**Neutron-Antineutron Oscillations: Appearance, Disappearance, and Baryogenesis**

**Institute for Nuclear Theory,**

**Seattle, October 25, 2017**

## Neutron-Antineutron Oscillations and Discrete Symmetries

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## C, P and T Symmetries  $\ln |\Delta B| = 2$  Transitions In this note we discuss the issue of C, P and T sym- $\text{net}$ ries  $\ln |\Delta \mathcal{B}| = 2$  transitions.  $\text{matrix}$   $\ln |AB| = 2$   $\text{Transitions}$ incu ics in  $\left|\Delta\nu\right|$  -**C. P and T Symmetr**  $\epsilon$ , and  $\epsilon$  of external magnetic field and show that it does not it does n s In  $|\Delta \mathcal{B}| = 2$  Transitions  $\sim$  m.  $\sim$  there are for  $\sim$  for  $\sim$  for  $\sim$ metries in the *|B|* = 2 transitions. We also analyze extrice  $\ln |AB| = 2$  Transitions  $\frac{1}{2}$ |<br>**B**|<br>**B|**<br>**B|**<br>**B|**<br>**B|**<br>**B|**<br>**B|** metries  $\ln |\Delta \mathcal{B}| = 2$  Transitions conjugation C, and antineutron.

In our 2015 text Zurab Berezhiani, AV, arXiv:1506.05096  $initvD$  defined in que Essentially the same in our control in our control in the same is a set of the same in our control in our control in our control in the same in our control in the same in the same in our control in the same in our control  $P^2 = 1$ , is broken in n-nbar transition as well as  $\text{CP}$ . We took away our claim of CP breaking in September of the same 2015 when we presented at a similar workshop  $\frac{1}{2}$ here a modified definition of parity  $P_z$ , such that  $P_z^2 = -1$ . With this modification all discrete symmetries are preserved in n-nbar transition. This is a correct this is a correct this is a correct to correct this is a correct to correct the  $t$  the issue of  $p$  and  $p$  we noted that the parity P, defined in such a way that Essentially the same issues were addressed in our previous note that the point that we emphasize the point that  $\mathbf{S}$ claim of CD broaking in Soptamber of automatical diversity in depertured of of relations  $\frac{1}{2}$ . not add any new *|B|* = 2 operator if the rotational in in v we noted that the party.  $M_0$  took quay que claim We cook away our claim we dified definition here a modified definition  $n = 2$ Here *C* = *i*<sup>2</sup><sup>0</sup> is the charge conjugation matrix in the -nbar transition as well as CP. aim of CP breaking in September of these modifications (4) with a help of field redefinitions (4) with a help of field redefinitions (4)  $\alpha$ n we presented at a similar workshop ition of parity P<sub>s</sub>, such that  $P^2 = -1$ urab Berezhiani, AV, arXiv:1506.05096<br>R. N. Mohapatra and R. R. N. Mohamatra and R. E. Marshall  $\sum_{i=1}^n P_i$  such that  $P_2$  is broken in the neutron-intervalse and of CP breaking in beptender of  $\text{P}$  inition of parity  $\mathbf{P}_z$ , such that  $\mathbf{P}_z^2 = -1$ .  $\mu$  is the expression of  $\mu$  in the form  $\alpha$  or  $\mu$ n-nbar transition as well as CP. im of CP breaking in September of (7) <sup>P</sup>*↵* = Pe*iB↵* : <sup>n</sup> ! <sup>e</sup>*i↵*0n, n*<sup>c</sup>* ! e*i↵*0n .  $\pm$   $\frac{1}{2}$  way that ↵ = ⇡/2 neutron-antineutron-antineutron-antineutron-antineutron-antineutron control is under active discussion active [2] D. G. Phillips, II *et al.*, Phys. Rept. 612, 1 (2016) *lation,* arXiv:1506.05096 [hep-ph]. *Neutron-antineutron oscillation and parity and CP symmetries*, and  $\overline{a}$ 

This modification was later discussed by S. Gardner and X 2. Let us start with the Dirac Lagrange County of the Dirac Lagrange County o *<sup>L</sup><sup>D</sup>* <sup>=</sup> *in*¯*<sup>µ</sup>@µ<sup>n</sup> <sup>m</sup> nn*¯ (1) *I* **will present some details of an interesting history of the** subject which goes back to Majorana and Racah's papers of 1937. Lagrangian gives the Lorentz-invariant description of free **DACK CO** Fidjorand and Nacall's papers This modification was later discussed by  $\alpha$  Cerebraneal V, Ver *L*<br>*L***D** interest come detail with the four-component spinor *n↵ ,* (*↵* = 1*, ...,* 4) and subject which goes back **i** neutron and antineutron states and preserves the baryon vas later discussed by S. Gardner and X. Yan,  $\frac{1}{2}$  details of an interesting history of the Maigrana and Dacab's papers  $\mathsf{q}$ orana red to Majorana and Racab's papers ack contrajorana and Racano papers back to Majorana and Racah's papers parity in neutron-antineutron transition reflects the well-known feature of the opposite nowadays (see the resent review for a clear evidence of baryon and be a clear evidence of baryon of baryon and ask to majorana and katang papers  $\mathbf{R} \cdot \mathbf{R}$ 1 Kacan's papers

Dirac Lagrangian for neutron **The Dirac Lagrangian for neutron** and the Dirac Lagrangian for neutron Lagrangian gives the Lorentz-invariant description of free neutron and antineutron states **Dirac Lagrangian for neutron** existence the baryon charges of the 1 for n and B  $\alpha$ . This can be considered by an open set of the 1 for n and B  $\alpha$  is charge control to 1 for n and B  $\alpha$  is charge control to 1 for n an *<sup>L</sup><sup>D</sup>* <sup>=</sup> *in*¯*<sup>µ</sup>@µ<sup>n</sup> <sup>m</sup> nn*¯ (1) with the four-component spinor *n↵ ,* (*↵* = 1*, ...,* 4) and *<sup>L</sup><sup>D</sup>* <sup>=</sup> *in*¯*<sup>µ</sup>@µ<sup>n</sup> <sup>m</sup> nn*¯ (1) *<sup>L</sup><sup>D</sup>* <sup>=</sup> *in*¯*<sup>µ</sup>@µ<sup>n</sup> <sup>m</sup> nn*¯ (1) <sup>4</sup>*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA* Dirac Lagrangian for neutron and the control of the contr

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

describes free neutron and antineutron and preserves the baryon charge,  $B = 1$  for  $n$ ,  $B = -1$  for  $\bar{n}$ . Continuous U(1)<sup>B</sup> symmetry: describes free neutron and antineutron and preserves  $\mathcal{L}_{\text{max}}$  becomes the Lorentz-invariant description of  $\mathcal{L}_{\text{max}}$ and particular graphs of  $B = 1101 h$ ,  $B = -1101 h$ .  $-1$  for  $\bar{n}$ . the baryon charge,  $B = 1$  for  $n$ ,  $B = -1$  for  $\bar{n}$ . neutron and antineutron and preserves Continuous U(1)<sub>B</sub> symmetry: noutron and antinoutron and proserves neutron and antineutron states and preserves the baryon describes free neutron and antineutron and preserves neutron and antineutron states and preserves the baryon che bar yon charge,  $B = 1$  for  $B = -1$  for  $\bar{n}$ . the baryon charge,  $B = 1$  for  $n$ ,  $B = -1$  for  $\bar{n}$ .  $\overline{\mathbf{n}}$  $\frac{1}{2}$  and  $\frac{1}{2}$  besteps in the parity we apply this to  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$ describes free neutron and antineutron and preserves  $t_{\text{max}}$  hence and antineutron provided that rotational invariance is not been. describes free neutron and antineutron and preserves the baryon charge,  $B = 1$  for  $n$ ,  $B = -1$  for  $\bar{n}$ . **Continuous** C(1)*B* symmetry.  $\mathbf{F}(\mathbf{A})$ exclude the term (3) and reduce four terms (4) to one

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

Another term  $-im'\bar{n}\gamma_5n$  consistent with B conservation can be rotated away by the chiral rotation,  $n \to e^{i\beta \gamma_5} n$ . **Four degenerate s**  $A = \frac{1}{2}$ 1 **C** and  $\frac{1}{2}$  **b** and  $\frac{1}{2}$  an Four degenerate states: two spin doublets differ by B. How the baryon number non-conservation shows up at the level of free one-particle of  $L$   $\sim$   $L$  $\tau$ un  $\pi$ y $5\pi$  consistent with  $\beta$  conservation antineutron states doublets different property e states: two spin doublets *e*  $\frac{1}{2}$  $f$ ur  $f_0$  is consistent with  $D$  conservation a states two spin doublets differ by R e states: two spin doublets Another term  $-im'\bar{n} \gamma_5 n$ , con four degenerate states, the spin doublet of neutron states can be rotated away by the ch Four degenerate states: two sping which die by the baryon charge  $\frac{1}{2}$ fields,  $\alpha$  tation,  $n \rightarrow e^{i\beta \gamma_5}n$  .  $\frac{1}{2}$  doublets differ by  $\mathcal{R}$  $\frac{1}{2}$  is the Majorana representation in the Majorana representation in the Majorana representation in the Majorana representation of  $\frac{1}{2}$ neutron and antineutron states and preserves the baryon states t with *B* conservation ur degenerate states: two spin doublets differ by  $\mathcal{B}$ .  $\overline{\phantom{a}}$  mass parameter  $\overline{\phantom{a}}$  $\frac{i\beta\alpha_E}{i\beta\alpha_E}$ n be rotated away by the chiral rotation,  $n \rightarrow e^{n \log n}$ . the neutron and antineutron provided that rotational invariance is not broken. e*i*<sup>5</sup> *n*. Another term  $-im'\bar{n}\gamma_5 n$  consistent with *B* con can be rotated away by the chiral rotation,  $n \rightarrow e^{i\beta\gamma_5}n$ . In this note we discuss the interval of  $\mathcal{L}$ Four degenerate states: two spin doublets differ by  $B$ . be rotated away by chiral *U*(1) transformation *n !*  $\frac{1}{2}$  the level of free one-particle states?  $\mathcal{A}$  also show that presence of external magnetic field does not induce any new operator mixing  $\mathcal{A}$ Another term  $-i m \, n \gamma_5 n \,$  consistent with B conservation  $\frac{1}{2}$  $\overline{a}$  Lagrangian (1). At each spatial momentum there are are are as  $\overline{a}$ egenerate states, two spin doublets differ by  $\mathsf{on}$ viewed as a plain exchange symmetry between *n* and *n<sup>c</sup>*  $\iota$  .

Low doos barvon pumber non conservative consistent with the baryon charge conservation, can be reduced away by chiral transformation, can be reduced away by chiral transformation, can be reduced away by chiral transformation, can be reduced away by chiral transf At the level of free particles it could be only bilinear<br>the baryon charges the baryon charge.  $|\Delta \mathcal{B}| = 2$  mass terms:  $\epsilon = \frac{1}{2}$  mass terms: consistent with the baryon number non-edition, can birother app. How does baryon number non-conservation shows up? At the level of free particles it could be only bilinear The case ideas of the bar charge At the level of free particles it could be only bilinear  $|\Delta \mathcal{B}| = 2$  mass terms: *i*mproved the *in* and *in*  $\frac{1}{2}$  ,  $\frac{1}{2}$  , Note that another bilinear mass term, where At the level of free particles it could be only bilinear *nc* = *n⇤ .* (7) of Lagrangian (1). At each spatial momentum there are servation shows up! and b  $\frac{1}{2}$  = 1, i.e., two spins doublets with  $\frac{1}{2}$  $C=i\gamma^2\gamma^0$ tion corresponds to the continuous U(1)*<sup>B</sup>* symmetry  $S<sub>1</sub>$  Lagrangian (1). At each spatial momentum there are are are as  $\sim$  $\zeta = \frac{1}{2}e^{\frac{2}{3}}$ doos baryon number non-conservation s at the level of free oriental conservation  $\ddot{\textbf{a}}$  $m_{\rm s}$  there are formed as  $\sim$  $|\mathcal{D}| = 2$  inds terms even a magnetic field and show that it does not be in the internal magnetic field and show that it does not be How does baryon number non-conservation shows up:  $\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$  the same issues were addressed in our case of  $\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$  $|\Delta \mathcal{B}| = 2$  mass terms: mass term. Generically, there are four such Lorentz in*n<sup>T</sup>Cn , n<sup>T</sup>C*5*n , nC*¯ *n*¯*<sup>T</sup>*  $C=i\gamma^2\gamma^0$ How does baryon number non-conservation The this network we discuss the combe rotated away by chiral *U*(1) transformation *n !* Apply bilings number of the baryon shows up to the baryon shows up to the baryon shows up to the show of the s<br>Apply to the baryon shows up to the show was a show to the show was a show was a show was a show was a show wa<br>  $\mathbf c$  only binnear description is contained by  $\alpha$  modification of the bilinear  $\alpha$ with the baryon charge  $B$  and the spin doublet of the spin do loes baryon number non-conservation shows level of free particles it could when we have the could be This is a sort of discrete *Z*<sup>2</sup> symmetry, C<sup>2</sup> = 1. The

 $\mathbf{v} = \mathbf{v} + \mathbf{v}$ 

 $n^T C n$   $n^T C \gamma n$   $\bar{n} C \bar{n}$   $\bar{n} C \gamma \bar{n}$   $\bar{n} C \gamma$ states? In Lagrangian description it could be only modification of the bilinear mass term.  $\frac{n}{v}$  in Lie  $\frac{n}{5}$  is  $\frac{n}{2}$ ,  $\frac{n}{v}$ ,  $\frac{n}{5}$  $s=\tau$  in  $\tau$  is contained be only modification in the bilinear modification of the bilinear mass term.  $n^T\!Cn\,,\quad n^T\!C\gamma_5n\,,\quad {\bar nC}{\bar n}^T,\quad {\bar nC}\gamma_5{\bar n}^T$  $\mathbf{v} = \mathbf{v}$  in the set of the  $p^T C p$   $p^T C \gamma p$   $\bar{p} C \bar{p}$   $\bar{p} C \gamma p$  $\alpha$  and  $\alpha$  as  $\beta$  are  $\beta$  as  $\alpha$  as  $\beta$  as  $\alpha$ e↵ects of external magnetic field and show that it does  $n^{\mu}Cn\,,\quad n^{\mu}C\gamma_{5}n\,,\quad \bar{n}C\bar{n}^{\mu}\,,\quad \bar{n}$  $\bar{n}$ <sup>r</sup>

