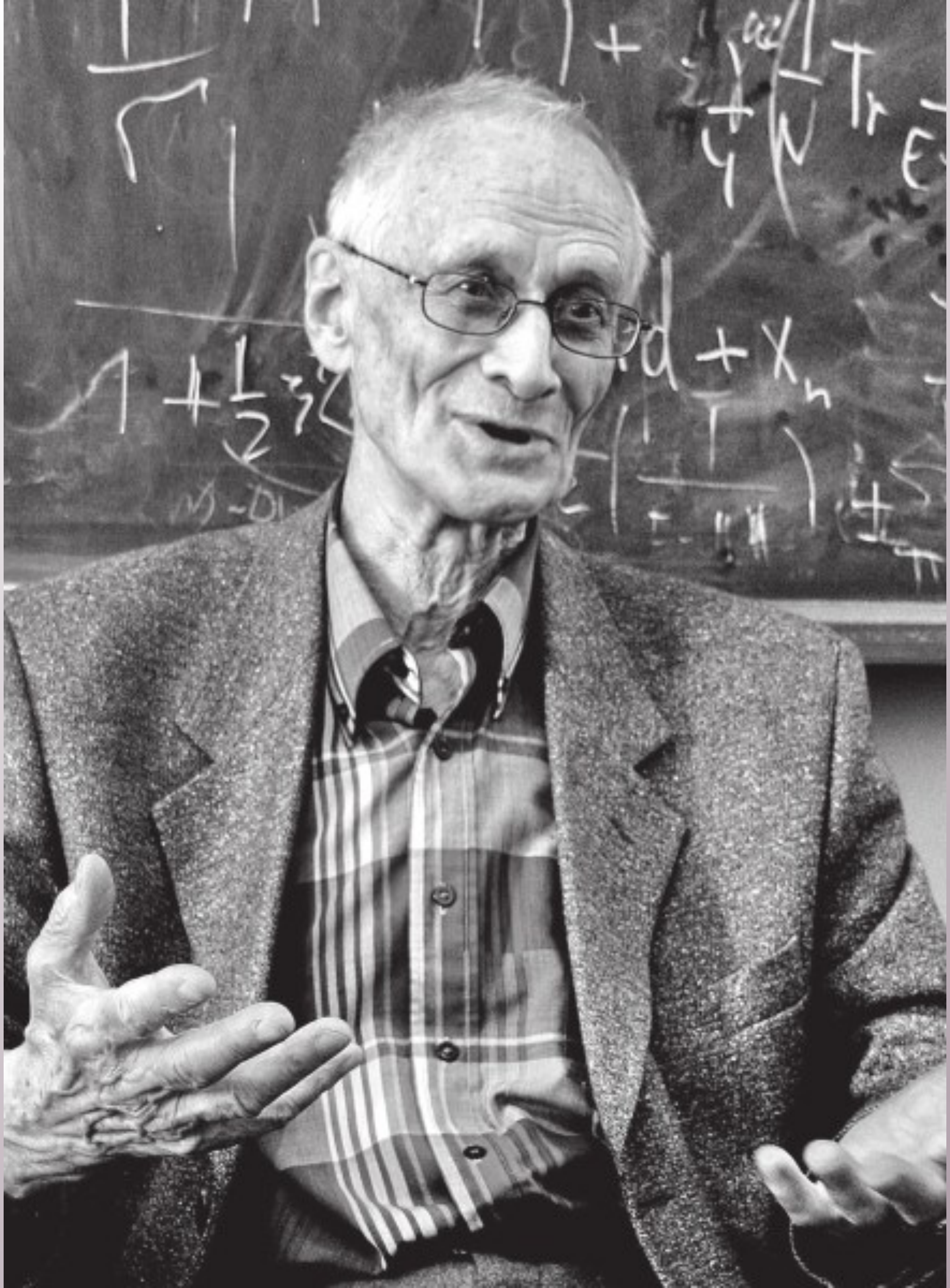

To memory of

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Some Aspects of Neutron-Antineutron Oscillation

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to be updated soon

Vadim Kuzmin suggested in 1970 to search for a neutron-antineutron oscillation, the process which breaks conservation of the baryon charge $\mathcal{B}$ by two units, $|\Delta\mathcal{B}| = 2$. The experiment is under intensive discussion now.

