On Unparticles and $K^+ \to \pi^+ + \text{Missing Energy}$

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Abstract

We analyze the branching ratio and spectrum for the decay mode $K^+ \to \pi^+ + \vec{E}$ (missing energy) in the unparticle model, where an unparticle can also serve as the missing energy. A vector unparticle can even mediate the $K^+ \to \pi^+ + \nu \bar{\nu}$, resulting complicated interference with the Standard Model.

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The rare decay $K^+ \to \pi^+ + \nu \bar{\nu}$ is one of the cleanest decay modes in the Standard Model (SM)\[1\]. Due to its smallness within the SM, it might be very sensitive to the new physics beyond the SM. Since only the $\pi^+$ in the final state will be detected, the neutrino-anti-neutrino pair will behave as missing energy. Consequently, in the presence of new physics, the decay mode $K^+ \to \pi^+ + \nu \bar{\nu}$ is not only modified by the new interactions, but also polluted by possible new final state if it also behaves as missing energy.

In the Unparticle Model suggested by Georgi\[2\], an interesting observation is that a nontrivial scale invariant sector of scale dimension $d_U$ might manifest itself at the low energy as a non-integral number $d_U$ of invisible massless particles, dubbed unparticle $U$. In the effective theory below the scale $\Lambda_U$, the Banks-Zaks operators\[3\] match onto the unparticles operators, and the interactions match onto the form\[2\]

$$\frac{C_U A_U^{d_A - d_U}}{M_U^k} O_{SM} O_U,$$

where $C_U$ is a coefficient function. If $M_U$ is large enough, the unparticle stuff doesn’t couple strongly to the ordinary particles. Many forms of interactions have been introduced in the literature, resulting very different features from those in the SM\[4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70\].

In the present work, we will study $K^+ \to \pi^+ + \text{Missing Energy}$ in the Unparticle Model. In this model, the mode $K^+ \to \pi^+ + \nu \bar{\nu}$ is modified by the unparticle mediation, and $K^+ \to \pi^+ + U$ also behaves as the missing energy. They are constrained by the data\[71\]. We will analyse the spectra of $\pi^+$ in the final states, present numerical results and give further discussions.

In the Unparticle Model, we study the mode $K^+ \to \pi^+ + U$ firstly. The quark-unparticle couplings are taken to be

$$(\bar{q}q)_{V \pm A} O_{U,}^\mu,$$

and

$$(\bar{q}q)_{V \pm A} \partial^\mu O_{U},$$

where $V \pm A$ here refers to $\gamma^\mu (1 \pm \gamma^5)$ and the couplings are omitted. The propagator for the vector unparticles is

$$\Delta_V = -i \int e^{i P x} \langle 0 | T(O_{U}^\mu O_U^\nu) | 0 \rangle \ d^4 x = -i A_{d_{U}} \frac{g^{\mu\nu} + P^\mu P^\nu / P^2}{\sin (d_{U} \pi)} (-P^2 - i \epsilon)^{d_{U} - 2}. \quad (3)$$

$A_{d_{U}}$ is defined as\[2\]

$$A_{d_{U}} = \frac{16 \pi^{5/2}}{(2 \pi)^{2d_{U}}} \frac{\Gamma (d_{U} + 1/2)}{\Gamma (2d_{U})}, \quad \Gamma (d_{U} - 1/2) \frac{\Gamma (2d_{U}) - 1/2}{\Gamma (d_{U} - 1/2)}.$$

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where $d_{U}$ is a non-integral number, counting for the non-integral number of massless particle behavior of the unparticle[2]. The effective Hamiltonian for an unparticle emission process is

$$\mathcal{H}_{\text{eff}}^{S} = \frac{c^{q}k_{U}^{d_{U}}}{M_{U}^{L}}(\bar{s}d)v_{A}\partial^{\mu}O_{U}$$

for the scalar unparticle, and

$$\mathcal{H}_{\text{eff}}^{V} = \frac{c^{q}k_{U}^{d_{U}}}{M_{U}^{L}}(\bar{s}d)v_{A}\partial^{\mu}O_{U}$$

for the vector unparticle. We have defined the two dimensional coefficients corresponding to scalar and vector unparticles

$c_{S}^{q} = \frac{c^{q}k_{U}^{d_{U}}}{M_{U}^{L}}$, and $c_{V}^{q} = \frac{c^{q}k_{U}^{d_{U}}}{M_{U}^{L}}.$