All these bilinear in fields, presenting the most generic Lorentz invariant modifications, are reduced by field redefinitions to the only one term, breaking baryon charge by two units, the phase rotation (2) of n field. NEUTRON–ANTINEUTRON OSCILLATION AS A SIGNAL OF CP VIOLATION 3  $\frac{1}{2}$  and by two units, the baryon charge breaking by two units,  $\frac{1}{2}$  $\frac{1}{6}$  bar *f* on charge 2 **Lorentz invariant modifications, are reduced by field** matrices, and effinitions to the only one term, breaking baryon charge P ese bilinear in fields, presenting the most generic Lorentz invariant modifications, are reduced by field mate the only one term breaking baryon charge be always achieved by the phase rotation (2) of n field. one could add a term of the form natural add also *i*<sup>B</sup>  $\frac{1}{2}$  term of the form natural and  $\frac{1}{2}$  term of the form natural and  $\frac{1}{2}$  term in the form of the form natural and  $\frac{1}{2}$  term in the form of the fo I invariant modifications, are reduced by field to the only one term, breaking baryon charge matrices, and ✏ is a real positive parameter. The reality of ✏ as a coecient for n*<sup>T</sup>* Cn can  $\lambda$  in  $\mathsf{A}$ ll  $\overline{a}$ also noted that in absence of interaction it does not **a**red  $\mathbf{h}$  $h_{\rm F}$ standard representation of gamma matrices. these modifications (4) with a help of field redefinitions rifuons to the only one term, breaking bar  $\Delta$ ll these hilippen in Colde research of the meast consult reduced to one presenting the most generic<br>The baryon charge breaking for the baryon charge breaking the baryon charge breaking of the baryon charge breaking of the baryon charge breaking of the baryon charge of the baryon **L**OI EIILE IIIVAI K  $\frac{1}{2}$ All these bilinear in fields, present  $\mathbf{a}$ **Lorentz invariant modifications, a** redefinitions to the only one terr here we are trying to correct the trying to correct the trying our note  $\mathcal{S}$ the issue of parity definition was addressed in a number of  $\mathbf{r}_i$ standard representation of gamma matrices. :he most generic  $\hspace{0.1mm}$ the modification in the moduration of the set reduced by field redefinitions to the only one term, breaking baryo  $\frac{1}{2}$  $\Delta$ ll th  $\mathbf{t}$  is used in a number of parity definition was addressed in a number of  $\mathbf{t}$ *<sup>L</sup><sup>D</sup>* <sup>=</sup> *in*¯*µ@µ<sup>n</sup> <sup>m</sup> nn*¯ (1) by two units, *L*<br>T*Modific*  $\mathsf{C}$ *✏* ⇥ *n<sup>T</sup>Cn* + ¯*nCn*¯*<sup>T</sup>* ⇤ *,* (5) of such redefinitions is based on U(2) symmetry of the U(2) symmetry of th kinetic term *in*¯*µ@µn* as it is demonstrated in the part *L*oren  $\mathbf{I}$  $\tau$  invariant modification  $\mathbf{b}$  such redefinitions is based on U(2) symmetry of the U(2) symmetry **by two units,**  $\frac{1}{2}$ All these bilinear in fields preser by two units, *L*<br>Folishin *✏ n<sup>T</sup>Cn* + ¯*nCn*¯*<sup>T</sup>* ⇤ *,* (5) ⇥ where *the complete* parameter. The positive parameter parameter. The positive parameter parameter parameter. The possibility of the possibility o of such redefinitions is based on U(2) symmetry of the particle term  $\mathcal{P}(\mathcal{A})$ we did not present a detailed analysis of the problem. So here **All** t the issue of parity definition was addressed in a number *<sup>L</sup><sup>D</sup>* <sup>=</sup> *in*¯*<sup>µ</sup>@µ<sup>n</sup> mnn*¯ (1) by the two units, the two u  $\overline{\text{Int}}$  modi 2  $\frac{1}{2}$  cations, are reduced by **IItions to the only one term, breaking ba**  $\alpha$  such redefinitions is based on U(2) symmetry of the U(2) symmetry of

$$
\Delta \mathcal{L}_{\mathcal{B}} = -\frac{1}{2} \epsilon \left[ n^T C n + \bar{n} C \bar{n}^T \right] \qquad C = i \gamma^2 \gamma^0
$$

where  $\epsilon$  is a real positive parameter. Redefinitions are thanks to  $U(2)$  symmetry of the kinetic term  $i\bar{n}\gamma^{\mu}\partial_{\mu}n$ . away by the chiral rotation <sup>n</sup> *!* <sup>e</sup>*i*5n. The price for this is, as we mentioned above, an appearance of the 5 mass term (3). Also mass term (3). Also mixed kinetic terms *are* the *z* in  $\frac{1}{2}$  +  $\frac{1$  $\mathbf{v}$ appearative of the 5 mass term (3). Also mass term (3). Also mass terms in the 5 mass *quadrator* Redefinitions are where  $\epsilon$  is a real positive parameter. Redefinitions are appearance of the kinetic term  $i\bar{n}\gamma^{\mu}\partial_{\mu}n$  .  $\left($ *<sup>L</sup><sup>D</sup>* <sup>=</sup> *in*¯*<sup>µ</sup>@µ<sup>n</sup> <sup>m</sup> nn*¯ (1)  $\epsilon$  to  $1/2$  symmetry of the kinetic term  $\epsilon$ kinetic term *in*¯*<sup>µ</sup>@µn* as it is demonstrated in the part thanks to U(2) symmetry of the kinetic term  $i\bar{n}\gamma^{\mu}\partial_{\mu}n$ . thanks to  $U(2)$  symmetry of the kinetic term  $i\bar{n}\gamma^{\mu}\partial_{\mu}n$ . where *D*  $\alpha$  definitions are  $\overline{\phantom{a}}$ . Incurrinitions are the mass parameter *m* which is real and positive. The **Lagrange** charge, *B* = 1 for *n* and *B* = 1 for *n*¯. This conservawhere *c* is a real positive parameter thanks to  $U(2)$  symmetry of the kinetic term  $i\bar{n}\gamma$ structure (5). 3. What is the status of discrete C*,* P and T symmetries the mass parameter *m* which is real and positive. The Lagrangian gives the Lorentz-invariant description of the Lorentz-invariant description of the Lorentz-invaria  $thor$ charge, *B* = 1 for *n* and *B* = 1 for *n*¯. This conserva $s$  is a page under the baryon charge breaking modification (5)? Let

What is the status of C, P and T discrete symmetries? be turned away with redefinition of the fermion field. Hence, a generic Lagrangian containing the fermion bilinears can always be brought to Let us start with the charge conjugation C: a form containing only the terms (1), (3) and (4). conjugation C, and a form containing only the terms (1), (3) and (4). Let us start with the charge conjugation C<sub>i</sub>.  $\mathcal{H}$  and  $\alpha$  general containing the fermion bilinears can always be brought to be a set of  $\alpha$ status only, thang I discrete symmetries: with the four-component spinor *n↵ ,* (*↵* = 1*, ...,* 4) and the mass parameter *m* which is real and positive. The **Let**  $\mathcal{A}=\mathcal{A}$  , and the U(2) transformations allow to  $\mathcal{A}=\mathcal{A}$  , and the U(2) transformations allow to  $\mathcal{A}$ is the status of  $\mathbf C, \mathbf P$  and  $\mathbf T$  discrete symn structure (5). kinetic term *in*¯*<sup>µ</sup>@µn* as it is demonstrated in the part  $\blacksquare$  Four parameters of  $U, P$  and  $T$  discrete symmetries: Let us start with the charge conjugation C:  $M/h$ <sup>2</sup> *is the status of*  $C$  **D** and  $T$  $\mathbf{v}$  which is the status of  $\mathbf{v}, \mathbf{r}$  and  $\mathbf{r}$ example the term (3) and reduce the terms (3) and reduce the terms (4) to one terms (4) to one terms (4) to one  $\frac{1}{\sqrt{2}}$ .  $\overline{M}$ *<sup>n</sup> !* <sup>e</sup>*i↵n, <sup>n</sup>*¯ *!* <sup>e</sup>*i↵n*¯ (2)  $\overline{\phantom{a}}$ the status of  $C$ ,  $P$  and  $T$  discrete symmet viewed as  $\alpha$  *n* and What is the status of  $C$ ,  $P$  an viewed is and stated simply between  $\alpha$ ,  $\alpha$ ,  $\beta$  $\mathbf{v} \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{v}$ **v** v nat is the status of  $C$ ,  $P$  and  $T$ l at us start with the charge con tion corresponds to the continuous U(1)*<sup>B</sup>* symmetry *<sup>n</sup> !* <sup>e</sup>*i↵n, <sup>n</sup>*¯ *!* <sup>e</sup>*i↵n*¯ (2) **Let**  $\mathbf{f}(\mathbf{x})$  first consider the charge conjugation  $\mathbf{f}(\mathbf{x})$ s the status of C, P and *T* discrete sym

 $=$   $Cn^ \sigma$  verify that the  $\sigma$  and  $\sigma$ conjugation control in the control of the  ${\bf C}: \quad n \longleftrightarrow n^c = C \bar n^T$ neutron and antineutron states and preserves the baryon conservative c  $\bar{n}^T$  is the status of discrete  $\bar{n}^T$  $\mathbf{C}: \quad n \longleftrightarrow n^c = C \bar{n}^T$  $C: n \downarrow \rightarrow n^c - C\overline{n}^T$ 

 $\mathcal{L} = \mathcal{L} = \mathcal$ te in the Majorana terms (1)  $\mathbf{C}: \quad n \longleftrightarrow n$ **Kind of**  $Z_2$  symmetry,  $C^2 = 1$ . Most simple in the majorana makes in the presentation  $\lim_{x \to 0} \frac{1}{x}$  f 7. symmatry  $C^2 - 1$  Most simp In the expression of the expression in the form (1) can be rewritten in the form (1) can be rewritten in the form (1)  $\sim$  $m$ metry,  $C^2 = 1$ . Plost simple in the Plajorana n epi escritation  $n^c - n^*$ Kind of  $Z_2$  symmetry,  $C^2 = 1$ . Most simple in the Majorana viewed as a planet symmetry between  $\mathcal{L}$ tion corresponds to the continuous U(1)*<sup>B</sup>* symmetry *n n* **e**  $\mathcal{L}$  under the baryon charge breaking modification (5). Letters and  $\mathcal{L}$ Kind of  $Z_2$  symmetry,  $C^2 = 1$ . Most simple in the fields, and the status of discrete C, P and T symmetries of the status of discrete C, P and T symmetries of the sy *<sup>n</sup> !* <sup>e</sup>*i↵n, <sup>n</sup>*¯ *!* <sup>e</sup>*i↵n*¯ (2) where under the baryon charge breaking modification (5)? Let unple in the chajorana  $V$  in d antineutron states with *B*  $\overline{B}$ Kind of  $Z_2$  symmetry,  $C^2 = 1$ . Most simple in the M most simple it looks in the Majorana representation most simple it looks in the Majorana representation antineutron states with *B* in  $\mathbf{f}$   $\mathbf{z}$  symmetry,  $\mathbf{z}^2$  symmetry,  $\mathbf{z}^2$ r  $z_2$  symmetry,  $C^2 = 1$ . Plost simple in th

$$
n^c=n^*\,.
$$

Lagrangians can be rewritten as *L<sup>D</sup>* = rengiano can ha roverittan Lagi and 1 *Lagran* 2  $\frac{1}{2}$  $\blacksquare$ which makes the contract of  $\blacksquare$ 

$$
\mathcal{L}_D = \frac{i}{2} [\bar{n}\gamma^\mu \partial_\mu n + \bar{n}^c \gamma^\mu \partial_\mu n^c] - \frac{m}{2} [\bar{n}n + \bar{n}^c n^c],
$$
  

$$
\Delta \mathcal{L}_{\mathcal{B}} = -\frac{1}{2} \epsilon [\bar{n}^c n + \bar{n} n^c],
$$

what makes C-invariance explicit.  $\overline{c}$ *n ± n<sup>c</sup>* rana fields *n*<sup>1</sup>*,*<sup>2</sup> , *n ± n<sup>c</sup>*

Lagrangians are diagonalized in terms of Majorana fields  $T_{m}$   $\pm$   $m$ <sup> $c$ </sup>  $\bf 1, \bf 2$ ana fields  $n_{1,2}$  ,  $\overline{a}$ P*<sup>z</sup>* parity. It means that all discrete symmetries, C, P*<sup>z</sup>*  $r$ ana fields  $n_{1,2}$ *<sup>p</sup>*<sup>2</sup> *,* (9) C-irival lance explicit.<br>are diagonalized in terms of Maiorana field  $\mathbf{R}$ gonalized in terms of Majorana fields  $n_{1,2}$ Couple of related comments. First, preservation of

$$
n_1=\frac{\overline{n}\pm n^c}{\sqrt{2}}\,,\qquad \quad \mathrm{C}n_{1,2}=\pm\,n_{1,2}.
$$
 
$$
\mathcal{L}_D=\frac{1}{2}\sum_{k=1,2}\big[\bar{n}_k\gamma^\mu\partial_\mu n_k-m\,\bar{n}_kn_k\big],
$$
 
$$
\Delta\mathcal{L}_\mathcal{B}\! =-\frac{1}{2}\,\epsilon\big[\bar{n}_1\,n_1-\bar{n}_2\,n_2\big].
$$

