Lepton flavor violating processes in unparticle physics

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We study the virtual effects of unparticle physics in the lepton flavor violating processes $M^0 \to l^+l^-$ and $e^+e^- \to l^+l^-$ scattering, where $M^0$ denotes the pseudoscalar mesons: $\pi^0, K_L, D_0, B_0, B_s^0$ and $l, l'$ denote two different lepton flavors. For the decay of $B^0 \to l^+l^-$, there is no constraint from the current experimental upper bounds on the vector unparticle coupling with leptons. The constraint on the coupling constant between scalar unparticle field and leptons is sensitive to the scaling dimension of the unparticle $d_{U}$. For the scattering process $e^-e^+ \to l^-l^+$, there is only constraint from experiments on the vector unparticle couplings with leptons but no constraint on the scalar unparticle. We study the $\sqrt{s}$ dependence of the cross section $\frac{1}{\sigma} \frac{d\sigma}{d\sqrt{s}}$ of $e^+e^- \to l^-l^+$ with different values of $d_{U}$. If $d_{U} = 1.5$, the cross section is independent on the center mass energy. For $d_{U} > 1.5$, the cross section increases with $\sqrt{s}$.

I. INTRODUCTION

In four space-time dimensions, there is no scale invariant interacting quantum field theory which contains massive particles. Even if scale invariance is preserved in massless field theory at classical level, it would be broken by renormalization effect which is known as the trace anomaly. Nevertheless, it is possible that at a much higher scale there exists a scale invariant sector with a nontrivial infrared fixed point. Recently, it has been argued that one kind of fields, under the name Banks-Zaks ($BZ$) fields [1], might appear at TeV scale. At low energy, these fields manifest themselves by matching onto a new sector called “unparticle” ($U$) with a non-integral number of scale dimension $d_{U}$ [2, 3].

Although the underlying structure of unparticles is still unclear, there indeed exist respectable interesting phenomena for testing unparticles experimentally. In many processes, $t \to uU$ [2], $e^+e^- \to \gamma U$ and $Z \to \bar{q}qU$ [4], the productions of these stuff might be detected by measuring the missing energies and the momentum distributions. The phenomenological studies on the unparticle effect in charged Higgs decays, anomalous magnetic moments, $B^0 - \bar{B}^0$ and $D^0 - \bar{D}^0$ mixing and hadronic flavor changing neutral current (FCNC) in $B$ decays are carried out in Ref. [4, 5, 6, 7, 8, 9]. In Ref. [10], the lepton flavor violation interaction is introduced to explore the phenomenology in $\mu^+ \to e^-e^+e^-$. In this work, we will investigate the lepton flavor changing processes $B^0 \to \mu^+\tau^\pm$, $e^+e^- \to e^\mp\mu^\pm$ and some other related processes. There are a number of experimental upper bounds on these processes which give stringent constraints to the effective couplings of unparticles. This can probably shed light on the internal structure of unparticles.
II. EFFECTIVE INTERACTIONS

At very high energy, the theory contains the Standard Model (SM) fields and the fields with a nontrivial infrared fixed point, called BZ fields \[BZ\]. These two sectors interact with each other by exchanging particles with a very large mass \[M_U\]. Below this mass scale, heavy particles are integrated out and thus the SM particles and the BZ sector interacts through non-renormalizable operators:

\[
\frac{1}{M_U^{d_{SM} + d_{BZ} - 4}} O_{SM} O_{BZ} ,
\]

where \(O_{SM}\) and \(O_{BZ}\) are local operators made up of the SM and BZ fields, respectively. The renormalization effects in the scale invariant sector induce the dimensional transmutation at the scale \(\Lambda_U\). Below the scale \(\Lambda_U\), the BZ operators match onto unparticle operators while the non-renormalizable operators in Eq. (1) match onto an effective interaction operator:

\[
\frac{C_U \Lambda_U^{d_{BZ} - d_U} M_U^{d_{SM} + d_{BZ} - 4}}{O_{SM} O_U} ,
\]

where \(d_{BZ}\) and \(d_U\) are the scaling dimensions of the \(O_{BZ}\) and unparticle \(O_U\) operators respectively. The scaling dimension of unparticle field has been taken as \(1 < d_U < 2\) in the literature.

