On the effective meson-nucleon Lagrangian for neutrino-less double β decay from R-parity violating SUSY

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There exist several possible mechanisms to generate the neutrinoless double β decay ($0\nu\beta\beta$) which provides crucial constraints on the physics beyond the Standard Model. One of them originates from the R-parity violating supersymmetric extension of the Standard Model (SUSY), in which the $0\nu\beta\beta$ is mediated by the superparticles.

To make theoretical predictions for the $0\nu\beta\beta$ decay in nuclei, we need the hadronic effective Lagrangian to describe the $0\nu\beta\beta$ decay in place of the original SUSY Lagrangian. We construct the effective Lagrangian for mesons and baryons from the R-parity violating SUSY by taking into account the quark-gluon structure of the hadrons. We shall deal with the pion-nucleon dynamics and the $0\nu\beta\beta$ interaction consistently based on the current algebra beyond the naive factorization approximation, taking analogy with the pionic decay of hyperons in the standard weak theory[1]. We remark that the procedure presented here is rather general and can be applied to any model for the $0\nu\beta\beta$ decay.

Diagrams which contribute to the $0\nu\beta\beta$ transition in the R-parity violating SUSY are considered in ref. [2, 3] (e. g. Fig.1). The low energy quark-lepton Lagrangian after integrating out the superfields, in which the $0\nu\beta\beta$ decay is caused by the subprocess $dd \to uu + 2e^-$, is given by

$$\mathcal{L}_{ql} = \frac{G_F^2}{2m_p} e(1+\gamma^5)e^c \left[\eta_{ps}\mathcal{O}_{ps} - \frac{1}{4}\eta_T \mathcal{O}_T\right] \ , \tag{1}$$

where the operators are $\mathcal{O}_{ps} = \bar{u}\,(1+\gamma^5)\,d\;\bar{u}(1+\gamma^5)\,d$ and $\mathcal{O}_T = \bar{u}\,\sigma^{\mu\nu}(1+\gamma^5)\,d\;\bar{u}\,\sigma_{\mu\nu}(1+\gamma^5)\,d$. Here, the coupling constants η are expressed in terms of the R-parity violating coupling constant λ'_{111}, other SUSY parameters and the unification scale [3, 4].

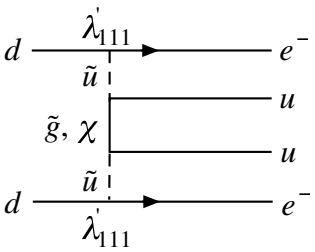

Fig.1

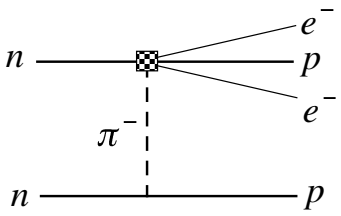

Fig.2

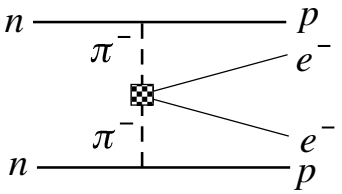

Fig.3

The effective Lagrangian for the pion-nucleon system can be generally written as

$$\mathcal{L}_{Had} = \mathcal{L}_{2N} + \mathcal{L}_{N\pi} + \mathcal{L}_{2\pi} \tag{2}$$

The first term represents the point interaction between nucleons and electrons, $nn \to pp{+}2e^-$, whose matrix element is suppressed very much by the nucleon-nucleon hard core potential [4]. Remaining terms which involve pion fields can be written by

$$\mathcal{L}_{N\pi} \;=\; \frac{G_F^2}{2m_p} m_\pi^2\, e(1+\gamma^5)e^c \;\left[A_{N\pi}\;\bar{p}\,n\;\pi^- \;+\; B_{N\pi}\bar{p}\;i\gamma^5 n\;\pi^-\right] \tag{3}$$

$$\mathcal{L}_{2\pi} \;=\; -A_{2\pi}\,\frac{G_F^2}{2m_p}m_\pi^4\; e(1+\gamma^5)e^c\;(\pi^-)^2 \qquad (4)$$

These contributions are schematically shown in Fig.2 and 3, respectively. We note that the first term of eq. (3) is not considered in the previous works. In order to relate unknown coupling constants, $A_{N\pi}, B_{N\pi}, A_{2\pi}$ with $\eta_{ps,T}$ of the original Lagrangian (1), we must evaluate $\langle p\,2e^-|\mathcal{L}_{ql}|n\;\pi^-\rangle$, $\langle\pi^+2e^-|\mathcal{L}_{ql}|\pi^-\rangle$ using some non-perturbative method based on QCD

Our purpose of this work is to construct the improved effective Lagrangian in more systematic way based on the chiral dynamics, instead of the crude vacuum insertion approximation adopted in ref. [4]. Let us consider the standard weak theory, because the weak interaction Hamiltonian has a similar 4-Fermi operator structure with eq. (1). The transition $nn \to pp + 2e^-$ has the same topological structure as the $\Lambda N \to NN$ decay. One can see that such a decay is dominated by the diagram corresponding to Fig.2. It is also well known that the vacuum insertion gives miserable results for those decay matrix elements. Therefore, we make use of the soft pion theorem based on the current algebra which is proved to work very well for the pionic hyperon decay process of the weak theory. Using the reduction formula and the PCAC relation, one gets

$$\begin{aligned}\langle p\;\pi_a|\mathcal{O}_{ps,T}\,|n\rangle \;&=\; \int d^4x\,e^{-iqx}(\partial^2+m_\pi^2)\,\langle p\,|T\,\{\pi^a(x),\mathcal{O}_{ps,T}\}\;|n\rangle \\ &=\; \frac{-1}{f_\pi}\left\langle p\;\middle|\left[i\int d^3x\;A_a^0(x),\mathcal{O}_{ps,T}\right]\;\middle|n\right\rangle \\ &\quad +\frac{iq_\mu}{f_\pi}\int d^4x\,e^{-iqx}\,\langle p\,|T\,\{A_a^\mu(x),\mathcal{O}_{ps,T}(0)\}\;|n\rangle \qquad (5)\end{aligned}$$

One can see that the first term of eq. (5) corresponds to the so called commutator term. The second one provides the baryon pole contribution, by inserting the intermediate baryon states between $A_\mu(x)$ and $\mathcal{O}_{ps,T}(0)$.

$$\sum_i \frac{2M_N}{f_\pi}\left(\frac{G_{pi}^a W_{in}}{M_N-M_i}+\frac{W_{pi}G_{in}^a}{M_N-M_i}\right)\quad , \qquad (6)$$

where the matrix elements G_{ij},W_{ij} are defined by $\langle B_i|A^{a\mu}|B_j\rangle = G_{ij}^a\bar{u}(i)\gamma^\mu\gamma^5u(j)$ and $\langle B_i|\mathcal{O}_{ps,T}|B_j\rangle = h_{ij}\bar{u}(i)u(j)$. Note that the $\Delta I = 1/2$ enhancement of the non-leptonic weak hyperon decay is well reproduced by taking into account contributions coming from them.

To obtain the explicit expressions for $A_{N\pi}$,$B_{N\pi}$ with the SUSY parameters, $\eta_{ps,T}$, we must rely on the quark model and thus results are model dependent. In any cases, we have found that the contribution of Fig.2 is larger than the pion exchange current Fig.3. However, the complete dominance over the factorization results, which is seen in the pionic decay of the hyperon, is not realized, because of the $S+P$ operator structure of the Hamiltonian instead of $V-A$. Nevertheless, the contributions from Fig.2 are important, and their magnitudes are at least comparable with others.

References

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