*L*<br>*L*<br>Daid  $\mathsf{r}$ *k*=1*,*2  $\frac{1}{2}$ (10) *L*<br> *L*<br>
into two Majorana spin doublets with masses pnceng m doublets with masses Splitting into two Majorana spin doublets with masses field gets the mass *M*<sup>1</sup> = *m* + *✏* while the mass of the

$$
M_1 = m + \epsilon \qquad \qquad M_2 = m - \epsilon
$$

The parity transformation P involves, besides reflection of space coordinates, the substitution and (3) and (3) and (3) and (3) are all invariant under the charge of the conjugation C, space coordinates, the substitution M<sup>±</sup> = m *±* ✏ <u>P2 and</u>  $\Box$  **P** = Periodicial space coordinates, the substitution [5] V. B. Berestetskii, Zh. Eksp. Teor. Fiz. 10 21, 1321 (1951)  $\mathsf B$  parity transformation  $\mathsf P$  involves, besit coordinates, the substitution  $\overline{a}$  X.W. B. Lu,  $\overline{a}$  $\,$  tion  $\, {\bf P}$  involves, besides reflection of Turn now to the parity transformation P. It involves tion<br>tion Turn now to the participants of the parity transformation  $P$ D involves hesides reflection of (besides reflection of the space coordinates) the substitution of the substitution of  $\mathbf{r}$ space coordinates, the substitution It demonstrates that the baryon charge breaking leads to The parity transformation P involves, besides reflection of CP*z*=P*z*C, in contrast with P which anticommute with field gets the mass *M*<sup>1</sup> = *m* + *✏* while the mass of the space coordinates, the substitution Thus, we demonstrated that  $\frac{1}{2}$ It demonstrates that the baryon charge breaking leads to varity transformation P involves, besides reflection CP*z*=P*z*C, in contrast with P which anticommute with The parity transformation splitting into two Majorana spin doublets, The C-even *n*<sup>1</sup> C-odd *n*<sup>2</sup> is *M*<sup>2</sup> = *m ✏*. D<sub>involves</sub> hosides reflection of ty transformation P involves, besides reflection of ing by *B* = *±*2 Majorana term in the mass matrix field gets the mass *M*<sup>1</sup> = *m* + *✏* while the mass of the space coordinates, the substitution and *n*<sup>2</sup> is *m*  $\alpha$  is *m* field gets the mass *M*<sup>1</sup> = *m* + *✏* while the mass of the  $\blacksquare$ field gets the mass *M*<sup>1</sup> = *m* + *✏* while the mass of the CPP CPAINS CONTRAST WITH **P** INTERCITE WITH  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  are  $\frac{1}{2}$   $T_{\text{univeto}}$ , which calculated that neutron-antineutron-antineutron-antineutron mix-

$$
{\bf P}: \hspace{1cm} n \rightarrow \gamma^0 n \, , \hspace{1cm} n^c \rightarrow - \gamma^0 n^c \, .
$$

We use  $\gamma^0 C \gamma^0 = -C$ . The opposite signs reflect the opposite parities of feur The particle of the more and a space of the Secondary 31 opposite parities of fermion and antifermion parity of fermion and antifermion. The term L*m*<sup>0</sup> also breaks P parity, it is evidently  $1.1$  Experimental search for neutron-antineutron-antineutron-antineutron  $\frac{1}{2}$  is under active discussion  $\frac{1}{2}$ we use  $\gamma^{\rm o} C \gamma^{\rm o} \,=\, -C$ . The opposite signs re conosite parities of fermion and antifermic antineutron oscillation also breaks CP invariance. This conclusion is based on the Lorentz We use  $\gamma^0 C \gamma^0 = -C$  The opposite signs reflect the  $\mathbf{v} \cdot \mathbf{v} = \mathbf{v}$ . The opposite signs reflect the well-known feature of the opposite signs reflect the opposite of the opposite signs reflect the  $\mathbf{v}$ opposite parities of fermion and antifermion C.N. Yang 50  $\mathbf{R} \mathbf{B} = \alpha^0 C \alpha^0 = -C$  The opposite [9] P. Ramond, *Journeys Beyond the Standard Model*, [10] M. B. Voloshin, Sov. J. Nucl. Phys. 48, 512 (1988) [Yad. C.N. Yang '50 V.B. Berestetsky '51 The opposite signs reflect the transformations for an and *n*<sup>2</sup> reflect the well-known themon and antifermion  $\frac{6.444}{V.B. Berestetsky}$  <sup>51</sup> pioneered by Berestetsky [5]. The definition (11) satisfies transformations for  $\frac{1}{2}$  reflect the well-known the-Thilon and antifermion  $\frac{1}{V.B. Bersetesky}$  <sup>51</sup> pioneered by Berestetsky [5]. The definition (11) satisfies  $t_{\text{max}}$  and  $\epsilon$  reflections for  $CN$   $Y_{\text{ang}}$  <sup>750</sup> opposite partities of fermion and antifermion  $V.B.$  Berestetsky '51  $\mathcal{A}$  (besides  $\mathcal{A}$  ordinates) the substantial substitution of  $\mathcal{A}$ making it complex and satisfying P<sup>2</sup> pposite signs reflect the used in an  $ion$  C.N.  $Yang$   $50$ N.B. Berestetsky '51 p annosite parities of ferm where <sup>0</sup>*C*<sup>0</sup> <sup>=</sup> *<sup>C</sup>* is used. The opposite signs in (+1). It is this definition which should be used in ana- $N_{\text{max}}$  is the majoral connection with  $N_{\text{max}}$  neutrino the  $N_{\text{max}}$ s of itermion and and critical conducts  $V.B.$  Berestetsky  $31$ discussed long ago [8]. Here we apply this to mixing of  $\int_0^{\pi} f(x) dx = \int_0^{\pi} f(x) dx$  The space is substance reflect the  $\overline{c}$ lyzing CP<sup>z</sup> violating interactions. P : *<sup>n</sup> !* <sup>0</sup>*n, n<sup>c</sup> !* <sup>0</sup>*n<sup>c</sup> ,* (11) Note that in connection with Majorana neutrino the (a). The should be used in an interesting in an interesting in an interesting in an interesting in an interest lyzing CP<sup>z</sup> violating interactions. subtletty in a definition of  $\mathbf{V}.\mathbf{B}.\; \mathbf{B}$  errestetsky for  $\mathbf{V}$ p *n nosite signs reflect the* fermion and antifermion C.N. Yang '50 transformation and antificial motion v.B. Berestetsky  $31$ *r minn C.N.* Yang '50 where  $\mu$  is the opposite signal and  $\mu$  is used. The opposite signs in  $V.B.$  Berestetsky  $31$ We use  $\gamma^0 C \gamma^0 = -C$  The opposite signs reflect  $\eta_{\text{U}} = -\nu$ . The opposite signs reflect parities of fermion and  $V.B.$ 

substitution apposite parties for formion and anti-This substitution changes L*B*<sup>6</sup> to L*B*<sup>6</sup> because 0C<sup>0</sup> <sup>=</sup> C. The breaking of parities of neutron and antineutron implies that their mixing breaks P parity. Indeed, P-transformation changes  $\rho$  is explored to parameter the particle complies that  $\rho$  is also  $\Delta\mathcal{L}_{\beta}$  is a local contracted by a local building by a local depth of the Lagrangian model in the Lagrangian.  $\mathbf C\mathbf P$  odd. We demonstrate that observation of neutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineu The definition satisfies  $P^2 = 1$  so eigenvalues of P are  $\pm 1$ , opposite parities for fermion and antifermion. Different  $\Delta \mathcal{L}_{\mathcal{B}}$  to  $(-\Delta \mathcal{L}_{\mathcal{B}})$ . With C- invariance it implies that  $\Delta \mathcal{L}_{\mathcal{B}}$  is also odd.  $T_{\rm eff}$  and observation of neutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antin opposite pariti  $\limsup$  introduce the  $\frac{3}{2}$  bit can see flavor  $\limsup$ copposite parities for fermion and antifermion. Differ parities of neutron and antineutron implies that their mixing breaks P parity. Indeed, P-transformation changes of Lagrangian (1). At each spatial momentum there are four degenerate states, two spinnings of two spinnings of  $\alpha$  $\sum_{i=1}^{n}$ C invariance it implies that  $\Lambda f_B$  is also However, the complete versus  $\Delta\mathcal{L}_{\mathcal{B}}$  is also ermion and antifermion Diff  $\frac{1}{2}$ C invariance it implies that *AC<sub>p</sub>* is also Invariance it implies that  $\Delta L_{\beta}$  is also  $f$  and antifermion  $\Gamma$  $D_{\text{II}}$  and and control and and and antineutron inplied  $D_{\text{III}}$ Tuccu, + Fu ansion mation changes variance it implies that  $\Delta\mathcal{L}_{\mathcal{B}}$  is also ately into observable CP breaking e↵ects. To get them opposite parities for fermion and anti- $\overline{\phantom{a}}$  or  $\overline{\phantom{a}}$  fermion and antiperturban in parties of head on and and reduced by mixing breaks P parity. Indeed, P-trai  $\Lambda$ cito (Ac) M  $\Delta \mathcal{L}_{\beta}$  CV  $($   $\Delta \mathcal{L}_{\beta}$ ). Y Y ICH  $\cup$  - Intranance it imply  $s = \frac{1}{2}$  $\frac{1}{2}$  discussed and  $\frac{1}{2}$ . opposite parities for fermion and antifermion. Different  $m$ rituation changes  $\Delta\mathcal{L}_{\mathcal{B}}$  to ( $-\Delta\mathcal{L}_{\mathcal{B}}$ ). With C- invariance it implies that  $\Delta\mathcal{L}_{\mathcal{B}}$  is also The definition setiation **T** orthus of the opposite participate parties of the second state  $\frac{1}{2}$ P2 = 1, so the eigenvalues of partition and opposition of **P** pariue miving hreaks P narity li  $\frac{1}{\sqrt{2}}$  mixing breaks P arrivers  $\frac{1}{\sqrt{2}}$ C invariance it implies then that *L6B* is also CP odd. C invariance it implies then that *L6B* is also CP odd. However, this CP oddness does not translate immedi-The definition satisfies  $P^2 = 1$  so eigenvalues of *P* are  $\overline{a}$  and above above a generic covers a generic covers a generation cover  $\overline{a}$ neutron implies that their  $\frac{1}{\sqrt{2}}$  *<sup>i</sup> ↵ , i* = 1*,* 2*, ↵* = 1*,* 2 *,* (14) to the with the complex complex complex considered the contract  $\rho$  to discover ite parities for fermion and antifermion. Different orem original ordinal distinguished that the in Bergested by Bereitsky and an interested by Berestersky and the definition of the definition of the definition o mixing breaks P parity. Indeed, P-transformation chang fermion and antifermion states.  $\Delta \mathcal{L}_{\beta}$ , we funct the neutron increase of  $\mathcal{L}_{\beta}$  is  $\mathsf{Id}.$  their mixing breaks  $\mathsf{Id}.$  $s_{\rm max}$ where  $C_0$  is used. The opposite signs in the orem on the opposite particle particles of  $f$ opposite parities for fer parities of neutron and **:** par ities that the indeed, indeed, indeed, indeed, the sub- $\Delta\mathcal{L}_{\mathcal{B}}$ to ( $-\Delta\mathcal{L}_{\mathcal{B}}$ ). With C- in However, this CP oddness does not translate immedi-C invariance it implies then that *L6B* is also CP odd. discussed long ago [8]. Here we apply this to mixing of  $=$  1 so eigenvalue  $\bullet$  . To show that the above covers a generic covers and  $\bullet$ id antineutron implies that their weightrity Indeed, P-transformation changes  *<sup>i</sup> ↵ , i* = 1*,* 2*, ↵* = 1*,* 2 *,* (14) to the thermal complete complex conditions  $\varphi$  is defined the set of  $\varphi$ orem on the opposite particle particles of fermion and antifermion and antife ries  $P^2 = 1$  so eigenvalues of P are  $\pm 1$ , r fermion and antifermion. Different fermion and antifermion states. stitution (110) changes **Land Communication** Changes **Land with the communication**  $\Delta\mathcal{L}_{\mathcal{B}}$  to  $(-\Delta\mathcal{L}_{\mathcal{B}})$ . With C- invariance it implies that  $\Delta\mathcal{L}_{\mathcal{B}}$  is also  $\alpha$   $\alpha$  *n*  $\alpha$  *n*  $\alpha$  *n*  $\alpha$  *n*  $\alpha$  *n*  $\alpha$   $\alpha$   $\pm$  1  $\sigma$  organization of  $f$  and  $\pm 1$ , opposite parities for fermion and antifermion. Different <sup>P</sup><sup>2</sup> = 1, so the eigenvalues of <sup>P</sup> are *<sup>±</sup>*<sup>1</sup> and opposite for parities of neutron and antineutron implies that their that the threaks parameters  $\frac{1}{2}$ The definition satisfies  $P^2 = 1$  so eigenvalues of transformations for *n* and *n<sup>c</sup>* reflect the well-known thepioneered by Berestetsky [5]. The definition (11) satisfies <u>Diuwurk parities</u> stitution (11) changes *L6B* to (*L6B*) . Together with subtlety in a definition of parity P (and CP) and was neutron and antineutron. f neutron and antineutron implies that the case it is convenient to internal convenient to internal convenient of the convenient of the convenient of the reaks  $\rm P$  parity. Indeed, I

This CP-oddness, however, does not translates immediately into observable CP-breaking effects. To get them one needs an interference of amplitudes provided by interaction. *Neutron-antineutron oscillation and parity and CP sym-*D. McKeen and A. E. Nelson, Phys. Rev. D 94, no. 7, To get them one needs an interference of amplitudes (2016) [arXiv:1602.00693 [hep-ph]]; [14] Z. Berezhiani and L. Bento, Phys. Rev. Lett. 96, 081801 64, 421 (2009) [arXiv:0804.2088 [hep-ph]]. This CP-oddness, however, that their mixing breaks P parity, and, indeed, the substitution (11) changes *L6B* to (*L6B*) . Together with  $P(X)$  or overled by interaction provided by filteraction. pidnoss, however does not translates *<u></u>*  $\frac{1}{2}$  **e** 12, 2 *x* 2*,* 2 *x* torance of amplitudes lefter en amplie <sup>P</sup><sup>2</sup> = 1, so the eigenvalues of <sup>P</sup> are *<sup>±</sup>*<sup>1</sup> and opposite for tely into observable CF Di↵erent parities of neutron and antineutron imply To get them one needs an interference of amplituded analysis of the problem. The problem and problem. The problem strike **Lands Lands Lands Landsa to (***C***<sub>6</sub>B) . To** C invariance it implies then that *L6B* is also CP odd. This CP-oddness, however, does not translates  $\frac{1}{2}$  CP hroaking offects **field Fundaning eneces.** parity P, such that P<sup>2</sup> = 1, is broken in the neutronimmodiately inte observed automatical interventions and CP breaking physics of CP breaking physics of CP breaking physics and ph here we are trying to correct this. Following our note [3] the interaction was addressed in a number of neutron was addressed in a number of neutron and antineutron in an index of neutron and antineutron in an in standard representation of gamma matrices. **The chiral basis we show in the part 4 that all 1 that all 1 that all 1 the eigenvalues of P are**  $\mathbf{r}$ Fily into observable CP-breaking effects. reduce to one possibility for the baryon charge breaking **interreren** pioneered by Berestetsky [5]. The definition (11) satisfies Di↵erent parities of neutron and antineutron imply m one needs an interference of amplitudes. stitution (11) changes *L6B* to (*L6B*) . Together with transformations for *n* and *n<sup>c</sup>* reflect the well-known theddness, however, does not translates P2  $\mu$  into observable of PD earing enects. Di↵erent parities of neutron and antineutron imply Poddness however does not translat  $\sf L$ P-oggness, nowever, goes not translat  $distolv$  into observable  $CD$  breaking of nediately into observable CP-breaking effects. t them one needs an interference of ar  $\frac{1}{\sqrt{2}}$  and  $\frac{1}{\sqrt{2}}$  and  $\frac{1}{\sqrt{2}}$  and  $\frac{1}{\sqrt{2}}$  and  $\frac{1}{\sqrt{2}}$  and  $\frac{1}{\sqrt{2}}$ that their mixing breaks P parity, and, indeed, the sub- $\ddotsc$  that the above consideration covers a generic covers a generi **lo get them one needs an interference of amplitudes**  $\overline{r}$  $\mathbf{p}$  original particle parametermion and antifermion and  $\sqrt{1+\frac{1}{n}}$ lyzing CP<sup>z</sup> violating interactions. smalitudes of particular of particular of particular and was defined as a series of particular and was and was amplitudes and we apply the set of mixing of  $\mathbb{R}$ .