To be more specific, unparticles have some different characters from ordinary particles in phase space, virtual propagator, and the effective interaction with the SM particles. It was demonstrated in \[2\] that scale invariance can be used to fix the two-point functions of the unparticle operators and the propagators. The propagator of the scalar unparticle field can be written by \[3, 4\]:

\[
\int e^{i P \cdot x} d^4 x \langle 0 | T [O_U(x) O_U(0)] | 0 \rangle = i \frac{A_{d_U}}{2} \frac{1}{\sin((d_U - \frac{1}{2}) \pi)} (-P^2 - i \epsilon)^{d_U - 2} .
\]

If the vector unparticle is assumed to be transverse, its propagator has the form

\[
\int e^{i P \cdot x} d^4 x \langle 0 | T [O_{\mu U}(x) O_{\mu U}(0)] | 0 \rangle = i \frac{A_{d_U}}{2} \frac{g_{\mu \nu} + P^\mu P^\nu / P^2}{\sin((d_U - \frac{1}{2}) \pi)} (-P^2 - i \epsilon)^{d_U - 2} ,
\]

where the coefficient \(A_{d_U}\) is given by

\[
A_{d_U} = \frac{16 \pi^{5/2}}{(2\pi)^{2d_U}} \frac{1}{\Gamma(d_U - \frac{1}{2}) \Gamma(2d_U - 1)} \frac{\Gamma(d_U + 1)}{\Gamma(2d_U - 1)} .
\]

There are other possible Lorentz structures: a spinor field \[5\] or even a tensor field \(O_{\mu \nu}^U\). The only difference is the spin structure which has been comprehensively discussed in Ref. \[11\].

The effective interactions that satisfy the standard model gauge symmetry for the scalar and vector unparticle operators with standard model fields are given, respectively, by

\[
\lambda_0 \frac{1}{\Lambda_U^{d_U - 1}} f O_U , \quad \lambda_0 \frac{1}{\Lambda_U^{d_U - 1}} \bar{f} \gamma_5 f O_U , \quad \lambda_0 \frac{1}{\Lambda_U^{d_U - 1}} \bar{f} \gamma^\mu f (\partial_\mu O_U) , \quad \lambda_0 \frac{1}{\Lambda_U^{d_U - 1}} \bar{f} \gamma^\mu \gamma_5 f (\partial_\mu O_U) , \quad \lambda_0 \frac{1}{\Lambda_U^{d_U - 1}} \bar{f} \gamma_\mu \gamma_5 f O_{\mu U} ;
\]

\[
\lambda_0 \frac{1}{\Lambda_U^{d_U - 1}} G_{\alpha \beta} G^{\alpha \beta \mu} O_U , \quad \lambda_1 \frac{1}{\Lambda_U^{d_U - 1}} \bar{f} \gamma_\mu f O_{\mu U} , \quad \lambda_1 \frac{1}{\Lambda_U^{d_U - 1}} \bar{f} \gamma_\mu \gamma_5 f O_{\mu U} ;
\]

\[
(6)
\]
where \( f \) stands for a standard model fermion and \( \lambda_i \) are dimensionless effective couplings \( C_U \lambda_i^d B Z / M_U^{d S M + d B Z - 4} \) with the index \( i = 0, 1 \) labeling the scalar and vector unparticle operators, respectively. In principle, the coupling constants \( \lambda_0, \lambda_1 \) can be different for different flavors and are then distinguished by additional indices. For example, the hadronic FCNC via scalar unparticle, taking \( b \to d \) as an example, can proceed through the effective interaction term:

\[
L_{\text{eff}} = i \frac{\lambda_{db}}{\Lambda^d_U} \bar{d} \gamma_\mu (1 - \gamma_5) b \partial^\mu O_U + h.c.,
\]

where we have used the subscript \( db \) to denote the coupling with \( d \) and \( b \) quark. Similarly, for the vector unparticle, the effective interaction is considered as,

\[
L_{\text{eff}} = \frac{1}{\Lambda^d_U} \bar{l} \gamma_\mu (\lambda_{Vll'} + \lambda_{All'} \gamma_5) l' O^\mu U + h.c..
\]