We analyze discrete symmetries C, P and T in the the amplitude of neutron-antineutron mixing. While all these symmetries are preserved at the level of free particles, there are certain subtleties in their definition for baryon charge breaking amplitudes.

We also show that the presence of external magnetic field does not add any new operator to $n\bar{n}$ mixing provided that rotational invariance is not broken.

Dirac Lagrangian for neutron

$$\mathcal{L}_D = i\bar{n}\gamma^\mu\partial_\mu n - m\,\bar{n}n$$

describes free neutron and antineutron and preserves the baryon charge, $\mathcal{B} = 1$ for n, $\mathcal{B} = -1$ for $\bar{n}$.

Continuous U(1) symmetry:

$$n \to \mathrm{e}^{i\alpha} n, \quad \bar{n} \to \mathrm{e}^{-i\alpha}\bar{n}$$

Another term $-im'\bar{n}\gamma_5 n$ consistent with $\mathcal{B}$ conservation can be rotated away by chiral rotation $n \to \mathrm{e}^{i\beta\gamma_5} n.$

Four degenerate states: two spin doublets differ by $\mathcal{B}$.

How does baryon number nonconservation show up?

At the bilinear n fields level the most generic Lorentz invariant modification reduces to only one term which breaks the baryon charge by two units,

$$\Delta\mathcal{L}_{\not{B}} = -\frac{1}{2}\,\epsilon\left[n^T C n + \bar{n} C \bar{n}^T\right] \qquad C = i\gamma^2\gamma^0$$

What is status of discrete $\mathbf{C}$, $\mathbf{P}$ and $\mathbf{T}$ symmetries?

The Dirac Lagrangian preserves, of course, all of them. Indeed, we can rewrite it as

$$\mathcal{L}_D = \frac{i}{2}\left[\bar{n}\gamma^\mu\partial_\mu n + \overline{n^c}\gamma^\mu\partial_\mu n^c\right] - \frac{m}{2}\left[\bar{n}n + \overline{n^c}n^c\right] \qquad n^c = C\bar{n}^T$$

This form demonstrates the C invariance, $n \to n^c$.

Similarly, C invariance for $\Delta\mathcal{L}_{\not{B}}$ is visible from

$$\Delta\mathcal{L}_{\not{B}} = -\frac{1}{2}\,\epsilon\left[\overline{n^c}\,n + \bar{n}\,n^c\right]$$

The Lagrangian are diagonalized in terms of Majorana fields

$$n_{1,2} = \frac{n \pm n^c}{\sqrt{2}}$$

even and odd under C, $\quad C n_{1,2} = \pm n_{1,2}.$

$$\mathcal{L}_D = \frac{1}{2}\sum_{k=1,2}\left[\bar{n}_k\gamma^\mu\partial_\mu n_k - m\,\bar{n}_k n_k\right],$$

$$\Delta\mathcal{L}_{\not{B}} = -\frac{1}{2}\,\epsilon\left[\bar{n}_1\,n_1 - \bar{n}_2\,n_2\right].$$

Two Majorana spin doublets. For C-even n_1 its mass is $m+\epsilon$ while for C-odd n_2 the mass is $m-\epsilon.$

Parity transformation P involves (besides reflection of the space coordinates) the substitution:

$$\mathrm{P}: \quad n \to \gamma^0 n\,, \qquad n^c \to -\gamma^0 n^c\,,$$

where $\gamma^0 C \gamma^0 = -C$ is used

The opposite signs reflect the opposite parities of fermion and antifermion (Berestetsky 1951).

This definition satisfies $\mathrm{P}^2 = 1$ with eigenvalues ± 1, opposite for fermion and antifermion.

The P substitution changes $\Delta\mathcal{L}_{\not B}$ to $(-\Delta\mathcal{L}_{\not B})$.

