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Role of Chiral Symmetries for Baryons

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We discuss roles of chiral symmetry for baryons. General classification of linear chiral representations of baryons allows two distinguished ones; the naive and mirror representations. Based on these representations we construct linear sigma models for baryons and mesons and discuss some consequences derived from them. We emphasize the role of the non zero baryon mass m_0 which may survive when chiral symmetry is restored. Possible experiments to distinguish the two representations are discussed.

§1. Introduction

If chiral symmetry $SU(2)_L \times SU(2)_R$ is manifest, particles are classified into irreducible representations of the chiral group. In reality of hadronic world, however, chiral symmetry is spontaneously broken down to the diagonal vector group $SU(2)_V$, and hence the observed particles are realized as vector representations. A general formalism in the broken phase is then served in the non-linear realization of chiral symmetry, where we cannot tell the would-be chiral group representations of hadrons when chiral symmetry is restored at high temperature or density. From a general consideration of symmetry, however, the particles in the broken phase may be expressed as superposition of chiral group representations. The expansion coefficients then reflect the nature of the symmetry breaking. In particular, if the symmetry is only weakly broken, we expect that the expansion is saturated by a finite (hopefully a small) number of terms.

The simplest example is provided by the case where particles are expressed by a single term of chiral representation. Having the nucleon belonging to the fundamental chiral representation of $(1/2, 0) + (0, 1/2)$ and the chiral mesons (σ, π) to $(1/2, 1/2)$, the linear sigma model is constructed *a la* Gell-Mann-Levy.[1)]

Due to larger symmetry group of $SU(2)_L \times SU(2)_R$ than the isospin symmetry $SU(2)_V$, in linear sigma models, there are more algebraic relations available for physical quantities such as masses and couplings than in the non-linear sigma models. For instance, the axial charge of the nucleon in the Gell-Mann-Levy's linear sigma model is $g_A = 1$ which is a consequence of the nucleon belonging to the fundamental representation $(1/2, 0) + (0, 1/2)$ when the meson-baryon interaction is only through the three point Yukawa coupling. Further such relations were studied long ago by Weinberg for chiral mesons and vector mesons, and for nucleons and delta with much success.[2),3)] Later, the idea was extended by Lee[4)] and DeTar-Kunihiro[5)] by

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including negative parity baryons. More complete analyses with some applications were then made by Jido-Oka-Hosaka.[6)]

One of interesting observations of such linear sigma models is that as originally discussed by Weinberg,[2)] there are two types of masses; one transforming as the zeroth component of a chiral vector and the other as a chiral scalar. The former may be related to the quark scalar condensate $\langle 0|\bar{q}q|0\rangle$ and hence decreases as chiral symmetry is being recovered. On the contrary, the latter mass of chiral scalar nature is not necessarily subject to such behavior, and so it can remain finite even when chiral symmetry is recovered. Such masses may have gluonic origin. The fact that there are two types of masses is very interesting when we discuss the dynamical generation of hadron masses.

§2. Linear sigma models with baryons

The studies for chiral mesons and vector mesons, and for the nucleon, delta and Roper resonances were extended to include negative parity baryons. A traditional wisdom is that the baryons of opposite parities may form chiral partners. Such chiral partners transform each other under chiral symmetry transformations and form a degenerate partner when chiral symmetry is recovered. Since the degeneracy occurs for opposite parity states, it is called parity doubling.[7),8)] In the spontaneously broken phase, however, they may have different masses. A careful consideration, however, reveals that baryon pairs having opposite parities do not necessarily belong to the same chiral representation. Rather they can be totally independent. This becomes clear when possible chiral representations for baryons are established.[6)]

In the spontaneously broken phase of chiral symmetry, the baryon field may be a sum of left and right handed components of the Lorentz group (helicity states). They are subject to independent isospin chiral transformations, which is nothing but the definition of the chiral transformations. When there are two different kinds of baryons, $\psi_1 = \psi_{1L} + \psi_{1R}$, $\psi_2 = \psi_{2L} + \psi_{2R}$, there are two cases of chiral transformations. In the one case called the *naive representation*, ψ_{1L} and ψ_{2L} (and another pair of $L \to R$) are transformed by the same isospin group (and another isospin group). In the other case called the *mirror representation*, ψ_{1L} and ψ_{2R} (and another pair of $L \leftrightarrow R$) are transformed by the same isospin group (and another isospin group). In general, the baryon chiral representations are linear combinations of the naive and mirror representations.

Linear sigma models based on the two representations have been constructed together with chiral mesons and systematically investigated in Ref. 6). Interesting properties are summarized as follows.