III. LEPTON FLAVOR VIOLATION DECAYS \( M^0 \to l^+ l^- \)

In this section, we will consider the lepton flavor violation in neutral meson decays, including \( \pi^0, K_L, D^0, B_0 \) and \( B_0^s \). To be more specific, we will consider the scalar coupling in Eq.(7) and the vector coupling in Eq.(8). As discussed above, the vector unparticle is assumed to be transverse. Thus this kind of unparticle gives zero contribution, when contraction with \( p^\mu U \) from the matrix element \( \langle 0| \bar{q}_1 \gamma_\mu \gamma_5 q_2 | M^0 \rangle \).

In the following, we will first focus on the decay channel \( B^0 \to \mu^+ \tau^- \) induced by scalar unparticle. The decay amplitude for \( B^0 \to \mu^+ \tau^- \) reads

\[
i \mathcal{M} = \bar{u}(p_{\tau}) \left[ i \frac{\lambda_{db}}{\Lambda^d_U} \gamma_\mu (1 - \gamma_5) P^\mu_B \right] v(p_\mu)
\times \frac{i A_{dU}}{2} \frac{1}{\sin(d_{dU})} \times (-m_B^2 - i \epsilon)^{d_{dU} - 2} \times i \frac{\lambda_{\mu\tau}}{\Lambda^d_U} (-P^\mu_B) (-i f_B P_B \mu)
= -m_B \frac{A_{dU}}{2 \sin(d_{dU})} \frac{\lambda_{db} \lambda_{\mu\tau}}{\Lambda^d_U} f_B m_B^2 (-m_B^2 - i \epsilon)^{d_{dU} - 2} \times \bar{u}(p_{\tau}) (1 + \gamma_5) v(p_\mu),
\]

where the mass of lighter lepton \( \mu \) is neglected. Thus, the decay width for this decay channel can be written as

\[
\Gamma = \frac{\bar{p}^2}{8 \pi m_B^2} \times \sum_{\text{pol.}} |\mathcal{M}|^2 = \frac{f_B^2 m_B^5 m_{\tau}^2}{4 \pi} \frac{A_{dU}}{2 \sin(d_{dU})} \frac{\lambda_{db} \lambda_{\mu\tau}}{\Lambda^d_U} (-m_B^2)^{d_{dU} - 2}.
\]

This decay width is proportional to the lepton mass square, due to the \( V - A \) current for the interaction type, which indicates this kind of process is helicity-suppressed.

As an illustration, we use the following inputs

\[
\Lambda^d_U = 1 \text{TeV}, \quad d_U = 0.5.
\]

The experimental upper bound on the branching fraction:

\[
\text{BR}(B^0 \to \mu^+ \tau^-) < 3.8 \times 10^{-5},
\]

\[
\text{BR}(B^0 \to \mu^+ \tau^-) < 3.8 \times 10^{-5},
\]
TABLE I: Experimental upper bounds on $M \rightarrow l^+l^-$ at 90% confidence level [12] and their constraints on the effective coupling constants $\lambda$ performed at $\Lambda = 1$ TeV and $d_U = 0.5, 1.5$.