Thus, $\Delta\mathcal{L}_{\not B}$ is P and CP odd (Gardner and Jafari '14).

Also odd under T because of CPT.

This CP- oddness does not translate, however, into observable CP-breaking, need an interference terms provided by interaction. Subtlety in definition of parity.

The definition we used above is based on $\mathrm{P}^2 = 1$. When there is no B breaking one can include the U(1) phase rotation and define P as

$$\mathrm{P}_\alpha = \mathrm{P}\mathrm{e}^{iB\alpha} : \qquad n \to \mathrm{e}^{-i\alpha}\gamma^0 n\,, \qquad n^c \to -\mathrm{e}^{i\alpha}\gamma^0 n^c\,.$$

Of course, then $\mathrm{P}_\alpha^2 = \mathrm{e}^{2iB\alpha} \neq 1$ but the phase is unobservable when B is conserved.

When the $\Delta L_{\not B}$ is switched on the only remnant of the baryonic U(1) is a discrete Z_4 , i.e., $\alpha = \pm\pi/2, \ \pm\pi$.

Thus, we can choose $\alpha = \pi/2$ to define P_z

$$\mathrm{P}_z = \mathrm{P}\mathrm{e}^{iB\pi/2} : \qquad n \to i\gamma^0 n\,, \qquad n^c \to i\gamma^0 n^c\,.$$

with $\mathrm{P}_z^2 = -1$. Now P_z parities of n and n^c are the same $\cdot i$ and they can mix without breaking P_z. Thus, $\Delta L_{\not B}$ preserves all discrete symmetries, C, P_z and T.

Couple of comments.

First, CPT theorem for local Lorentz-invariant Lagrangians implies that the definition of $\mathbf{T}$ would follow the definition of $\mathbf{P}_z$.

Second, it is amusing that the same $\mathbf{P}_z$ for n and n^c is still consistent with is consistent with the opposite parity for for fermion and antifermion. $\mathbf{P}_z(n)$ should be compared with $[\mathbf{P}_z(n^c)]^*$. Also for the fermion-antifermion pair

$$\mathbf{P}_z(n)\mathbf{P}_z(n^c) = -1$$

Thus, $\Delta\mathcal{B} = \pm 2$ neutron-antineutron mixing leads to specific definition of parity with $\mathbf{P}_z^2 = -1$ .This should used for analyzing $\mathbf{CP}_z$ in interactions.

Similar effects for neutrino were noted by Wolfenstein ’81.

Magnetic field effects

Probability of $n\bar{n}$ conversion is described by

$$P(n(t)=\bar{n}) = \left[\frac{(\delta m)^2}{(\Delta M/2)^2+(\delta m)^2}\right]\sin^2\left[\sqrt{(\Delta M/2)^2+(\delta m)^2}\; t\right] e^{-\lambda t}$$

$$\lambda^{-1} = \tau_n = 880 \text{ s} \qquad \Delta M = -2\vec{\mu}_n\cdot\vec{B}$$

$$|\vec{\mu}_n|B = (6.03\times10^{-23}\text{ MeV})\left(\frac{B}{10^{-9}\text{ Tesla}}\right)$$

At sufficiently small time, $|\vec{\mu}_n\cdot\vec{B}|t \ll 1$ while $t \ll \tau_n$,

$$P(n(t)=\bar{n}) \simeq [(\delta m)\,t]^2 = (t/\tau_{n-\bar{n}})^2$$

Experimentally (ILL, Grenoble)

$$\tau_{n-\bar{n}} > 0.86\times10^8 \text{ s}$$

Nuclear stability (Super-K) gives about 3 times larger value for the lower limit.

No new $|\Delta B| = 2$ operators appear, $n^T \sigma^{\mu\nu} C n F_{\mu\nu}$ and $n^T \gamma_5 \sigma^{\mu\nu} C n F_{\mu\nu}$ vanish due to Fermi statistics.