This subtlety is discussed in textbooks, see e.g. Let's remind it.  $\overline{\mathbf{T}}$ lais subtletuis dissussed in teud **FITIS SUDLICLY IS GISCUSSEG III LEXLUOURS, SET** V. B. Berestetsky, E. M. Lifshitz and L. P. Pitaevsky, *Quantum Electrodynamics*, Oxford, UK: Pergamon Let's remind it.  $\mathbf{S} \cdot$  $T<sub>l</sub>$ U.B. Berestetsky. E.M. Lifshitz and L.P. Pitaeysky. matic P (1990) P, see the Refs.  $\frac{1}{2}$ . one can real intext books, see e.g.  $\ldots$  these von $y$ , *v*. D. Derestetsky, E.W. Emsing a **It shows a subtletty in the definition of parity transformation. P : 1 1115 SUDLICLY IS GISCUSSEG IN LEXLDOOKS, SEE E.g.**<br>Let us be prostatsly in Finishitz and L.P. Pitagysly. with the four-component spinor *n↵ ,* (*↵* = 1*, ...,* 4) and ubtlety is discussed in textbooks, see e.g.  $\overline{a}$  is based on U(2) symmetry of the U(2) symmet and L.P. Pitaevsky,  $v<sub>1</sub>$  by interaction. It shows a subtlety in the definition of  $p$ C invariance it implies then that *L6B* is also CP odd.  $\mathbf{L}_{\text{adv}}$  into  $\mathbf{L}_{\text{adv}}$  is defined to  $\mathbf{L}_{\text{adv}}$  becomes the matrix of the matrix  $\mathbf{L}_{\text{adv}}$  $\alpha$ ony,  $\Delta$ . IVI. Lititude and  $\Delta$ . I feat vony, abuely is discussed in textbooks, see  $\epsilon$ V.B. Berestetsky, E.M. Lifshitz and L.P. Pitaevsky, one needs an interference of amplitudes and this is pro-This subtlety is discussed in texthooks fermion superior is anseed  $t_{\rm obs}$  the theoretical breaks  $\mu$ stitution (11) changes *L6B* to (*L6B*) . Together with case it is convenient to international convenient to international convenient to international convenient to i spinors, forming a flavor doublet<sup>1</sup>

When *B* is conserved there is there is no transition  $(1995)$  $\blacksquare$  Detween sectors with different  $\beta$ . with a  $I(f)$ , phase rotation and define  $R = \frac{C(1)}{D}$  prido Books. E. J. Konopinski and H. M. Mahmoud, Phys. Rev. 92,  $10<\frac{1}{2}$ between sectors with different  $\beta$ . One can combine with a  $U(1)_B$  phase rotation and define  $P_\alpha$ Let us reminded When is conserved there is charge is no transition of the conserved there is no transition of between sectors with different *B*. One can combine P orem on the opposite parities of fermion and antifermion When  $B$  is conserved there is there is no transition  $\mathcal{L}$  $\alpha$ ind define  $\alpha$ the mass parameter *m* which is real and positive. The with a  $U(1)_B$  phase re structure (5). There is there is no transition In sectors with different  $B$ . One can combine  $P$  $p$  and dofing  $p$  $\frac{1}{\alpha}$  first consider the charge conjugation  $\alpha$ between sectors with di↵erent *B*, and one can combine <sup>P</sup>*↵* =Pe*<sup>i</sup>B↵* : *<sup>n</sup> !* <sup>e</sup>*i↵*<sup>0</sup>*n, n<sup>c</sup> !* e*i↵*<sup>0</sup>*n<sup>c</sup> .* s conserved between sectors with dilleted and one can combine<br>**B**, and one can combine the canonic can compute with a  $U(1)_B$  phase rotation and define  $P_\alpha$ of gamma-matrices, mation proposes that discussion the sum is no text Let us conseil between sectors with dillet entrept. One can combine these two right-handed Weyl spinors are associated with *n<sup>R</sup>* and (*nL*)*⇤*. Particularly, in the chiral (Weyl) basis  $hat{p}$ C invariance it implies then that *L6B* is also CP odd. When  $\beta$  is conserved there is there is a  $\blacksquare$  $transition$  $\mathbf{p}$  = 1,  $\mathbf{p}$  = 1

 ${\rm P}_{\alpha}={\rm P}\,{\rm e}^{i\mathcal{B}\alpha}:\quad n\rightarrow{\rm e}^{i\alpha}\gamma^0n\,,\quad n^c\rightarrow-{\rm e}^{-i\alpha}\gamma^0n^c\,.$ Of coarse, then  $P^2_{\alpha} = e^{2i\beta\alpha} \neq 1$  but the phase is unobservable while  $\beta$  is is conserved.  $\mathbf{1}$  $\mathbf{r}_{\alpha} = \mathbf{r} e \quad : \quad n \to 0$ Of coarse, then  $P^2_\alpha = e^{2i\beta\alpha} \neq 1$  but the phase is  $\overline{\phantom{a}}$  is  $\overline{\phantom{a}}$  book  $\overline{\phantom{a}}$  be in the description of description  $\overline{\phantom{a}}$  $\mathrm{P}_{\alpha}=\mathrm{P}\,\mathrm{e}^{i\mathcal{B}\alpha}:\hspace{2ex} n\rightarrow\mathrm{e}^{i\alpha}\gamma^0n\,,\hspace{2ex} n^c\rightarrow-\mathrm{e}^{-i\alpha}\gamma^0n^c$ Of coarse, then  $P^2_{\alpha} = e^{2i\beta\alpha} \neq 1$  but the phase is  $\alpha$  is a latter that  $\alpha$  is also conserved. However, this conserved, the conserved, the conserved of the conserved of  $\mathbb{R}^n$ four degenerate states, the spin doublet of neutron states utionservable with *B*  $f = \mathbf{h}$ C : *<sup>n</sup> ! <sup>n</sup><sup>c</sup>*  ${\rm P}_\alpha = {\rm P}\,{\rm e}^{i\mathcal{B}\alpha}:\quad n\to{\rm e}^{i\alpha}\gamma^0n\,,\quad n^c\to-{\rm e}^{-i\alpha}\gamma^0n^c$ ase is a served.  $\sum_{\alpha=1}^{\infty}$  could be phase is  $\sum_{\alpha=1}^{\infty}$  *a*<sup>1</sup> *but the phase is* unit the while  $\bm{\mathcal{B}}$  is is cons Of coarse, then  $P^2_{\alpha} = e^{2i\mathcal{B}\alpha} \neq 1$  but the phase i servable while *p* is is  $\mathbf{I}(\mathbf{s})$  shows a subtlety in the definition of parity transformation of parity transformati  ${\rm P}_\alpha = {\rm P\,e}^{\imath\boldsymbol{\varphi}\alpha}:\quad n\to {\rm e}^{\imath\alpha}\gamma^{\mathtt{u}}n\,,\quad n^c\to -{\rm e}^{-\imath\alpha}\gamma^{\mathtt{u}}n^c\,.$  $\alpha$  baryon conserved there is no transition there is no transition to the interval  $\alpha$ unobservable while *B* is is conserved. using *✏↵ , ✏↵*˙ ˙ and *✏ik*. In terms of Dirac spinor *n n<sup>R</sup>* and (*nL*)*⇤*. Particularly, in the chiral (Weyl) basis  $\overline{\phantom{a}}$ 

When  $\beta$  is its not conserved the only remnant of rotations is  $Z_2$  symmetry,  $n \to -n$ . It means that we can consider a different parity definition  $P_z$ , such that  $P_z^2 = -1$ . Thus, choosing  $\alpha = \pi/2$  we come to conjugation C, When  $\beta$  is its not conserved the only remnant of  $U(1)_B$  $I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ consider a different parity definition  $P_z$ , such that  $P_z^2 = -1$ .  $T_{\text{base}}$  paradigation  $P_{\text{base}}$  is the space for the space coordinates) the space coordinates of the space coordinates o substitution rotations is  $Z_2$  symmetry,  $n \to -n$ . It means that we a  $(2)$  $\frac{111}{2}$  is  $\frac{111}{2}$  if  $\frac{1}{2}$  is  $\frac{1}{2}$  is  $\frac{1}{2}$  if  $\frac{1}{2}$  is  $\frac{1}{2}$  $\frac{1}{2}$  see, e.g., the book  $\frac{1}{2}$  where it is graciously applied to description to description to description charge, *B* = 1 for *n* and *B* = 1 for *n*¯. This conserva-When  $\beta$  is its not conserved the only remnant of  $U(1)_{\beta}$ rotations is  $Z_2$  symmetry,  $n \rightarrow -n$ . It means that we can four degenerate states, the spin doublet of neutron states  $\alpha = \pi/2$  we come to  $\alpha = \pi/2$  and  $\alpha = \pi/2$ most different parity definition D of baryonic U(1)*<sup>B</sup>* rotations is *Z*<sup>2</sup> symmetry associated consider a different parity definition<br>P Thus, choosing  $\alpha = \pi/2$  we come to makes its Cinvariance explicit. served the only remnant of  $\rm U(1)_\mathcal{B}$  $\text{parity definition } \mathbf{P}_z \text{, such that } \mathbf{P}_z^2 = -1.$ IV is simple to verify that  $\mathcal{U}$  $\alpha$ *nn*¯ + *n<sup>c</sup>n<sup>c</sup>*⇤ 3 is its not conserved the only remnant ons is *z* symmetry associated the present  $\sum_{i=1}^n a_i$  symmetry,  $n \to -n$ . It means the means that the original parameter of the original parameter that the original parameter that the state of the constant the state of the state of the constant the constant of the constant of the constant of the constant of a dinerent parity definition  $P_z$ , such that  $P_z$  $\sigma$ , choosing  $\alpha = \pi/2$  we come to  $\mathbf{N}$ hon  $\mathbf{R}$  is its not sopponyed the oply remport rotations is z. symmetry consider a different parity definition P. [6] V. B. Berestetsky, E. M. Lifshitz and L. P. Pitaevsky, *Quantum Electrodynamics*, Oxford, UK: Pergamon is its flut current ved the Unity Feminism UP  $\frac{18}{2}$  S/m. e.g.  $\frac{18}{2}$  is the fine direction of  $\frac{18}{2}$  $\frac{1}{2}$  v. A. Kuzmin, In  $\frac{1}{2}$ [20] Ya. B. Zeldovich, Dokl. Akad. Nauk SSSR 86, 505 (1952);

 ${\rm P}_z={\rm P}{\rm e}^{iB\pi/2}:\qquad n\to i\gamma^0n\,,\qquad n^c\to i\gamma^0n^c\,.$  $\mu \rightarrow \nu \gamma$  the baryon charge  $\mu$  $\qquad \qquad n^2 \rightarrow i \gamma^0 n\,, \qquad n^c \rightarrow i \gamma^0 n^c\,.$  $1.16$  search for neutron-antineutron-antineutron-antineutron-antineutron  $2.1$  $n\to\imath\gamma^\circ n\,,\qquad n^\circ\to\imath\gamma^\circ n^\circ\,.$  $\mathbf{r} \cdot \mathbf{r} = \mathbf{r} \cdot \mathbf{r$  $\mathbf{P}_{\mathbf{P}}iB\pi/2$ ,  $\mathbf{n} \rightarrow i\gamma^{0}\mathbf{n}$   $\mathbf{n}^{c} \rightarrow i\gamma^{0}\mathbf{n}^{c}$ 1045 (1953).  $\mathbf{P}_z = \mathbf{P}_z$ 

parity of fermion and antifermion. The term L*m*<sup>0</sup> also breaks P parity, it is evidently