| Modes          | Experiments | $\lambda$ ($d_U = 0.5$) | $\lambda$ ($d_U = 1.5$) |
|----------------|-------------|--------------------------|--------------------------|
| $\pi^0 \rightarrow \mu^+\mu^-$ | $3.8 \times 10^{-10}$ | $|\langle \lambda_{uu} - \lambda_{dd} \rangle | < 3.7 \times 10^{-5}$ | $|\lambda_{uu} - \lambda_{dd} \rangle | < 2.4 \times 10^6$ |
| $\pi^0 \rightarrow e^+e^-$      | $3.4 \times 10^{-9}$  | $|\langle \lambda_{uu} - \lambda_{dd} \rangle | < 1.1 \times 10^{-2}$ | $|\lambda_{uu} - \lambda_{dd} \rangle | < 7.3 \times 10^6$ |
| $K_L \rightarrow e^{\pm}e^{\mp}$ | $4.7 \times 10^{-12}$ | $\text{Re}(\lambda_{ed}) |\lambda_{ee}| < 1.3 \times 10^{-10}$ | $\text{Re}(\lambda_{ed}) |\lambda_{ee}| < 0.02$ |
| $D^0 \rightarrow e^{\pm}e^{\mp}$ | $8.1 \times 10^{-7}$  | $|\lambda_{uu}| < 3.6 \times 10^{-5}$ | $|\lambda_{uu}| < 400$ |
| $B^0 \rightarrow e^{\pm}e^{\mp}$ | $4.0 \times 10^{-6}$  | $|\lambda_{dd}| < 7.6 \times 10^{-5}$ | $|\lambda_{dd}| < 108$ |
| $B^0 \rightarrow e^{\pm}\tau^{\mp}$ | $1.1 \times 10^{-4}$  | $|\lambda_{dd}| < 2.4 \times 10^{-5}$ | $|\lambda_{dd}| < 34$ |
| $B^0_s \rightarrow e^{\pm}e^{\mp}$ | $3.8 \times 10^{-5}$  | $|\lambda_{uu}| < 1.4 \times 10^{-5}$ | $|\lambda_{uu}| < 20$ |
| $B^0_s \rightarrow e^{\pm}\tau^{\mp}$ | $6.1 \times 10^{-6}$  | $|\lambda_{uu}| < 7.8 \times 10^{-5}$ | $|\lambda_{uu}| < 107$ |

leads to a constraint on the coupling constant $|\lambda_{dd}\lambda_{e\mu}| \leq 1.4 \times 10^{-5}$. If we take the scaling dimension $d_U$ larger, the constraint becomes less stringent, for example, the constraint for $|\lambda_{dd}\lambda_{e\mu}| \leq 20$ is obtained by taking $d_U = 1.5$. As mentioned above, the $V-A$ coupling of unparticles with the standard model fermions results in the famous helicity suppression. If other interactions are introduced such as $S \pm P$, the helicity rule is invalid, which can constrain $\lambda$ more strictly.

The analysis can be easily generalized to other processes, such as $\pi^0\rightarrow l^+l^-$. These processes can give different constraints. For example, the constraint on $|\langle \lambda_{uu} - \lambda_{dd} \rangle | < 3.7 \times 10^{-5}$ is obtained from $\pi^0 \rightarrow l^+l^-$. In table I we collect the experimental upper bounds [12] for these channels and their constraints on the leptonic flavor violating processes in $\pi^0$, $K_L$, $D^0$, $B^0$, $B^0_s$ decays. From this table, we can see the results dramatically depend on the scaling dimension of the unparticle field.

Since the transversely polarized vector unparticle gives zero contribution to the neutral meson decays, there is no constraint from experiments to their effective couplings.

### IV. LEPTON FLAVOR VIOLATING SCATTERING PROCESS $e^+e^- \rightarrow l^+l^-$

In the following, we will consider the process $e^- (p_1) e^- (p_2) \rightarrow e^- (p_3) \mu^+ (p_4)$ as an example. In the calculations, we will neglect the small masses of the leptons. The coupling between scalar unparticle and SM particles in Eq. [11] is proportional to the momentum of unparticle, when contraction with the Dirac matrix and using equation of motion, the amplitude is proportional to the mass of the lepton and thus negligible. This kind of helicity suppression bring on the negligible contributions of the scalar unparticle. Therefore, only the vector unparticle coupling given in Eq. [12] will be considered in this scattering process.