We get the hadronic amplitudes

$$A_{\text{eff}}^{S} = c_{S}^{q}(f_{+}(q^{2})(k+p)_{\mu} + f_{-}(q^{2})(k-p)_{\mu})\partial^{\mu}O_{U}.$$  

$$A_{\text{eff}}^{V} = c_{V}^{q}(f_{+}(q^{2})(k+p)_{\mu} + f_{-}(q^{2})(k-p)_{\mu})O_{U}^{\mu}.$$ 

The differential width for the scalar and vector unparticles respectively are,

$$\frac{d\Gamma^{SU}}{dE_{\pi}} = \frac{c_{S}^{q}A_{d_{U}}}{4\pi^{2}m_{K}}\sqrt{E_{\pi}^{2} - m_{\pi}^{2}}(m_{K}^{2} + m_{\pi}^{2} - 2m_{K}E_{\pi})^{d_{U}-2}$$

$$\times \left[f_{+}(m_{K}^{2} - m_{\pi}^{2}) + f_{-}(m_{K}^{2} + m_{\pi}^{2} - 2m_{K}E_{\pi})\right]^{2},$$

$$\frac{d\Gamma^{VU}}{dE_{\pi}} = \frac{c_{V}^{q}A_{d_{U}}}{4\pi^{2}m_{K}}\sqrt{E_{\pi}^{2} - m_{\pi}^{2}}(m_{K}^{2} + m_{\pi}^{2} - 2m_{K}E_{\pi})^{d_{U}-2}$$

$$\times \left[f_{+}^{2}(m_{K}^{2} + m_{\pi}^{2} + 2m_{K}E_{\pi}) + f_{-}^{2}(m_{K}^{2} + m_{\pi}^{2} - 2m_{K}E_{\pi}) \right.$$

$$+ 2f_{+}f_{-}(m_{K}^{2} - m_{\pi}^{2}) - (f_{+}^{2} + f_{-}^{2} + 2f_{+}f_{-}) \frac{(m_{K}^{2} - m_{\pi}^{2})^{2}}{m_{K}^{2} + m_{\pi}^{2} - 2m_{K}E_{\pi}} \bigg].$$

3

In the Unparticle Model, the decay $K^{+} \rightarrow \pi^{+} + \nu \bar{\nu}$ receives two sources of contributions. One is from the SM and the other is from the unparticle mediation. In the SM, the relevant effective Hamiltonian is\[1\]

$$\mathcal{H}_{\text{eff}} = \frac{G_{F}}{\sqrt{2}} \frac{\alpha}{2\pi \sin^{2}\theta_{W}} \sum_{l=e,\mu,\tau} \left[V_{cs}^{*}V_{cd}X_{NL}^l + V_{ts}^{*}V_{td}X(x_{t})\right](\bar{s}d)v_{A}(\bar{\nu}_{l}\nu_{l})v_{A}. $$

(12)
The index \( l = e, \mu, \tau \) denotes the lepton flavor. We have taken the functions \( X, X_{NL}^l \) and the coefficients following [1, 72]. The hadronic amplitude is

\[
A_{\text{eff}}^{SM} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2 \pi} \sin^2 \theta_W \sum_{l=e,\mu,\tau} \left[ V_{cs}^* V_{cd} X_{NL}^l + V_{ts}^* V_{td} X(x_l) \right] \\
\times \left( f_+(q^2)(k+p)_\mu + f_-(q^2)(k-p)_\mu \right) (\bar{\nu}_l \nu_l)_{V-A},
\]

where \( q^2 = (k-p)^2 \), and \( f_\pm(q^2) \) are the form factors [73, 74]. The differential decay width, where \( E_\pi \) is the pion energy in the rest frame of the decaying kaon, reads

\[
d\Gamma_{\text{SM}}^{SM} = \frac{G_F^2}{4} \frac{\alpha^2 \lambda}{(2\pi)^5 \sin^4 \theta_W M_K^2} \sum_{l=e,\mu,\tau} \left[ V_{cs}^* V_{cd} X_{NL}^l + V_{ts}^* V_{td} X(x_l) \right]^2 \\
\times f_+^2 \left[ (m_K^2 - m_\pi^2 - q^2)^2 - 2m_\pi^2 q^2 - \frac{2}{q^2} \left( \frac{\lambda^2}{3} + m_\pi^2 q^2 \right) \right],
\]

where

\[
m_\pi \leq E_\pi \leq (m_K^2 + m_\pi^2)/2m_K, \quad \lambda = [(m_K^2 + m_\pi^2 - q^2)^2 - 4m_K^2 m_\pi^2]^{1/2}.
\]

