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Effective Operators and Neutron-Antineutron Oscillations Versus Nuclear Instability

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Search for the neutron-antineutron oscillations was suggested by Vadim Kuzmin in 1970, and such experiments are under active discussion now, see D. G. Phillips, II *et al.*, Phys. Rept. **612**, 1 (2016)

This is a transition where the baryon charge $\mathcal{B}$ is changed by two units. The observation of the transition besides demonstration of the baryon charge non-conservation could be also important for explanation of baryogengesis. Of course, following Sakharov conditions, it should be also accompanied by CP non-conservation.

Thus, discrete symmetries associated with neutron-antineutron mixing are of real interest.

C, P and T symmetries in $|\Delta \mathcal{B}| = 2$ transitions

In our 2015 text Zurab Berezhiani, AV, arXiv:1506.05096

we noted that the parity $\mathbf{P}$, defined in such a way that $\mathbf{P}^2 = 1$, is broken in n-nbar transition as well as $\mathbf{CP}$.

Indeed, eigenvalues of parity $\mathbf{P}$ are ± 1 and opposite for neutron and antineutron. So, n-nbar mixing breaks $\mathbf{P}$.

We noted, however, that it does not automatically imply an existence of CP breaking in absence of interaction.

In September of the same 2015 we presented at the INT workshop in Seattle a modified definition of parity $\mathbf{P}_z$, such that $\mathbf{P}_z^2 = -1$, and parities $\mathbf{P}_z$ are i for both, neutron and antineutron. With this modification all discrete symmetries are preserved in n-nbar transition

The story goes back to Majorana and Racah's papers of 1937. Details are in Berezhiani, AV, arXiv: 1809.00997

Six-quarks operators: discrete symmetries

New physics beyond the Standard Model, leading to $|\Delta B| = 2$ transitions, induces the effective six-quark interaction,

$$\mathcal{L}\,(\Delta\mathcal{B} = -2) = \frac{1}{M^5}\sum c_i \mathcal{O}^i\,,$$

$$\mathcal{O}^i = T^i_{A_1 A_2 A_3 A_4 A_5 A_6} q^{A_1} q^{A_2} q^{A_3} q^{A_4} q^{A_5} q^{A_6}\,,$$

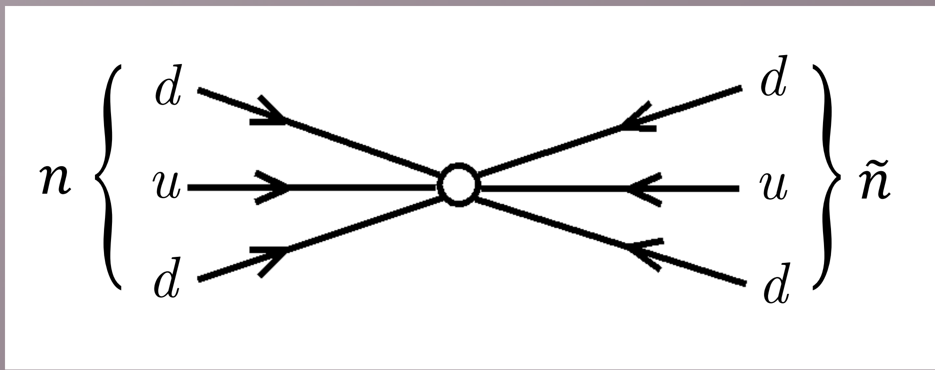
where coefficients T^i account for color, flavor and spinor structures.

In particular, for n-nbar mixing

$$\langle\bar{n}|\,\mathcal{L}\,(\Delta\mathcal{B} = -2)\,|n\rangle = -\frac{1}{2}\,\epsilon\, v^T_{\bar{n}} C\, u_n$$

it lead to an estimate

$$\epsilon = \frac{1}{\tau_{n\bar{n}}} \sim \frac{\Lambda^6_{\mathrm{QCD}}}{M^5}\,.$$



This implies that $M > 10^3$ TeV

For u and d quarks of the first generation the full list of operators was determined S. Rao and R. Shrock, W. E. Caswell, J. Milutinovic and G. Senjanovic

$$\mathcal{O}^1_{\chi_1\chi_2\chi_3} = u^{iT}_{\chi_1} C u^j_{\chi_1} d^{kT}_{\chi_2} C d^l_{\chi_2} d^{mT}_{\chi_3} C d^n_{\chi_3} \big[\epsilon_{ikm}\epsilon_{jln} + \epsilon_{ikn}\epsilon_{jlm} + \epsilon_{jkm}\epsilon_{nil} + \epsilon_{jkn}\epsilon_{ilm}\big],$$

$$\mathcal{O}^2_{\chi_1\chi_2\chi_3} = u^{iT}_{\chi_1} C d^j_{\chi_1} u^{kT}_{\chi_2} C d^l_{\chi_2} d^{mT}_{\chi_3} C d^n_{\chi_3} \big[\epsilon_{ikm}\epsilon_{jln} + \epsilon_{ikn}\epsilon_{jlm} + \epsilon_{jkm}\epsilon_{nil} + \epsilon_{jkn}\epsilon_{ilm}\big],$$

$$\mathcal{O}^3_{\chi_1\chi_2\chi_3} = u^{iT}_{\chi_1} C d^j_{\chi_1} u^{kT}_{\chi_2} C d^l_{\chi_2} d^{mT}_{\chi_3} C d^n_{\chi_3} \big[\epsilon_{ijm}\epsilon_{kln} + \epsilon_{ijn}\epsilon_{klm}\big].$$

Here χ_i stand for L or R quark chirality. Accounting for relations

$$\mathcal{O}^1_{\chi LR} = \mathcal{O}^1_{\chi RL}, \quad \mathcal{O}^{2,3}_{LR\chi} = \mathcal{O}^{2,3}_{RL\chi},$$

$$\mathcal{O}^2_{\chi\chi'} - \mathcal{O}^1_{\chi\chi'} = 3\mathcal{O}^3_{\chi\chi'},$$

we deal with 14 operators for $\Delta\mathcal{B} = -2$ transitions.