*r* **101** COVCI, in ease of *r* agorana refinions it is the only possible choice. Indeed, in Majorana representation where  $\gamma^0 = \begin{pmatrix} 0 & \sigma_2 \\ \sigma_2 & 0 \end{pmatrix}$ orana fermions it is the only  $P_z = PC$ <br>**M**<sub>2</sub> :  $P_z = PC$  :  $P_z = PC$  :  $P_z = PC$  ,  $P_z = PC$  possible choice. Indeed, in Majorana re  $\rho$  where  $\rho$   $(0, \sigma_2)$ requients to the unit of the unit This substitution changes L*B*<sup>6</sup> to L*B*<sup>6</sup> because 0C<sup>0</sup> <sup>=</sup> C. The breaking of charge nonconservations it is the only and the interest of the emphasize to the model of the set of the set of and communities in the CP invariance. This conclusion is based on the Lorentz on the Lorentz CP in the Lorentz d, in Majorana i To demonstrate our assertion let us start with the Dirac Lagrangian  $\mathbb{R}$  $P$ O with P<sup>2</sup> = 1. Now P*<sup>z</sup>* parities of *n* and *n<sup>c</sup>* states are possible choice. Indeed, in Majorana representation P*<sup>z</sup>* parity. It means that all discrete symmetries, C, P*<sup>z</sup>*  $\gamma^0 = \begin{pmatrix} 0 & \sigma_2 \end{pmatrix}$  $\sigma_2$  and  $\sigma_2$  and  $\sigma_3$  and  $\sigma_4$  and  $\sigma_5$  are set of  $\sigma_1$ Moreover, in case of Majorana fermions it is the only [9] P. Ramond, *Journeys Beyond the Standard Model*, V.B. Berestetsky '51  $\gamma^{\mathbf{0}}=% \begin{bmatrix} \omega_{0}-i\frac{\gamma_{\mathbf{0}}}{2} & g_{\mathbf{0}} & g_{\$  $\begin{pmatrix} 0 & \sigma_2 \end{pmatrix}$  $\sigma_2$  0 ◆ with changing sign of the fermion field, *n ! n*. It possible choice a di<br>A dia mandro P Thus, choosing *↵* = *⇡/*2 in Eq. (12), we come to a

This substitution changes L*B*<sup>6</sup> to L*B*<sup>6</sup> because 0C<sup>0</sup> <sup>=</sup> C. The breaking of  $p_1$  parameter in neutron-and the Maiorana spinor and  $i\gamma^0$  preserves reality of the Maiorana spinor particles of the term and anticipal and anti-fermion. The term L<sub>m</sub>0 also breaks P particles P particles P particles  $\sigma$  is  $\sigma^0$  processes follows from  $\sigma$ United the presentes reality. Or the riagon with four-component spinor n and the mass parameter m which is real and positive. The mass parameter  $\mu$ only  $i\gamma^0$  preserves reality of the Majorana spinor. *<sup>p</sup>*<sup>2</sup> *,* (9) of parity transformation defines a specific T transforma-

This was derived by Giulio Racah in 1937. *n* and *i* is *i* is still consistent with the nonto the continuous symmetry (2) n **acan in 1797.** N : eilen eilen eilen eilen er der antalt er eilen tion. Second, it is amusing that the same P*<sup>z</sup>* parity for This was derived by Giulio Racah in 1937. opposite parities of fermion and antifermion, having in P*<sup>z</sup>* parity. It means that all discrete symmetries, C, P*<sup>z</sup>*

 $\sqrt{2}$  of  $\sqrt{2}$ 

Now P<sub>z</sub> parities of  $n$  and  $\bar{n}$  are the same  $i$ , so their mixing does not break the  $P_z$  parity. It means that all discrete symmetries, C,  $P_z$  and T are preserved by  $\Delta \mathcal{L}_{\mathcal{B}}$ . discrete symmetries,  $C, P_z$  and I are preserved by  $\Delta t$ mix discrete symmetries, C, P<sub>z</sub> and <sup>1</sup>  $\overline{a}$ Now P<sub>z</sub> parities of n and  $\bar{n}$  are the same  $i$ , so their  $\frac{1}{2}$  discrete symmetries C P and T are preserved by  $\Lambda$   $\mathcal{L}_n$ aberete symmetries,  $\sigma$ ,  $\frac{1}{z}$  and  $\frac{1}{z}$  are preserved by  $\frac{1}{z}$ , mixing does not break the P<sub>z</sub> parity. It means that all discrete symmetries, C,  $P_z$  and T are preserved by  $\Delta \mathcal{L}_{\mathcal{B}}$ .  $\tau$  the  $\mathbf{D}$  parity, it means that all  $\alpha$  che  $\alpha$   $\beta$  partly. It includes that an makes its C invariance explicit. rities of  $\bm{n}$  and  $\bm{n}$  are the same  $\bm{i}$ , so their oes not br  $T_{\rm eff}$   $T_{\rm eff}$  are diagonalized in terms of  $T_{\rm eff}$ *n ± n<sup>c</sup>*  $\mathsf{z}$ he same $\cdot i$ , so their and T are presented by the baryon breaking term **T** and the baryon breaking term in the baryon of the baryon of the baryon of the baryon o  $\mathbf{c}_j$ . To ricture critical comments. Figures is  $\mathbf{c}_j$ P<sup>2</sup> = 1, so the eigenvalues of P are *±*1 and opposite for e same  $\bm{\imath}$  , so their  $H$  means that all  $t_f$ : it in dans chat an *nixing* does not break the  $P_z$  parity. It means that all  $discrete$  symmetries the same and equal to *i*, so their mixing does not break  $\overline{\text{erete}}$ *n ± n<sup>c</sup>* rete symmetries,  $\mathbf{C}, \mathbf{P}_z$  and T are product that  $\mathbf{P}_z$ P*<sup>z</sup>* parity. It means that all discrete symmetries, C, P*<sup>z</sup>* and T are preserved by the baryon breaking the baryon breaking the baryon breaking the baryon breaking the bar<br>**L**  $d$  by  $\Lambda$   $c$  $T U U y \Delta E p.$  $T_{\rm eff}$  The Lagrangians are diagonalized in terms of  $T_{\rm eff}$ rana fields *n*<sup>1</sup>*,*<sup>2</sup> , *n ± n<sup>c</sup>*  $p_{\text{S}}$  **d**<sub>2</sub> and **1** are provided. P*<sup>z</sup>* parity. It means that all discrete symmetries, C, P*<sup>z</sup>*  $d$  by  $\Lambda$   $C_{\mathcal{F}}$  $\frac{1}{\sqrt{2}}$  in  $\frac{1}{\sqrt{2}}$  in  $\frac{1}{\sqrt{2}}$ discrete symmetries, C,  $P_z$  and T are preserved by *l*  $N_{\text{QW}}P$  parities of n and  $\bar{n}$  are new parity P*z*,  $\sum_{i=1}^{n} P_i$  *n B*<sup>*z*</sup> *p*<sup>2</sup> *z* Now P<sub>z</sub> parities of  $n$  and  $\bar{n}$  are the same  $i$ , so their new parity P*z*,  $\frac{P}{P}$  =  $\frac{P}{P}$   $\frac{P}{P}$  =  $\frac{P}{P}$   $\frac{P}{P}$  =  $\frac{P}{P}$   $\frac{P}{P}$  =  $\frac{P}{P}$  $\mathbb{R}^2$ mixing does not break the P<sub>z</sub> parity. It means that a  $\mathbb{R}^n$  is the status of discrete  $\mathbb{R}^n$  and  $\mathbb{R}^n$  and  $\mathbb{R}^n$  and  $\mathbb{R}^n$  is single symmetries in this simple  $\mathbb{R}^n$ by implement,  $\mathcal{C}_1$ ,  $\mathcal{L}_2$  and  $\mathcal{L}$  are presented by  $\Delta \mathcal{L}_{\beta}$ . P : *<sup>n</sup> !* <sup>0</sup>*n, n<sup>c</sup> !* <sup>0</sup>*n<sup>c</sup>*  $C_1$  red by  $\Delta E_{\beta}$ . with P<sup>2</sup> *z* = 1. Now P*<sup>z</sup>* parities of *n* and *n<sup>c</sup>* states are discrete symmetries,  $C, F_z$  and  $I$  do 2  $\bullet$  same  $\cdot i$  , so their  $diagonal$  are disguised in the Lagrangian in terms of  $\mathbb{R}$  and  $\mathbb{R}$  are discussed in the  $i$ anscream mixing does not break the  $P_z$  parity. It means that all the same and equal to *i*, so their mixing does not break  $P$  preserved by  $\Delta \mathcal{L}_\mathcal{B}.$ and T are preserved by the baryon breaking term *L6B* . INOW  $\mathbf{F}_z$  particles on the and the are the same  $v$ , so discrete symmetries C **P** and T are preserve and **n**  $\alpha$  is  $\alpha$  is  $\alpha$  is  $\alpha$ . more comment is to notice that P*<sup>z</sup>* commute with C, i.e. CP*z*=P*z*C, in contrast with P which anticommute with  $\mathbf{r}$  $y \Delta L_{\beta}$ . (8)  $T_{\rm eff}$  are diagonalized in terms of  $\alpha$   $\mu$  and  $\sigma$ **r**anscret <sup>P</sup>*<sup>z</sup>* =Pe*iB⇡/*<sup>2</sup> : *<sup>n</sup> ! i*<sup>0</sup>*n, n<sup>c</sup> ! i*<sup>0</sup>*n<sup>c</sup>* (13) <sup>z</sup>, so ar = 1. Now P*<sup>z</sup>* parities of *n* and *n<sup>c</sup>* states are the same and equal to  $\overline{a}$  $perved by  $\Delta \mathcal{L}_B$ .$ and T are preserved by the baryon breaking term *L6B* .