There are two leading order Feynman diagrams contributing to this process, which are depicted

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1 The mass of $\tau$ is also negligible compared with the large center mass energy.
in Fig. 1. With the interaction Lagrangian in Eq. (8), the amplitude for the left diagram is

$$iM_a = \bar{u}(p_3)\left[\frac{\lambda_{Ve\mu}}{\Lambda_{d\ell}} \gamma_\mu + \frac{\lambda_{Ae\mu}}{\Lambda_{d\ell}} \gamma_\mu \gamma_5\right]v(p_4)
\times iA_{d\ell} \times \frac{-g^{\mu\nu} + P^\mu P^\nu/P^2}{\sin(d_\ell \pi)} \times \frac{[-(p_1 + p_2)^2 - i\epsilon]^{d_\ell - 2}}{2}
\times \bar{v}(p_2)\left[\frac{\lambda_{Ve\mu}}{\Lambda_{d\ell}} \gamma_\mu + \frac{\lambda_{Ae\mu}}{\Lambda_{d\ell}} \gamma_\mu \gamma_5\right]u(p_1),$$

while the amplitude for the right diagram is

$$iM_b = -\bar{u}(p_3)\left[\frac{\lambda_{Ve\mu}}{\Lambda_{d\ell}} \gamma_\mu + \frac{\lambda_{Ae\mu}}{\Lambda_{d\ell}} \gamma_\mu \gamma_5\right]u(p_1)
\times iA_{d\ell} \times \frac{-g^{\mu\nu} + P^\mu P^\nu/P^2}{\sin(d_\ell \pi)} \times \frac{[-(p_3 - p_1)^2 - i\epsilon]^{d_\ell - 2}}{2}
\times \bar{v}(p_2)\left[\frac{\lambda_{Ve\mu}}{\Lambda_{d\ell}} \gamma_\mu + \frac{\lambda_{Ae\mu}}{\Lambda_{d\ell}} \gamma_\mu \gamma_5\right]v(p_4).$$

The second term in the vector unparticle propagator will give a contribution which is proportional to the lepton mass and thus will be neglected in our calculation. Since there are only three independent four-vectors in this kind of scattering, there is no interference between the vector and the axial-vector couplings. Thus we can consider these two different contributions independently. For simplicity, we only consider the vector coupling by taking $\lambda_{A\mu\nu} = 0$. The matrix element squared is then written by

$$\sum_{pol.} |M|^2 = \sum_{pol.} |iM_a|^2 + \sum_{pol.} |iM_b|^2 + \sum_{pol.} M_a M_b^* + \sum_{pol.} M_a^* M_b,$$

with

$$\sum_{pol.} |iM_a|^2 = 32|b|^2|(-s)^{d_\ell - 2}|^2 s^2(1 + \cos \theta),$$

$$\sum_{pol.} |iM_b|^2 = 32|b|^2|-(p_3 - p_1)^2|^{d_\ell - 2}|^2 s^2(1 + \cos\theta),$$

$$\sum_{pol.} M_a M_b^* = 32|b|^2(-s - i\epsilon)^{d_\ell - 2}[-(p_3 - p_1)^2 + i\epsilon]^{d_\ell - 2}s^2(1 + \cos\theta)\cos(d_\ell \pi),$$

$$\sum_{pol.} M_a^* M_b = 32|b|^2(-s + i\epsilon)^{d_\ell - 2}[-(p_3 - p_1)^2 - i\epsilon]^{d_\ell - 2}s^2(1 + \cos\theta)\cos(d_\ell \pi),$$

FIG. 1: Lowest order Feynman diagrams of $e^+e^- \rightarrow e^+\mu^-$. 
TABLE II: Experimental upper bounds for cross section of $e^+e^- \rightarrow l^+l^-$ (in units of fb) \cite{13,14}.

| $\sqrt{s}$ (GeV) | $\mu\tau$ | $e\tau$ | $e\mu$ |
|-----------------|-----------|---------|---------|
| $10.58$         | --        | $9.2$   | $3.8$   |
| $189$           | $58$      | $95$    | $115$   |
| $192 < \sqrt{s} < 196$ | $62$      | $144$   | $116$   |
| $200 < \sqrt{s} < 206$ | $22$      | $78$    | $64$    |