Voloshin '88 for neutrino

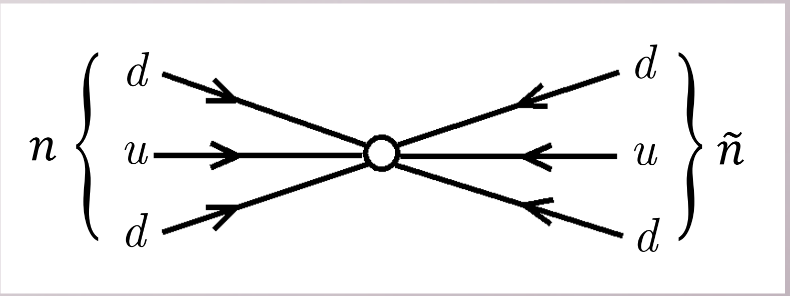
This is not spoiled by a composite nature of the neutron, as it was suggested by Gardner & Jafari '14.
Can be checked in the crossing channel

$$n(p_1) + n(p_2) \to \gamma^*(k)$$

We also checked that the external magnetic field does suppress neutron-antineutron oscillations in contrast to the claim by Gardner & Jafari '14 .

BSM $|\Delta B| = 2$ operators

$$\mathcal{O} = \frac{1}{M^5}\, uddudd$$

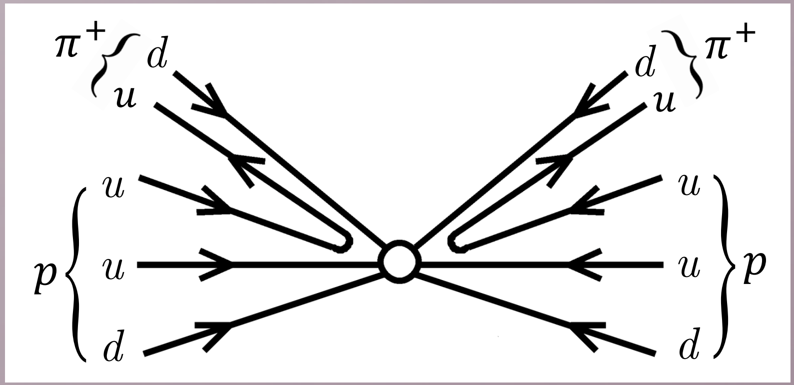


$$\Delta\mathcal{L}_{\not{B}} = -\frac{1}{2}\,\epsilon\left[n^T C n + \bar{n} C \bar{n}^T\right] = \langle \bar{n}|\mathcal{O}|n\rangle + \text{H.c.}$$

$$\epsilon \sim \frac{\Lambda_{\rm QCD}^6}{M^5}$$

Only $\mathbf{C}$ and $\mathbf{P}_z$ even $|\Delta B| = 2$ operators contribute to oscillations. Others leads to instability of nuclei.

$$pp \rightarrow \pi^+\pi^+ \text{ annihilation}$$



In the Standard Model and with u- and d-quarks

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

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

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

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

χ_i stands for L or R quark chirality

14 operators overall accounting for $\Delta\mathcal{B}=-2$ transitions

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

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

plus another 14 Hermitian conjugated, $\Delta\mathcal{B}=2$ transitions.

Only 7 out of 28 operators, which preserve C, P and CP, contribute to the neutron-antineutron transition,

$$\left[O^{i}_{\chi_1\chi_2\chi_3} + L \leftrightarrow R\right] + \mathrm{H.c.}$$

Remaining operators, which breaks P or C, contribute nuclear instability.

Thus, it is possible to have an effect of nuclear instability with suppressed $n\bar{n}$ mixing.

Conclusions

We demonstrate that Lorentz and CPT invariance lead to the unique $|\Delta B| = 2$ operator in the neutron-antineutron mixing. This mixing is even under the charge conjugation $\mathbf{C}$ as well as under the modified parity $\mathbf{P}_z$, which takes the same value i for both, neutron and antineutron in contrast with standard (+1) and (-1) values. Oscillations *per se* do not signal $\mathbf{CP}$ violation.

We also show that switching on an external magnetic field does not add any new $|\Delta B| = 2$ operator and suppress the oscillations.

Could be useful for classification of operators coming from new physics. Particular, in application to baryogenesis.