MBB type, where B stands for baryon resonances and M for chiral mesons, (2) MBN type, where N stands for the ground state nucleon. For a mirror model, there is also (3) a chiral invariant (and off diagonal) mass term between the naive and the mirror fields. Once having all these Lagrangians, we can perform a standard analysis for masses and coupling constants when chirak symmetry is spontaneously broken.

In the present model, because of the use of the chiral symmetry several restrictions apply among various coupling constants. Because of this, for instance, we find a relation $(g_{\pi N \Delta^+} + g_{\pi N \Delta^-}) = 2\sqrt{3}(g_{\pi N N^{*-}} + g_{\pi N N^{*+}})$, which is satisfied by the experimental data with a numerical error of about 20%. Considering the simplicity of the present description, this is an encouraging result suggesting that the spin-$\frac{3}{2}$ baryons are good candidates of the chiral partners.

The interaction Lagrangian contains also the two pion coupling which is inevitable due to chiral symmetry. Hence the two pion decay can be determined by the one pion coupling constants. We find that the resulting properties of the two pion decays of the above resonances are consistent with experimental data.

References

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