TABLE III: Constraints on the lepton coupling constants from $e^+e^- \rightarrow l^+l^-$. 

| $d_U$ | $1.1$ | $1.3$ | $1.5$ | $1.7$ | $1.9$ | $\sqrt{|\lambda_{Vee}\lambda_{Ve\mu}|}$ |
|-------|------|------|------|------|------|----------------------------------------|
|       |      |      |      |      |      | $0.007 < 0.03 < 0.28 < 0.37 < 0.53$ |

where $\theta$ is the scattering angle (the angle between the 3-momentum of electron: $\vec{p}_1$ and $\vec{p}_3$) and 

$$b = \frac{-iA_{d_U} \lambda_{Vee} \lambda_{Ve\mu}}{2 \Lambda_{d_U}^{2d_U-2} \sin(d_U \pi)}.$$  \hspace{1cm} (20)

The cross section is 

$$\sigma = \frac{1}{2s} \int \frac{d^3\vec{p}_3}{(2\pi)^3 2E_3} \frac{d^3\vec{p}_4}{(2\pi)^3 2E_4} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \sum_{\text{pol.}} |M|^2$$  \hspace{1cm} (21)

One interesting thing is the dependence on the invariant mass with different scaling dimension $d_U$. In order to show the dependence on $d_U$ of the cross section, we plot the $\sqrt{s}$ dependence of the function $R(s) \equiv \frac{d\sigma}{d\sqrt{s}}$ of $e^+e^- \rightarrow e^-\mu^+$ with different values of $d_U$ in Fig. 2. The amplitude square in Eq.(15) has the behavior of $s^{2d_U-2}$ which gives $\sigma \sim s^{2d_U-3}$. If $d_U = 1.5$, the cross section is independent on the invariant mass. For $d_U > 1.5$, the cross section increases with $\sqrt{s}$. At low energy, the function $R$ has a strong dependence on the scaling dimension $d_U$ while at high energy it is close to 0 and almost independent on $d_U$.

On the experimental side, OPAL and BABAR collaborations have performed some studies on the lepton flavor changing processes at different invariant masses \cite{13,14}. The upper bounds are collected in table III. We take 

$$\Lambda_{d_U} = 1\text{TeV},$$  \hspace{1cm} (22)

to give the combined constraint on the coupling constant as in table III. The results in the table strongly depend on the scaling dimension $d_U$.

The constraint on the axial-vector coupling constants can also be similarly analyzed. Since the scalar unparticle coupling does not contribute to the $e^+e^-$ process in the zero lepton mass limit, there is no constraint for their effective coupling from these experiments.
FIG. 2: $\sqrt{s}$ dependence of $d\ln \sigma/d\sqrt{s}$ with various values of $d_U = 1.1, 1.3, 1.5, 1.7, 1.9$ (from bottom to top), respectively

V. CONCLUSION

In a short summary, we have explored the phenomenology of unparticle physics with the help of lepton flavor changing processes $M^0 \to l^+ l'^-$, $e^+ e^- \to e^\pm \mu^\mp$ and other related processes. In the zero lepton mass limit, the vector unparticle coupling does not contribute to the neutral meson leptonic decays; while the scalar unparticle coupling does not contribute to the $e^+ e^-$ scattering processes. Therefore, the experimental upper bounds of $M^0 \to l^+ l'^-$ decays will only constrain the scalar unparticle coupling $\lambda$, which is sensitive to the scaling dimension of the unparticle $d_U$. For the scattering process $e^- e^+ \to e^- \mu^+$, there is only constraint to the vector unparticle coupling from current experiments. We also study the $\sqrt{s}$ dependence of the cross section $\frac{1}{\sigma} \frac{d\sigma}{d\sqrt{s}}$ of process $e^- e^+ \to e^- \mu^+$ with different values of $d_U$. If $d_U = 1.5$, the cross section is independent on the invariant mass. For $d_U > 1.5$, the cross section increases with $\sqrt{s}$.

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