A few comments. First, preservation of T follows from CPT theorem provided by Lorentz invariance and locality. Second, it is amusing that the same parity for  $n$  and  $n<sup>c</sup>$ equal to  $i$  is consistent with the notion of the opposite parities for fermion and antifermion: one should compare  $P_z(n)$  with  $[P_z(n^c)]^*$ . Third,  $P_z$  commutes with C, i.e.,  $CP_z = P_z C$ , in contrast with P which anticommutes,  $CP = -PC$ . paula to *i* is consistent with the notion of the opposite of Lagrangian (1). At each spatial momentum there are four degenerate states, two spin Second, it is amusing that the same parity for *n* and *n*<sup>c</sup> coquation for constitution and ontiformation, and a bould approach parities for fermion and antifermion: one should compare<br>**D** (n) with D  $\int e^{c}$  is not integral seeming the baryon is not integral seeming the baryon is not integral seeming the baryon is not integral to the baryon is not  $\mathbf{P}_z(n)$  with  $\mathbf{P}_z(n^c)$ . be always achieved by the phase rotation (2) of n field. A Tew comments. First, preservation of 1 tollows from<br>CPT theorem provided by Lorentz inverience and locality CPT theorem provided by Lorentz invariance and locality.<br>Second it is amusing that the same parity for m and m<sup>c</sup> equal to  $i$  is consistent with parities for fermion and antifermion: one should compare  $P_z(n)$  with  $[P_z(n^c)]^*$ . Third,  $P_z$  commute  $\text{CP}_z = \text{P}_z \text{C}$ , in contrast with P which anticommutes,  $\text{CP} = -\text{PC}$ . A few comments. First, preservation of T follows from CPT theorem provided by Lorentz invariance and locality. Second it is amusing that the same parity for n and  $n^c$ one possibility for the baryon charge breaking because the possible breaking by the proposition of the approxite ✏ e should compare (7) <sup>P</sup>*↵* = Pe*iB↵* : <sup>n</sup> ! <sup>e</sup>*i↵*0n, n*<sup>c</sup>* ! e*i↵*0n . ately into observable CP breaking e↵ects. To get them is amusing that the same parity for  $n$  and  $n<sup>c</sup>$ is consistent with the notion of the opposite parities for fermion and antifermion: one should compare  $\alpha$  comments. First, preservation of  $\alpha$  follows from  $\alpha$ It the same parity for n and  $n^c$ matic discussion Partly for *to* and *to*  $\cdot i$  is consistent with the notion of the opposite  $\mathbf{B}$  commutes with  $\mathbf{C}$  is  $\mathbf{U}, \mathbf{F}_z$  commutes with  $\mathbf{U}, \mathbf{E}, \mathbf{F}_z$ **P**  $\frac{1}{2}$  **b**  $\frac{1}{2}$  *n*  $\frac{1}{2}$  *n* $\frac{1}{2}$  **<b>***n*  $\frac{1}{2}$  *n*  $\frac{1}{2}$  it is amusing that the same parity for  $\bm{n}$  and  $\bm{n^c}$  $p_{\alpha}(n^c)^*$  Third P commutes with  $C$  is evidently  $P_{\alpha}$  and  $P_{\alpha}$  particles  $P_{\alpha}$ which are even and odd under the charge conjugation  $\mathcal{L}_{\mathcal{A}}$ C*n*<sup>1</sup>*,*<sup>2</sup> = *± n*1*,*2. Namely, *n***<br>Second. it is amusing t h** the notion of the opposite  $P_z(n)$  with  $[P_z(n^c)]^*$ . Third,  $P_z$  commutes with C, i.e.,  $SP<sub>z</sub>=P<sub>z</sub>C$  in contrast with P which anticommutes, a field gets the mass *M*<sup>1</sup> = *m* + *✏* while the mass of the of parity transformation defines a specific T transforma- $\overline{\phantom{a}}$  of fermion and antifermion and antifermion and antifermion, having in ie parity for  $\boldsymbol{n}$  and  $\boldsymbol{n^c}$ on. One should compare Thus, we demonstrated that neutron-antineutron mix-<sup>P</sup>*↵* =Pe*<sup>i</sup>B↵* : *<sup>n</sup> !* <sup>e</sup>*i↵*<sup>0</sup>*n, n<sup>c</sup> !* e*i↵*<sup>0</sup>*n<sup>c</sup> . Trandition* and ideality Lion of the op parities for fermion and antifermion: one should compare between sectors with die and one can combine can combine can combine can combine can combine can combine combine  $\text{P}$  with  $\text{P}$ ,  $\text{P}$ ,  $\text{P}$ and T are present by the baryon breaking the baryon breaking the baryon breaking term **L** A few comments. First, preservation of T follows from CPT theorem provided by Lorentz invariance and locality. Lorentz invariance and locality. A specific P*<sup>z</sup>* definition Second, it is amusing that the same parity for  $n$  and  $n^c$ pause to *i* is consiste **n** and *i* is consistent with the normal consistent with  $\boldsymbol{v}$  is consistent with  $\boldsymbol{v}$ mind that the complex value of participate of participate of participate of participate of participate of parity we should be a shock of participate of participate of participate of participate of participate of participat  $P_z(n)$  with  $[P_z(n^c)]^*$ . Third,  $P_z$  commutes with C, i.e.,  $CP_z = P_z C$ , in contrast  $\mathbf{C_1} \mathbf{z}$  **i**  $\mathbf{z} \in \mathbb{R}$ , i.e. **commute with**  $\mathbf{z} \in \mathbb{R}$ equal to *i* is consistent with the  $CP_z = P_z C$ , in contrast Lorentz invariance and locality. A specific P*<sup>z</sup>* definition equal to  $i$  is consistent with the notion of the opposite parities for fermion and antifermion: one should compare compare P*z*(*n*) with [P*z*(*n<sup>c</sup>*)]*⇤*. Also for a fermionantifermion pair the product P*z*(*n*)P*z*(*n<sup>c</sup>*) = 1. One **cs**, CP=–PC. *,*  $\frac{P_z}{P}$  $\mathbf{C}$  $\mathbf{P} = \mathbf{P} \cap \mathbf{P}$  in contrast w Lorentz invariance and locality. A specific P*<sup>z</sup>* definition equal to *i* is consistent with the notion of the opposite mind that the compare of the compare of the compare of the compare of the contract of the cont compare P*z*(*n*) with [P*z*(*n<sup>c</sup>*)]*⇤*. Also for a fermionantifermion pair the product P*z*(*n*)P*z*(*n<sup>c</sup>*) = 1. One  $\text{CP}_z = \text{P}_z \text{C}$ , in contrast with P which anticommutes,  $\text{CP} = -\text{PC}$ . A few comments. First, preservation of T follows f CPT theorem provided by Lorent: parties for fermion and anthermion, one should comp Couple of related comments. First, preservation of second, it is amusing that the sam **r** equal to *i* is consistent with the n parities for fermion and antifermi mind that the complex value of participants were only we should antifermion pair the pair term pair the product P*z*(*n*)  $\text{CP}_z = \text{P}_z \text{C}$ , in contrast with P which and *A* few comments. First, preser Couple of related comments. First, preservation of  $CPT$  theorem provided by Lorentz Lorentz invariance and locality. A specific P*<sup>z</sup>* definition second, it is amusing that the sam aqual to *j* is consistant with the n equal to  $\boldsymbol{\imath}$  is consistent with the notion of the opposite parities for fermion and antifermi mind that the complex value of parity we should be complex value of parity we should be antifermion pair the product P*z*(*n*)P*z*(*n<sup>c</sup>*) = 1. One  $\text{CP}_z = \text{P}_z \text{C}$ , in contrast with P which w comments. First, preservation of ± follows from<br>Preservation of ± follows from In fact, the expression is the same parity for  $n$  and  $n^c$ It is amusing that the same parity for  $\bm{n}$  and  $\bm{n}^\text{c}$ for fermion A few comments. First, preservation of T follows from  $\frac{1}{\sqrt{2}}$  theorem provided by Lorentz invariance and locality  $P^2$  and locality. equal to  $i$  is consistent with the notion of the opposite  $t$  that the mixing breaks  $\frac{1}{t}$ stitution (11) changes *L6B* to (*L6B*) . Together with C , i.e.,  $\overline{CD}$  -  $\overline{D}$  component translate in the P which anticommutes  $\overline{CD}$  and  $\frac{1}{2}$  into  $\frac{1}{2}$  breaking equations the mass of  $\frac{1}{2}$ and T are preserved by the baryon breaking term *L6B* . CPT theorem provided by Lorentz invariance and locality. of parity transformation defines a specific T transformasecond, it is amusing that the same **P**  $\alpha$  and  $\alpha$  is consistent with the fioth parities for fermion and antifermion parities for fermion and antifermion-<br>  $\overline{P}$  $\text{CP}_z=\text{P}_z\text{C}$ , in contrast with P which anti *n*<sup>1</sup> = *<sup>p</sup>*<sup>2</sup> *,* (9) T invariance follows from CPT theorem provided by  $\int_{0}^{1}$ *<u>C</u>* 1 L(  $\hat{i}$  is consistent with the notion of the opposite *n*¯<sup>1</sup> *n*<sup>1</sup> *n*¯<sup>2</sup> *n*<sup>2</sup> (10) compare P*z*(*n*) with [P*z*(*n<sup>c</sup>*)]*⇤*. Also for a fermion- $\overline{D}$  demonstrates that the baryon charge breaking leads to be a state breaking leads to be a state of the bre  $\text{CP}_z = \text{P}_z \text{C}$ , In Contrast with  $\Gamma$  which due Lorentz invariance and locality. A specific P*<sup>z</sup>* definition tion. Second, it is amusing that the same P*<sup>z</sup>* parity for *n* and  $n^c$  is amusing that the same parity for  $n$  and  $n^c$ equal to *i* is consistent with the notion of the opposite antifermion pair the product P*z*(*n*)P*z*(*n<sup>c</sup>*) = 1. One  $\mathsf{with}~\mathbf C$  , i.e., with  $\mathbf C$ i.e. CP*z*=P*z*C, in contrast with P which anticommute  $\text{CP}_z = \text{P}_z \text{C}$ , in contrast with P which anticommutes,  $\text{CP} = -\text{PC}$ . A few comments. First, preservation of T foll  $\overline{CD'}$ parities for fermion and antifermion: one should  $\overline{D}$  or  $\overline{D}$  on the opposite parameter  $\overline{D}$  for  $\overline{D}$  and an anomalism  $\overline{D}$   $\overline{D}$  $\mathbf{r}_z(n)$  with  $\mathbf{r}_z(n)$ , Filling,  $\mathbf{r}_z$  commutes with  $\mathbf{v}_z$ , i  $\frac{1}{2}$  from  $\frac{1}{10}$ . It is this definition which should be CP I theorem provided by Lorentz invariance and locality.  $n^{\bm c}$  in connection with  $\bm r$  $s$ ito  $\overline{\text{SIC}}$ npare and an  $\overline{R}$  $-$ - $\mathbf{i}$   $\mathbf{c}$ . *n ± n<sup>c</sup>* Pearts. First, preservation of T follows from Second, it is amusing that the same parity for  $n$  and  $n<sup>c</sup>$ **L**<br>D<sub>a</sub>  $\overline{\mathbf{t}}$  $\sim$ *n* fermion and antiferr  $P_z(n)$  W<br>*C***D** –**D***C*  $\epsilon$  $\frac{1}{2}$   ${\bf c}$  compared by the  ${\bf c}$  , i.e., Lorentz invariance and locality. A specific P*<sup>z</sup>* definition  $\sim$  and locally. *<u>in annosite</u>*  $\sum_{i=1}^{n}$ nould compare value nutes,  $\text{CP} = -\text{PC}$ .

Similar effects for neutrino was noted by Wolfenstein '81. One could add also <sup>|</sup>B<sup>|</sup> = 2 term of the form <sup>n</sup>*<sup>T</sup>* C5n. However, it can be rotated C-odd *n*<sup>2</sup> is *M*<sup>2</sup> = *m ✏*. Seed by Womenstein St. **<sup>2</sup>** ed by Wolfenstein '81. similial chects for fieud life was hoted by violienstein of. It demonstrates that the baryon charge breaking leads to the breakin Similar effects for neutrino was noted by Wolfenstein '81. It demonstrates that the baryon charge breaking leads to  $C_{\rm eff}$  . Corresponding  $\mathbb{C}$  , i.e.  $\mathbb{C}$  . ing by *B* = *±*2 Majorana term in the mass matrix (7) <sup>P</sup>*↵* = Pe*iB↵* : <sup>n</sup> ! <sup>e</sup>*i↵*0n, n*<sup>c</sup>* ! e*i↵*0n . Similar effects for neutrino was noted by Wolfenstein '81. leads to a specific definition of the conserved parity P*z*, C-odd *n*<sup>2</sup> is *M*<sup>2</sup> = *m ✏*. Similar effects for neutrino was noted by Wolfenstein '81. making it completely satisfy the parties of the satisfying P2. Di↵erent parities of neutron and antineutron imply Similiar effects for neutrino was noted by Wolfenst Similar effects for neutrino was noted **h figure gets the mass**  $\frac{1}{2}$  **which is the mass of t**  $\alpha$  ifenstein  $^{\prime}$ 81 **Thus, we demonstrated that neutron mix-**

matrices, and ✏ is a real positive parameter. The reality of ✏ as a coecient for n*<sup>T</sup>* Cn can

states? In Lagrangian description it could be only modification of the bilinear mass term.

Thus, we demonstrated that neutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-anti

It demonstrates that the baryon charge breaking leads to

.

How the baryon number non-conservation shows up at the level of free one-particle

CP*z*=P*z*C, in contrast with P which anticommute with

Six-quarks operators: discrete symmetries New physics beyond the Standard Model, leading to  $|\Delta B| = 2$ transitions, induces the effective six-quark interaction, 3. Our consideration above refers to the neutron-antineutron oscillation in vacuum. Now In the Medicine street we should be a find the substitute strengths in the symmetric symmetr orbital momentum *L* = 1 and total spin *S* = 1 in the conservation and Fermi statistics. The gauge-invariant **B and lepton in the relationship and lepton in the relationship and lepton in the relationship and lepton in the** ics beyond the Standard Model, leading to two units can originate only from  $\alpha$  originate only from  $\alpha$ which would induce the effective six-quark interactions, induces the effective six-quark interactions and *t* 6. In the Standard Model (SM) conservations of baryon *A* **and lepton is a lepton of the control of a Lie and Lie and September** stephysics hevand the Standard Madel leading to w physics beyond the standard model, leading to Now physics howard the Ctandard Madel leading to refers to the gauge potential. In space representation we ske operatore: discrete symmetion to updiature. The discrete symmetric *M*<sup>5</sup> ve six-c  $\overline{\mathbf{C}}$ where *u*1*,*<sup>2</sup> are Dirac spinors describing neutrons and *✏<sup>µ</sup>* refers to the gauge potential. In space representation we deal with *@⌫Fµ⌫* the quantity which vanishes outside of  $\boldsymbol{\mathsf{New}}$  p froncitions induces the effective six quark intersections **T** no place for magnetic moment of *n n*¯ transition, and **L** *<u>Report</u>ion M*<sup>5</sup>  $\cdot$ *disc A*<sub>2</sub> *A***<sub>2</sub> <b>***Q<sub>4</sub> A*<sub>2</sub> *A***<sub>2</sub> <b>***A*<sub>4</sub> *A*<sub>4</sub> *A*<sub>4</sub> *A*<sub>4</sub> *A*<sub>4</sub> *A*<sub>4</sub> *A* = *T <sup>i</sup>*  $\mathbf m$ s, induces the effective six-quark interact

$$
\mathcal{L}\left(\Delta \mathcal{B} = -2\right) = \frac{1}{M^5}\sum c_i \mathcal{O}^i\,,\\ \mathcal{O}^i = T^i_{A_1A_2A_3A_4A_5A_6}q^{A_1}q^{A_2}q^{A_3}q^{A_4}q^{A_5}q^{A_6}\,,
$$

where coefficients  $T^i$  account for color, flavor and spinor structures. where coefficients  $T^i$  account for color flavor and s Antisymmetry in flavor indices implies that spinors with the opposite baryon charge enter. So both operators preserve the baryon charge, they describe interactions with the magnetic no place for magnetic moment of *n n*¯ transition, and ere coefficients  $\, T^i \,$  account for color, flavor and  $\,$ violation. and spinor structures and the large mass scale *M* coming from new physics leads to the smallness of baryon in the smallness of baryon in the smallness of baryon in<br>The smallness of baryon in the smallness of baryon in the smallness of baryon in the smallness of baryon in th where coefficients  $T^i$  account for color, flavor and by actual set In particular, the *nn*¯ mixing term (5) emerges as a  $\frac{1}{2}$  independent for diagonal for  $\frac{1}{2}$ 

**and in particular, for n-nbar mixing term (6) emerges as a set of the mixing term (6) emerges as a set of the mixing of the set of the set of the neutron.**  $T$   $T$   $T$   $T$ Even in the absence of new *nn*¯ magnetic moment the authors of [12] claim that suppression of *nn*¯ oscillations  $m_{\text{max}}$  and  $m_{\text{max}}$  states of the operator  $1$ the magnetic field transversal to quantization axis. In their first example where the transversal field is time  $\frac{1}{2}$ direction of magnetic field. This clearly breaks rotational invariance. The source of this breaking is the wrong sign cicular, for n-nbar mixing **complex redefinition** 

$$
\bra{\bar{n}}\mathcal{L}\left(\Delta\mathcal{B}=-2\right)\ket{n}=-\frac{1}{2}\,\epsilon\,v_{\bar{n}}^TC\,u_n
$$

it lead to an estimate . The transversal field is time where the transversal field is time when the transversal fi  $\ddot{\mathbf{r}}$  $it$  load to direction components in the magnetic structure  $\mathbf{C}$ where *un*, *vn*¯ are Dirac spinors for *n*, *n*¯. Generically, it Eq. (20). The existing sign implies that *B* = 2 ampliit lead to an estimate

o an estimate 
$$
\epsilon = \frac{1}{\tau_{n\bar{n}}} \sim \frac{\Lambda_{\rm QCD}^6}{M^5}.
$$

## For  $u$  and  $d$  quarks of the first generation the full list of operators was determined <sup>S. Rao and R. Shrock,</sup> [16, 17],  $\overline{0}$  or  $\overline{a}$  and  $\overline{a}$  y  $\sum_{i=1}^{n}$  $f_{\text{inot}}$  conomision the full liet of  $\alpha$  generation the full fist of **16. S. Rao and R. Shrock, Phys. 238 (1982).**  $\begin{bmatrix} 1 & \mathbf{W} & \mathbf{E} & \mathbf{C}_{2\text{swell}} & \mathbf{I} & \mathbf{M} \end{bmatrix}$  Milutinovic and  $\mathbf{G}$ . Senjanovic, Phys. *metries,* arXiv:1510.00868 [hep-ph]; For  $\boldsymbol{u}$  and  $\boldsymbol{d}$  quarks of 076002 (2016) [arXiv:1512.05359 [hep-ph]]; operators was determined S. Rao and R. Shrock,  $\mathcal{L}^{\text{max}}$  (2009) [arxiv:0804.2088 [hep-ph]. [arxiv:0804.2088].  $\epsilon$  first generation the full list of  $\epsilon$  $\overline{P}$  December  $\overline{P}$  Chronized:  $\text{ed}$   $\beta$ . Rao and R. Shrock,  $\beta$ W. E. Caswell, J. Milutinovic and G. Senjanovic For *u* and *d* quarks of the first generation the full Only the first seven operators, which are both P*<sup>z</sup>* and C n the full lis , *novic*  $\overline{\phantom{a}}$ S. Rao and R. Shrock,  $\mathbf{S}$  $\mathbf{u}$  is the particular instability when  $\mathbf{v}$ vas determined<br>*W. E. Caswell, J. Milutinovic and G. Senjanovic d d d duarks of the first generation the full I* and *C complemes were determined* as S Raq and *R* Shrock S Rao and R 9  $\mathbf f$ in case of suppressed *nn*¯ oscillations.  $7.7$  The type of the type of the type of  $\sim$ janovic.<br>. For *u* and *d* quarks of the first generation the full list of **guarks of the first generation the full list** *W.* E. Caswell, J. Milutin ovic and G. S  $t\in [0,1]$ in case of support of support  $\mathbf{p}$  and  $\mathbf{p}$  or  $|v \rangle$  (17), 17 Only the first seven operators, which are both P*<sup>z</sup>* and C  $\mathfrak{g}$  . Other operators contributed c be in januaries

Lett. 122B, 373 (1983).