The $\mathbf{P}_z$ reflection interchanges L and R chiralities χ_i in the operators $O^i_{\chi_1\chi_2\chi_3}$. Thus, we can divide operators into $\mathbf{P}_z$ even and $\mathbf{P}_z$ odd ones,

$$O^i_{\chi_1\chi_2\chi_3} \pm L \leftrightarrow R$$

The charge conjugation $\mathbf{C}$ transforms operators $O^i_{\chi_1\chi_2\chi_3}$ into Hermitian conjugated $[O^i_{\chi_1\chi_2\chi_3}]^\dagger$. So, we have 14 C-even operators, $O^i_{\chi_1\chi_2\chi_3} + \mathbf{H.c.}$, and 14 C-odd ones, $O^i_{\chi_1\chi_2\chi_3} - \mathbf{H.c.}$

In total, we break all 28 operators in four sevens with different $\mathbf{P}_z$, $\mathbf{C}$ and $\mathbf{CP}_z$ features,

$$[O^i_{\chi_1\chi_2\chi_3} + L \leftrightarrow R] + \text{H.c.}, \quad \mathbf{P}_z = +, \ \mathbf{C} = +, \ \mathbf{CP}_z = +$$

$$[O^i_{\chi_1\chi_2\chi_3} + L \leftrightarrow R] - \text{H.c.}, \quad \mathbf{P}_z = +, \ \mathbf{C} = -, \ \mathbf{CP}_z = -$$

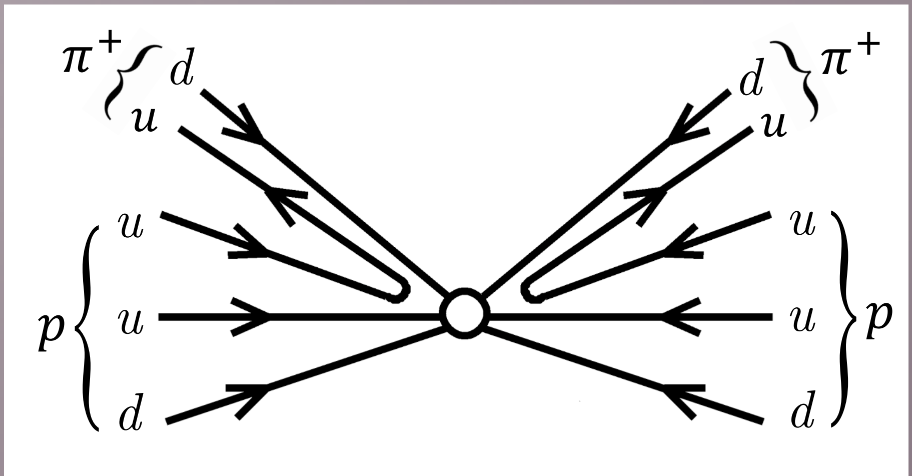
$$[O^i_{\chi_1\chi_2\chi_3} - L \leftrightarrow R] + \text{H.c.}, \quad \mathbf{P}_z = -, \ \mathbf{C} = +, \ \mathbf{CP}_z = -$$

$$[O^i_{\chi_1\chi_2\chi_3} - L \leftrightarrow R] - \text{H.c.}, \quad \mathbf{P}_z = -, \ \mathbf{C} = -, \ \mathbf{CP}_z = +$$

Only the first seven operators which are both $\mathbf{P}_z$ and $\mathbf{C}$ even contributes to n-nbar mixing. What about remaining 21 operators which are odd under $\mathbf{P}_z$ or $\mathbf{C}$? Although they do not contribute to nnbar oscillations they show up in instability of nuclei.

Diagram shows

$p + p \to \pi^+ + \pi^-$



Relation between nnbar oscillations and nuclear instability:

$$\Gamma_A = 4\,\frac{\delta m^2}{\Gamma_{\bar{n}}}$$

Here $\Gamma_A = 1/T_A$ is the width associated with the nuclei instability (per one neutron), $\delta m = 1/\tau_{n\bar{n}}$ and $\Gamma_{\bar{n}}$ is the width, associated with absorption of antineutron in nucleus.

Friedman and Gal in their 2008 paper made more refined calculations relating the lower bound

$$T_A > 1.77 \times 10^{32}\,\mathrm{yr}$$

from the oxygen lifetime measured in Super-Kamiokande to get the lower bound for the oscillation time

$$\tau_{n\bar{n}} > 3.3 \times 10^{8}\,\mathrm{s}$$

Their consideration does not account for annihilation processes with $|\Delta B| = 2$ such as

$$N + N \to n\,\pi$$

we discussed above.

These two-particle contributions are suppressed as compared to the one-particle nnbar part due to smallness of ratio of the nucleon size over distance between nucleons in in the nucleus.

However, the two-particle part grows with nucleon number A as A^2 while nnbar part is linear in A. Thus, the nucleus lifetime is more sensitive to $|\Delta B| = 2$ transitions and its relation to the oscillation time $\tau_{n\bar{n}}$ should be reconsidered.

Conclusions

Our classification of $|\Delta B| = 2$ operators coming from new physics could be useful in association with Sakharov conditions for theory of baryogenisis.

Relation between the nucleus instability and nnbar oscillations could be more subtle due to $|\Delta B| = 2$ two-particle annihilation processes. It calls for additional study.