- In the naive representation, ψ_1 and ψ_2 are just independent baryons, while in the mirror representation, they form chiral representation. In the latter, the mass eigenstates are mixed states of chiral eigenstates.
- Because of the above property, the pion coupling between ψ_1 and ψ_2 disappears for the naive representation, while it may survive in the mirror representation. Small coupling $g_{\pi NN^*} \sim 0.7$ for $N^* = N(1535)$ may be an indication that $N(939)$ and $N^*(1535)$ are just naive baryons.[9)]

- By the definitions of the chiral symmetry transformations, the axial charges of ψ_1 and ψ_2 have the same sign in the naive representation, while they are opposite for the mirror representations.
- The masses of the baryons are solely determined by the chiral vector for the naive case, while both chiral vector and scalar can contribute to masses of mirror baryons. The scalar mass was denoted as m_0 in the literatures.
- Assigning observed baryon states to the mirror representation ψ_1 and ψ_2, the scalar mass m_0 is determined. For heavier baryon pairs with smaller mass differences, m_0 becomes larger.[10),11)] This indicates that large part of baryon masses are due to chiral scalar mass and may remain finite when chiral symmetry is restored. It would be interesting to consider relations with the observation of parity doubling in high lying states.

The naive and mirror construction of the linear sigma model was extended by including $U(1)_A$ symmetry.[11)] There, four baryons (two positive and two negative parity baryons) are included in the linear sigma model and their properties such as masses were investigated. It turned out that the suppression of $U(1)_A$ breaking did not lead to the parity doubling.[12)] In general, spontaneous breaking of chiral symmetry can explain various pattern of baryon masses. Within the same framework, investigation on decay properties of the four baryons is an interesting question.

§3. $\eta\pi$ production

We can test the realization of possible chiral representations by measuring the sign of the axial charge g_A in order to differentiate the naive and mirror representations. There are two diagonal charges g_A^{NN} and $g_A^{N^*N^*}$ whose relative sign can be measured. Since the axial charge is related to the pion coupling through the Goldberger-Treimann relation, we can use the measurement of the latter. Namely, $g_A^{NN} \sim g_{\pi NN}$ and $g_A^{NN} \sim g_{\pi N^*N^*}$. In general, this is not an easy measurement, but there is one example which is sensitive to the relative sign by using interference effect.

Let us consider the baryon of $N(939)$ and $N(1535)$. An advantage of this choice is that $N(1535)$ couples η strongly, and hence it is rather easy to probe the creation of $N(1535)$. A proposed reaction is then $(\pi \,\text{or}\, \gamma) + N \to \eta + \pi + N$. As shown in Fig. 1, there are diagrams that interfere with the same or opposite signs, depending on the relative sign of the couplings $g_{\pi NN}$ and $g_{\pi N^*N^*}$.

In Fig. 2, we have shown the momentum and angular distributions of the final state pion for the cases of different πN^*N^* coupling constants as indicated in the

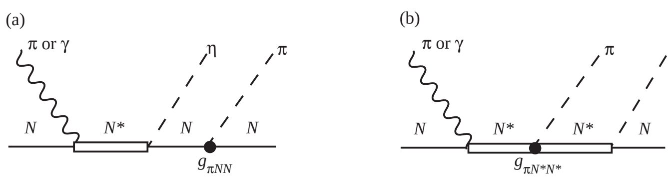

Fig. 1. Diagrams which interfere due to opposite signs of $g_{\pi NN}$ and $g_{\pi N^*N^*}$.

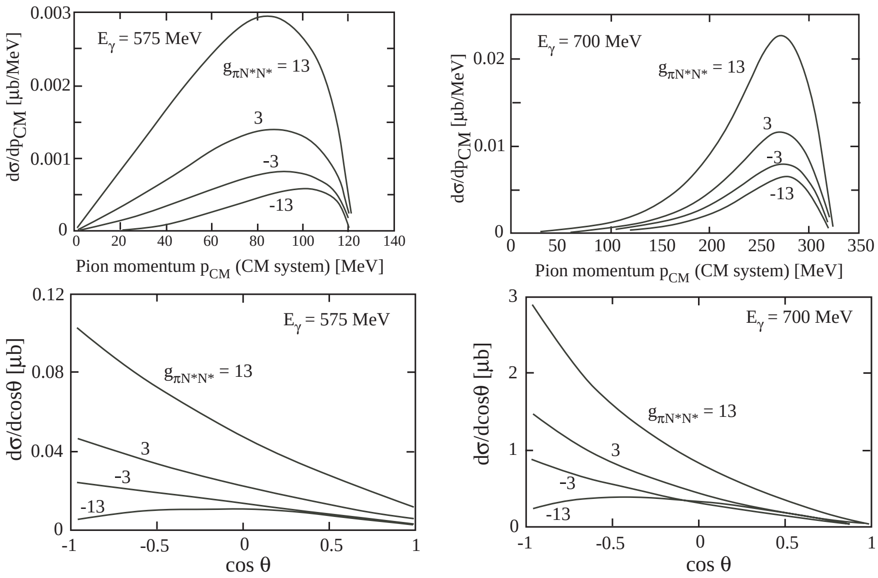

Fig. 2. Momentum (upper panel) and angular (lower panel) distributions of the pion.

figures. Here the πNN coupling constant is fixed $g_{\pi NN} = 13$. In general, the coupling constant may take any value in the broken phase, and so we show results for several cases of $g_{\pi N^* N^*}$. The cross sections may be either enhanced or suppressed depending on the sign of $g_{\pi N^* N^*}$ as expected. Angular distributions show qualitatively different behavior also. Comparison with experimental data of $\eta\pi$ production near the threshold region will be interesting to tell the nature of chiral symmetry properties of baryons.

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