 $\mathbf{r}$ 

 $\frac{1}{2}$ 

 $\mathbf{r}$ 

 $\mathsf{pr}$  in the  $\mathsf{pr}$ 

 $\mathbf{u}_1$ 

 $\mathbf{p}$ 

$$
\mathcal{O}_{\chi_1 \chi_2 \chi_3}^1 = u_{\chi_1}^{iT} C u_{\chi_1}^j d_{\chi_2}^{kT} C d_{\chi_2}^l d_{\chi_3}^{mT} C d_{\chi_3}^n [\epsilon_{ikm} \epsilon_{jln} + \epsilon_{ikn} \epsilon_{jlm} + \epsilon_{jkn} \epsilon_{ilm}],
$$
\n
$$
\mathcal{O}_{\chi_1 \chi_2 \chi_3}^2 = u_{\chi_1}^{iT} C d_{\chi_1}^j u_{\chi_2}^{kT} C d_{\chi_2}^l d_{\chi_3}^{mT} C d_{\chi_3}^n [\epsilon_{ikm} \epsilon_{jln} + \epsilon_{ikn} \epsilon_{jlm} + \epsilon_{jkn} \epsilon_{ilm}],
$$
\n
$$
\mathcal{O}_{\chi_1 \chi_2 \chi_3}^3 = u_{\chi_1}^{iT} C d_{\chi_1}^j u_{\chi_2}^{kT} C d_{\chi_2}^l d_{\chi_3}^{mT} C d_{\chi_3}^n [\epsilon_{ijm} \epsilon_{kln} + \epsilon_{ijn} \epsilon_{klm}].
$$
\nHere  $\chi_i$  stand for  $L$  or  $R$  quark chirality. According for relations

relations *O*3 = *uiT O*3 for relations for relations for relations

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

we deal with 14 operators for  $\Delta B = -2$  transitions.  $\frac{1}{2}$  and  $\frac{1}{2}$  is the *i*<sup>2</sup> of *R*  $\frac{1}{2}$  or *R*  $\frac{1}{2$  $O$ Perators for  $AB - D$ **O**<sub>2</sub>  $\frac{1}{2}$  ,  $\alpha$  ocal with 14 operators for  $\Delta D = -2$  transitions. *O*2 <sup>0</sup> *<sup>O</sup>*<sup>1</sup> <sup>0</sup> = 3*O*<sup>3</sup> <sup>0</sup> *,* Id operators for  $AB = 2$  transitions. ith 14 operators for  $\Delta \mathcal{B} = -2$  transitions.

we deal with 14 operators for 14 operators for B  $\sim$ 

we deal with 14 operators for 2 transitions. The 2 transitions of 2 transitions of 2 transitions. The 2 transitions of 2 transitions of 2 transitions of 2 transitions of 2 transitions. The 2 transitions of 2 transitions of

Only combinations of operators which are  $P_z$  even contributes to n-nbar mixing. The P<sub>z</sub> reflection interchanges L and chiralities interchanges  $L$  and  $\frac{1}{x_1x_2x_3}$ . are thus, only 7 combinations where the discrete symmetries are the discrete symmetries of  $\mathbb{R}^n$ we deal with 14 operators for *B*  $\sim$  2 transitions. combinations of operators which are P<sub>z</sub> even ment  $\alpha$  and  $\alpha$  of  $\alpha$  is, of course, up to small contract on to small corrections due to small corrections due to small corrections of  $\alpha$ rality *<sup>i</sup>* in the operators *O<sup>i</sup>* 12<sup>3</sup> . Note, that the P*<sup>z</sup>* With Computations of operators with 14 or **B**  $\frac{1}{2}$  transitions. contributes to n-nbar mixing. The P<sub>z</sub> reflection  $int$ or $\frac{1}{2}$  ment changes *D* and  $\frac{1}{2}$  $\theta$  $h$ <sub>z</sub> cycn oscillation due to operator *usbusb* suggested in Ref. [19].  $8.8 \times 10^{-2}$  construction we use  $\frac{1}{2}$ transition could be applied to mixing of massive neutri-*✏ijn✏klm*⇤ *. ✏ijn✏klm*⇤ *. ✏ijn✏klm*⇤ *.* (odd in terms of P) contribute to the *nn*¯ matrix eleinterchanges L and **accounting** to the neu-Thus, only 7 comb nuclear installation of  $\overline{\mathsf{A}}$  $z$  divide, with an order of magnitude, we respect to *n n*¯ mixing which makes hopeless the possibility to detect  $O^i$  $\alpha$  beams  $\alpha$ <sub> $\chi_1 \chi_2 \chi_3$ .</sub> nuclear decays into kaons in the large volume detectors.) The nuclear instability limits on a mixing are about  $n = \frac{1}{\sqrt{2}}$  $\mathbf n$  with an order of  $\mathbf n$  $\mathbf{p} \in \Omega^i$  $\mathcal{L}_{\chi_1\chi_2\chi_3}$ . ators  $O_{\chi_1\chi_2\chi_3}^i$  . which are  $P_z$  even are broken. The P*<sup>z</sup>* reflection interchanges *L* and *R* chireflection for *u* and *d* quarks is defined similar to the neutron by Eq. (13). This is consistent with the *udd* wave ment (30). It is, of course, up to small corrections due to small corre ombinations of operators which are  $\mathbf{P}_{\boldsymbol{z}}$ *i* die operators in the operator  $\frac{1}{2}$  in the Pz is contributed by  $\frac{1}{2}$ tron by Eq. (13). This is consistent with the *udd* wave  $\mathbf{R}$  $\mathbf{t}$ transition could be applied to mixing of massive neutri-*⌫<sup>e</sup>* and *⌫<sup>µ</sup>* and their conjugated partners, right-handed *F* = *L<sup>e</sup> L<sup>µ</sup>* (analog of *B*), to be (+1) for *⌫<sup>e</sup>* and (-1) Only combinations of operators which are P<sub>z</sub> even **contributes to n-nbar mixing. The** contributes to n-nbar mixing. The  $P_z$  reflection belied to the other interest to search for the interest to search for the search for th  $x_1x_2x_3$ 15 orders of magnitude stronger than the sensitivity Um, completed of operators will conare broken. The P*<sup>z</sup>* reflection interchanges *L* and *R* chiinterchanges *L* and tron by Eq. (13). This is consistent with the *udd* with the *udd* with the *udd* with the *udd* with the *u*ddle with t 8. The construction we used for neutron-antineutron transition could be applied to mixing of massive neutrinotare  $Q_i^i$  $a$ cors  $\sigma_{\chi_1 \chi_2 \chi_3}$ . *⌫*¯*<sup>e</sup>* and *⌫*¯*µ*. One can ascribe them [20] a flavor charge *F* = *L<sup>e</sup> L<sup>µ</sup>* (analog of *B*), to be (+1) for *⌫<sup>e</sup>* and (-1)

reflection for *u* and *d* quarks is defined similar to the neu-

are broken. The P*<sup>z</sup>* reflection interchanges *L* and *R* chi-

<sup>0</sup> *,*

function of neutron. Thus, only 7 combinations

*RL , <sup>O</sup>*<sup>2</sup>*,*<sup>3</sup>

*RL , <sup>O</sup>*<sup>2</sup>*,*<sup>3</sup>

of 14 operators contribute to n-nbar mixing. This is consistent with the *u*ddle with the *u*ddle with the *udd* with the *u*ddle with the *uddle* with th What about re $(d \rightarrow d)$  s mixing their effect  $\frac{a}{a}$  of  $\frac{a}{a}$  of  $\frac{a}{a}$  iclei. This source of instability and combination and compiled about the remaining  $PZ$  of the remaining  $PZ$  of the remaining  $PZ$ pions. Ĩ, *O<sup>i</sup> <sup>L</sup> \$ <sup>R</sup>* rality *<sup>i</sup>* in the operators *O<sup>i</sup>* of 14 operators comparations of What about re $(d \searrow d)$  $\sum_{d} h$  mixing their effect source of instabilit  $\sum_{\pi} P_{\text{A}}$ **L B**  $\overline{a}$  *R*  $\overline{b}$  *R*  $\overline{b}$  *R*  $\overline{b}$  *<i>R*  $\overline{b}$  *R*  $\overline{b}$  *R*  $\overline{b}$  *<i>R*  $\overline{b}$  *R*  $\overline{b}$  *R*  $\overline{b}$  *<i>R*  $\overline{b}$  *R*  $\overline{b}$  *R*  $\overline{b}$  *R*  $\overline{b}$  *<i>R*  $\overline{b}$ ment (30). It is, one concerned to small corrections due to small corrections due to small corrections due to s  $\sum_{\pi} P(\alpha)$ rality *<sup>i</sup>* in the operators *O<sup>i</sup>* <sup>0</sup> = 3*O*<sup>3</sup> mixing their effect **contributions** where  $\mathbf{r}$  and  $\mathbf{r}$ electroweak interactions where the discrete symmetries **V** *M* hat about re  $\int d^2$  $(n^{i} - L \leftrightarrow R)$  *n*  $\left\{ u \rightarrow \infty \right\}$  $\frac{1}{\sqrt{2}}$ rality *<sup>i</sup>* in the operators *O<sup>i</sup>* 113 . Note, that the P*z*<br>113 . Note, the P*zz*<br>113 . Note, the P*zz* **Pions.**  $\pi^{\dagger}$   $d$ *O<sup>i</sup>* 12<sup>3</sup> + *L \$ R* (34)  $\left(O_{\chi_1\chi_2\chi_3}^i-L\leftrightarrow R\right)$ FIG. 1. Diagram for generating *n n*¯ mixing terms

of 14 operators contribute to *nn*¯ mixing.



12<sup>3</sup> + *L \$ R* (34)



12<sup>3</sup> + *L \$ R* (34)

abar ba ibar <sub>p.</sub>  $int_0$ *F* = *L<sup>e</sup> L<sup>µ</sup>* (analog of *B*), to be (+1) for *⌫<sup>e</sup>* and (-1) *n I***<sub>c</sub> continue to** *n***-nbar** Again, *F* breaking mass term would be C and P*<sup>z</sup>* even iciei. This nilation into hopeless also the laboratory search of *bus*-like baryon ite to n-npar  $\ddot{a}$  $t_{\rm max}$ oscillation due to operator *usbusb* suggested in Ref. [19]. extending for neutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-antineutron-anti  $\left( \begin{array}{cc} d & \end{array} \right)$  and  $\left( \begin{array}{cc} d & \end{array} \right)$ (odd in terms of P) contribute to the *nn*¯ matrix ele- $\leftarrow u$   $\hat{n}$  to remain  $\int_a^b$   $\int_a^b$  ite to n-nbar  $\sim d$ <sup>)</sup> elsi This tud be a proposed to mixing of massive neutriihilation into massive neutrino. tion of two nucleons inside nucleus like *N* + *N ! ⇡* + *⇡*  $\blacksquare$  $\frac{1}{16}$ *O*i 12<sup>3</sup> into the Hermitian conjugated [*O*<sup>i</sup>  $\frac{1}{2}$ it inco

function of neutron. Thus, only 7 combinations

(33)

*O<sup>i</sup>*

but odd for P..

*LR* <sup>=</sup> *<sup>O</sup>*<sup>1</sup>

massive neutrino.

function of neutron. Thus, only 7 combinations

 $1\chi_2\chi_3$ 

nos. As an example, let us take the system of left-handed

15 orders of magnitude stronger than the sensitivity

⇤⇤¯ *⇠* 10<sup>6</sup> eV which can be achieved in the labora-

for *⌫µ*. Then, C conjugation is interchange of *⌫<sup>e</sup>* and *⌫µ*.

Again, *F* breaking mass term would be C and P*<sup>z</sup>* even

tory conditions [18]. The nuclear stability limits make

hopeless also the laboratory search of *bus*-like baryon

A similar scenario can be staged in case of Dirac

⇤⇤¯ *⇠* <sup>10</sup><sup>6</sup> eV which can be achieved in the labora-

 $\mathbf{18}$ 

nos. As an example, let us take the system of left-handed

*⌫<sup>e</sup>* and *⌫<sup>µ</sup>* and their conjugated partners, right-handed

*⌫*¯*<sup>e</sup>* and *⌫*¯*µ*. One can ascribe them [20] a flavor charge

*F* = *L<sup>e</sup> L<sup>µ</sup>* (analog of *B*), to be (+1) for *⌫<sup>e</sup>* and (-1)

for *⌫µ*. Then, C conjugation is interchange of *⌫<sup>e</sup>* and *⌫µ*.