In the presence of the unparticle, the vector unparticle can also mediate \( K^+ \to \pi^+ + \nu \bar{\nu} \) if we introduce the neutrino-unparticle couplings analogue to the quark-unparticle couplings of [2]. This couplings may conserve flavor,

\[
c^l_V (\bar{\nu}_l \nu_l)_{V-A} \mathcal{O}_U^\mu, \quad (16)
\]

the effective interactions of the vector unparticle mediation can be written as

\[
\Delta \mathcal{H}_{\text{eff}}^V = c^q_V c^l_V A_{dU} (-p_d^{2})^{d_d U - 2} \sum_{l=e,\mu,\tau} (s_d)_{V-A} (\bar{\nu}_l \nu_l)_{V-A}.
\]

The more general case that the lepton numbers are also violated are too complicated to be considered here. It is easy to see that the scalar unparticle couplings

\[
c^S_V (\bar{\nu}_l \nu_l)_{V-A} \partial^\mu \mathcal{O}_U
\]

do not contribute, as the neutrinos are taken as massless.

In this way, we have more four-fermion interactions which are different from the SM four-fermion interactions by the dependence on the momentum transfer. It also has a imaginary part because of the \((-1)^{d_d U}\), which could induce CP violation [7]. At the hadronic level we have the amplitude modified as

\[
\Delta A_{\text{eff}}^V = c^q_V c^l_V A_{dU} (-p_d^{2})^{d_d U - 2} \sum_{l=e,\mu,\tau} \left( f_+(q^2)(k+p)_\mu + f_-(q^2)(k-p)_\mu \right) (\bar{\nu}_l \nu_l)_{V-A}.
\]

Here, \( p_d^2 = q^2 \).
The total differential width for $K^+ \rightarrow \pi^+ + \nu \bar{\nu}$ including the SM and the vector unparticle contributions is

$$\frac{d\Gamma^{\nu \bar{\nu}}}{dE_\pi} = \frac{\lambda}{2(2\pi)^3 M_K^2} \sum_{i=e,\mu,\tau} \left| \left\{ \frac{G_F}{\sqrt{2} \pi} \frac{\alpha}{\sin^2 \theta_W} \left[ V_{cs}^* V_{cd} X_{NL}^e + V_{ts}^* V_{td} X(x_l) \right] + \left( \frac{\epsilon_i^e \epsilon_i^d A_{dU}}{2 \sin(\theta_W)} \right)^2 \right\} \right|^2 \times f_+^2 \left\{ (m_K^2 - m_\pi^2 - q^2)^2 - 2q^2 m_\pi^2 - \frac{2}{q^2} \left( \frac{\lambda^2}{3} + m_\pi q^2 \right) \right\}.$$

(19)

We take the parameters used in (12) as

$$V_{cs}^* V_{cd} = -0.22006^{+0.00093}_{-0.00091}, \quad V_{ts}^* V_{td} = (-3.13^{+0.20}_{-0.17} + i1.407^{+0.096}_{-0.096}) \times 10^{-4}, \quad |V_{us}| = 0.2248.$$

$$P_c = \frac{1}{|V_{us}|^4} \left[ \frac{2}{3} X_{NL}^e + \frac{1}{3} X_{NL}^\tau \right] = 0.375 \pm 0.024, \quad X(x_l) = 1.464 \pm 0.041.,$$

$$\alpha = 1/129, \quad \cos(\theta_W) = 0.8817$$

(20)

We take the formfactors as

$$f_+(q^2) = f_+(0)[1 + \lambda(q^2/m_\pi^2)], \quad f_-(q^2) = -0.332,$$

(21)

where $\lambda = 2.96 \times 10^{-2}$ and take $f_+(0) = 0.57$. We assume this choice of form factors to be valid for the unparticle processes. To the next-to-to leading logarithm approximation in the SM,

$$B_{SM}(K^+ \rightarrow \pi^+ + \nu \bar{\nu}) = (8.0 \pm 1.1) \times 10^{-11}.$$

(22)

4

The process $K^+ \rightarrow \pi^+ + \text{Missing Energy}$ may contain $\nu \bar{\nu}$ or $U$ in the final state. The decay width is

$$\frac{d\Gamma(K^+ \rightarrow \pi^+ E)}{dE_\pi} = \frac{d\Gamma^{\nu \bar{\nu}}}{dE_\pi} + \frac{d\Gamma^U}{dE_\pi},$$

(23)

where $d\Gamma^{\nu \bar{\nu}}/dE_\pi$ contains the SM and the (vector) unparticle contributions of (19). The decay width (23) is constrained by the experiments. The E787 and E949 Collaborations at Brookhaven give

$$B_{exp}(K^+ \rightarrow \pi^+ E) = (14.7^{+13.0}_{-8.9}) \times 10^{-11}.$$  

(24)

We now comment on the couplings of the unparticles in (7) and in (16). On the one hand, the couplings $c^a$'s in (7) are flavor changing while $c^l$'s in (16) are flavor conserving. If the Unparticle Model followed a GIM-like mechanism of the SM for the flavor changing neutral interactions, the $c^l$'s in (16) could be much larger than the $c^a$'s in (7). Even if the $c^l$'s are much smaller than the gauge couplings in the SM, the effect of interference between
the amplitudes of the SM and the vector unparticle mediation might be comparable to the \( \Gamma_U \).