*⌫<sup>e</sup>* and *⌫<sup>µ</sup>* and their conjugated partners, right-handed

*⌫*¯*<sup>e</sup>* and *⌫*¯*µ*. One can ascribe them [20] a flavor charge

The charge conjugation 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 oper Ltors,  $O_{\chi_1 \chi_2 \chi_3}^i + H.c.$ , and 14 C-odd ones,  $O_{\chi_1 \chi_2 \chi_3}^i$  – H.c. stitution (11) changes *L6B* to (*L6B*) . Together with  $x_1x_2x_3$  $H.c.,$  and  $H C$ -odd ones, into Hermitian conjugated  $[O^i_{\chi_1 \chi_2 \chi_3}]^\dagger$  . So, we have 14 function of neutron. Thus, only 7 combinations shown The The charge conjugation  $C$  transion  $\alpha$  and  $\alpha$  are consistent and  $\alpha$ C-even oper ltors,  $O^i_{\chi_1 \chi_2 \chi_3} + \text{H.c.}$ , and  $\mathbb{R}^n$ ، ^ أن<br>|  $\lambda$ C-even oper *Ltors*,  $O^i_{\chi_1 \chi_2 \chi_3}$  +  $\Omega^i$  the C invariance and 14  $\Omega$  $\frac{1}{2} \chi_1 \chi_2 \chi_3 = \frac{11.0}{10.000}$ FIG. Chaing conjugation  $\circ$  cransforms operators  $\chi_1 \chi_2 \chi_3$  $O^i_{\chi_1 \chi_2 \chi_3}$  – H.c.  $\sum_{\alpha=1}^{\infty}$ The charge conjugation C transforms operators  $O^i_{\chi_1 \chi_2 \chi_3}$  $\mathcal{D}_{\chi_1 \chi_2 \chi_3}^{\epsilon}$  is the solution. So, we have 14 H.c., and 14 C-odd ones, operators operators into four sevens with di↵erent P*z*, C and CP*<sup>z</sup>* 12<sup>3</sup> into the Hermitian conjugated [*O<sup>i</sup>* 12<sup>3</sup> ] *†*. into Hermitian conjugated  $[O^i_{\chi_1 \chi_2 \chi_3}]^\dagger$  . So, we have 14  $\int$ -even operators  $Q^i$  + H  $\alpha$ C-even oper zuots,  $\mathcal{O}_{\chi_1 \chi_2 \chi_3}$  +  $\mathbf{H}.\mathbf{C}$ , **The charge conjugat**  $C$ -even oper *Ltors*,  $O^i$  $\mathbf{C}$  crew operators,  $\mathbf{v}_{\chi_1 \chi_2}$ C-even  $\overline{\mathbf{1}}$  $proton$   $C$  transforms operators  $Q<sup>i</sup>$ igation C transforms operators  $\sigma_{\chi_1 \chi_2 \chi_3}$  $D^i$   $+$   $\text{H}_c$  and 14 C-odd ones  $\gamma_{\chi_1\chi_2\chi_3}$  T  $\pi$ .C., and  $\pi$  C-Oud Ones, ie conjugation C transforms operators  $O^i_{\chi_1 \chi_2 \chi_3}$ pitian conjugated  $O^i$  it. So we have  $14$  $\sum_{x=1}^{\infty} \frac{1}{x^2}$  and  $\sum_{x=1}^{\infty}$  and  $\sum_{x=1}^{\infty}$  and open oper Ltors,  $O^i_{\chi_1 \chi_2 \chi_3}$  + H.c., and 14 C-odd or  $\overline{\phantom{a}}$  $\frac{1}{2}$ charge conju  $\sum_{i=1}^{n}$  intrait conjugated  $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$   $\sum_{i=1}^{n}$  $\chi_1 \chi_2 \chi_3$  and  $\chi_1 \chi_2 \chi_3$  is  $\chi_1 \chi_2 \chi_3$  $\mathbf{c}_\bullet$  which preserves the C invariance and 14 C-odd invariance and 14 C-odd invariance and 14 C-odd invariance and 14 C-odd in into Hormitian conjugated  $\Omega^i$  if So we  $\frac{1}{2}$  **c**  $\frac{1}{2}$  **c**  $\frac{1}{2}$  **d**  $\frac{1}{2}$  **d**  $\frac{1}{2}$  $\sum_{\alpha}^{\alpha}$   $\sum_{\alpha}^{\alpha}$   $\sum_{\beta}^{\alpha}$   $\sum_{\beta}^{\beta}$  $Q^i$  – **H.c.**  $\lambda$ <sup>1</sup> $\lambda$  $\frac{d^2}{dx^2}$ *Cd <sup>n</sup>*  $\alpha_{\chi_1 \chi_2 \chi_3}^i$  $\chi_1\chi_2\chi_3$ via nucleon annihilation into kaons *N* + *N ! K* + *K*, and diagram in the diagram in upper lines and diagram in is substituted by *s* quark (and *⇡*<sup>+</sup> by *K*<sup>+</sup>). In fact,  $n = \frac{1}{2}$ Turn  $\frac{\chi_1 \chi_2 \chi_3}{\chi_1 \chi_2 \chi_3}$  $\epsilon$  have 14

In total, we break all 28 operators in four sevens with different  $P_z$ , C and  $CP_z$  features, Dopotope in four covens with operators in rour sevens with rators in four sevens with 12<sup>3</sup> H*.*c*.* . In total, we break all 28 **operators in coldi, we break all 20 operate** features, **defining in total, we break all 28** |
|
|
| operat 12<sup>3</sup>  $\frac{\lambda_2 \lambda_3 \lambda_4 \lambda_5}{\lambda_1 \lambda_2 \lambda_3}$ 12<sup>3</sup> H*.*c*.*  $\ldots$  to any  $\ldots$  be bare and we deal with 14 operators for **B**  $\frac{1}{2}$  transitions. k all 28 operators in four sevens with hopeless also the laboratory search of *bus*-like baryon the threads all 20 operators in four covered, with stitution (11) changes *L6B* to (*L6B*) . Together with otal,we break all 28 operators in four seve  $\overline{P}$   $\overline{P}$  and  $\overline{CP}$  footures  $\mathbf{c}$   $\mathbf{r}$   $z$   $, \mathbf{c}$  $\frac{3}{4}$ <br>∂⊿rotal we (32) evens with where <sup>0</sup>*C*<sup>0</sup> = *C* is used. The opposite signs in

c.,  $P_z = +$ ,  $C = +$ ,  $CP_z = +$  $P_z = +$ ,  $C = -$ ,  $CP_z = P_z = -$ ,  $C = +$ ,  $CP_z = P_z = -1, \quad C = -1, \quad C P_z = +1$ Only the first seven which are both  $P_z$  and C even <sup>+</sup>*<sup>L</sup> \$ <sup>R</sup>*⇤ +H*.*c*.,* P*<sup>z</sup>* = + *,* C=+ *,* CP*<sup>z</sup>* =+; <sup>+</sup>*<sup>L</sup> \$ <sup>R</sup>*⇤  $\mathbf{P}$ <sup>*i*</sup> = + *I*<sub>z</sub> =  $\mathbf{P}$  =  $\mathbf{P}$  =  $\mathbf{P}$  =  $\mathbf{P}$  =  $\mathbf{P}$  =  $\mathbf{P}$  =  $\mathbf{P}$ *<sup>L</sup> \$ <sup>R</sup>*⇤  $\lambda$ <sup>*i*</sup>.<sup>2</sup>  $\lambda$ <sup>*3*</sup>  $\lambda$ <sup>*7*</sup>  $\lambda$ <sup>7</sup>  $\lambda$ <sup>7</sup>  $\lambda$ <sup>2</sup>  $\lambda$ *<sup>L</sup> \$ <sup>R</sup>*⇤ H*.*c*.,* P*<sup>z</sup>* = *,* C = *,* CP*<sup>z</sup>* = + *.*  $\overline{a}$ even, contribute to *nn*¯ oscillations when we neglect by contribute to n-nbar mixing.  $\mathcal{L} \times \mathcal{L} \times 2 \times 3$   $\mathcal{L} \times \mathcal{L} \times 4$   $\mathcal{L} \times \mathcal{L} \times 4$  $\left[\mathbf{U}_{\chi_1 \chi_2 \chi_3} + \mathbf{U} \times \mathbf{H} \right] - \mathbf{H} \cdot \mathbf{C}$ ,  $\mathbf{H}$  $\left[ \nabla_{\chi_1 \chi_2 \chi_3} - L \leftrightarrow \mathbf{h} \right] + \text{H.c.,}$  F  $-H<sub>2</sub>$ Only the first seven operators, which are both P*<sup>z</sup>* and C **e** Child the first seven which contribute to n-phar miving to nuclei instability when the particular interesting interesting  $\frac{1}{2}$  $\begin{bmatrix} \mathbf{a} & \mathbf{b} & \mathbf{c} \\ \mathbf{b} & \mathbf{c} & \mathbf{d} \\ \mathbf{c} & \mathbf{d} & \mathbf{d} \end{bmatrix}$ Con *d* and the first seven which **B**  $\frac{1}{2}$  and the seven will  $[O_{\chi_1 \chi_2 \chi_3}^i+L \leftrightarrow R] + \text{H.c.,}$   $P_z = +, C = +, C P_z = +$  $[O_{\chi_1 \chi_2 \chi_3}^i+L \leftrightarrow R]-$ H.c.,  $P_z=+$ ,  $C=-$ ,  $CP_z= P_z = -$ ,  $C = +$ ,  $CP_z = \mathbf{C}$  and  $\mathbf{C}$  are both P  $\mathbf{C}$  are both P  $\mathbf{C}$  are both P  $\mathbf{C}$  $\mathbf u \in \mathcal{V}$ contribute to  $\mathbf v$  over  $\mathbf v$  $S_{\rm eff}$  electroweak corrections. Other operators contribute  $\sim$  $[O_{\gamma_1 \gamma_2 \gamma_3}^i - L \leftrightarrow R] + \text{H.c.,} \ \ \text{P}_z = \left[0_{\chi_1 \chi_2 \chi_3} - D \vee \mu\right] - \text{II.c., } 1_{z}$ Contractor contribution of the first seven, which are h SM, ene moe seven winen are by contribute to n-nbar mixing.  $\left[\frac{\nu_{\chi_1 \chi_2 \chi_3}}{\nu_{\chi_1 \chi_2 \chi_3}}\right]$  $\left[\begin{array}{c} \chi_1 \chi_2 \chi_3 & \chi_1 \chi_2 \chi_3 & \chi_2 \chi_3 & \chi_1 \chi_$  $\left[\begin{array}{ccc} \chi_1 \chi_2 \chi_3 & \chi_1 \chi_2 \chi_3 & \chi_2 \chi_3 & \chi_1 \chi_$ Only the first seven whi even, contribute to *nn*¯ oscillations when we neglect by (odd in terms of P) contribute to the *nn*¯ matrix element ( $O_{\chi_1\chi_2\chi_3}^i$ electroweak interactions where the discrete symmetries  $\Omega^i$ are broken. The  $\frac{1}{2}$   $\chi_1 \chi_2 \chi_3$  $\left[O_{\chi_1\chi_2\chi_3}^i\right]$ reflection for *u* and *d* quarks is defined similar to the neu-**Example 20 Proportional Contribute to n-1**  $8. \text{Fe}$  (1.1.0.,  $1 \text{ g} - 1$ ,  $0 \text{ g} - 1$ ,  $0 \text{ g} - 1$  $\mathbf{F}_x + L \leftrightarrow R$  - H.c.,  $\mathbf{P}_z = +$ ,  $\mathbf{C} = -$ ,  $\mathbf{CP}_z =$  $n^{1+1}$  $(-L \leftrightarrow R] +$ H.c.,  $P_z = -$ ,  $C = +$ ,  $CP_z = P_{\mathbf{z}} = \mathbf{P}_z = \mathbf{P}_z, \ \mathbf{C} = \mathbf{P}_z = \mathbf{P}_z = \mathbf{P}_z$ *F* = *L<sup>e</sup> L<sup>µ</sup>* (analog of *B*), to be (+1) for *⌫<sup>e</sup>* and (-1) *P*  $\alpha$  and C conserved the interchange is no transition in the is no transition is no transition in the is no transition i Again, *F* breaking mass term would be C and P*<sup>z</sup>* even but odd for P. However, this CP oddness does not translate immedi- $\mathbf{P}_{2x3} + L \leftrightarrow R$  +  $\mathbf{H}$ .c.,  $\mathbf{P}_z = +$ ,  $\mathbf{C} = +$ ,  $\mathbf{CP}_z = +$  $\frac{1}{2}$  interaction. The interaction of  $\frac{1}{2}$  $\mathbf{I} \leftrightarrow \mathbf{R}$  of  $\mathbf{P}$  in  $\mathbf{C}$  =  $\mathbf{C}$  =  $\mathbf{CP}$  =  $\pm$  $2\chi_3$  remind it. between sectors with dividend and one can combine can combine can combine the first seven operators, which provide a seven operators, which are both Pz and Combined and Combined and Combined and Combined and Combined and C P with a baryonic U(1)*<sup>B</sup>* phase rotation and define P*↵*, For *u* and *d* quarks of the first generation the full list of **B** cont  $[O^{i}_{\chi_{1}\chi_{2}\chi_{3}}+L \leftrightarrow R]$ +H.c., P<sub>z</sub> = +, C = +, CP<sub>z</sub> = +  $\left[O^{i}_{\chi_{1}\chi_{2}\chi_{3}}\!\!+\!L\leftrightarrow R\right]\!-\!\text{H.c.,}\;\;\text{P}_{z}\!=+\,,\;\text{C}=-\,,\;\text{CP}_{z}=-% \left[1\!\!1_{\{\chi_{1},\chi_{2}\chi_{3}\}}\!\!\!+\!L\leftrightarrow R\right]\!-\!\text{H.c.,}\;\;\text{P}_{z}\!=\!+\,,\;\text{C}=\!-\,,\;\text{CP}_{z}=\!-\,,\;\text{CP}_{z}=\!-\,,\;\text{CP}_{z}=\!-\,,\;\text{CP}_{z}=\!-\,,\;\text{CP}_{z}=\!-\,,\;\text{CP}_{z}=\!-\,,\;\text{CP}_{z$  $[O^i_{\chi_1 \chi_2 \chi_3} - L \leftrightarrow R] + \text{H.c.,} \ \ \ P_z = -, \ \ \text{C} = +, \ \ \text{CP}_z = [O_{\chi_1 \chi_2 \chi_3}^i - L \leftrightarrow R] - H.c., \ \ P_z = -, \ C = -, \ CP_z = +.$ contribute to *n*-nbar mixing. The contribute to n-nbar mixing. Only the first seven which are both  $P_z$  and C even Here *<sup>i</sup>* stands for *L* or *R* quark chirality. Accounting  $\overline{\phantom{a}}$  $x_1x_2x_3$   $\qquad \qquad$   $\qquad$   $\$ conditions to a note may  $\mathcal{S}$ .  $\mathbf{p}$  interest to search for the of interest to search for the of interest to search for the searc nuclear decays into kaons in the large volume detectors.)  $15$  orders of magnitude stronger than the sensitivity in  $15$  $$  $-$ ,  $CP_z = +$ oscillation due to operator *usbusb* suggested in Ref. [19]. orem on the opposite parities of fermion and antifermion fermion and antifermion states.  $\text{CP}_z =$ stitution (11) changes *L6B* to (*L6B*) . Together with