On the other hand, in case that the couplings \( c_l \)'s are not much larger than the \( c_q \)'s, the contribution of the vector unparticle mediation is negligible in the process \( K^+ \to \pi^+ + \text{Missing Energy} \). The contribution \( \Gamma_U \) can even dominate over \( \Gamma_{\nu \bar{\nu}} \) in the extreme case.

### 4.1

In this part, we study the effects of the scalar unparticle in \( K^+ \to \pi^+ + \nu \bar{\nu} \) and \( K^+ \to \pi^+ + U \). There is no mediation effect for the scalar unparticle in \( K^+ \to \pi^+ + \nu \bar{\nu} \). The scalar unparticle acts only as Missing Energy in the final state. We plot in Fig. 1 the dependence of the branching ratio \( K^+ \to \pi^+ \bar{E} \) on the \( d_U \), and in Fig. 2 the dependence on the coupling \( c_S^q \).

**Figure 1:** Branching ratio versus \( d_U \) for \( K^+ \to \pi^+ \bar{E} \) in the scalar unparticle model, with \( c_S^q = 1 \times 10^{-17}, 1 \times 10^{-16}, 1 \times 10^{-15} \) and \( 1 \times 10^{-14} \). The dash-length increases with \( c_S^q \). The horizontal lines represent the experimental bounds.

**Figure 2:** Branching ratio versus \( c_S^q \) \( K^+ \to \pi^+ \bar{E} \) in the scalar unparticle model, where \( d_U = 1.1, 1.3, 1.5 \), and 1.7. The dash-length increases with \( d_U \).
We find that, if $d_U = 1$, no contribution from the unparticle will reveal. The unparticle contribution goes up with $d_U$ and will dominate over the SM contribution. To fulfill the data, the scalar unparticle can have a large coupling $c_q^S$ for a small $d_U$, while the coupling is constrained for a large $d_U$.

![Figure 3](image1.png)

**Figure 3:** The energy spectrum for the charged $\pi$ in the scalar unparticle model, with $d_U = 1.5$, $c_q^S = 1 \times 10^{-15}$ with dash. The solid line represents the SM result.

We also plot in Fig. 3 the energy spectrum of the charged $\pi$. Note that apart from the soft $\pi$ region, the energy spectrum is much like the energy spectrum in the SM with a different number of neutrino spices.

### 4.2

The vector unparticle not only acts as the Missing Energy in the final state, but also mediates $K^+ \rightarrow \pi^+ + \nu\bar{\nu}$. There are numerous combinations of $c_q^V$, $c_l^V$ and $d_U$ which accord with experiment.

![Figure 4](image2.png)

**Figure 4:** Branching ratio versus $c_q^V$ in the vector unparticle model with $d_U=1.1, 1.3, 1.5, 1.7$ and $1.9$. The dash-length increasess with $d_U$. The unparticle mediation effect is neglected.
When the couplings $c^l$'s are not very large, the mediation effects are negligible. We plot in Fig. 4 the dependence of the branching ratio $K^+ \to \pi^+ E$ on the coupling $c^q_V$. The constraint on the coupling get stronger when $d_U$ increases. We get roughly $c^q_V \leq 10^{-13}\text{MeV}^{-d_U}$ in order to fit the experiments.

If the couplings $c^l$'s are large, the SM and the unparticle contributions interfere in $K^+ \to \pi^+ \nu \bar{\nu}$. The interference can be either constructive or destructive, depending on the number $d_U$ and the couplings. We plot the dependence of the total branching ratio $K^+ \to \pi^+ E$ on $d_U$ in Fig. 5 for $c^l_V = -0.01$, and in Fig. 6 for $c^l_V = 0.01$. The branching ratio becomes extremely large when $d_U$ approaching 2 or 3. When $d_U$ approaches 2 or 3 the couplings $c^q_V$ and $c^l_V$ are constrained strongly.

![Figure 5: Branching ratio versus $d_U$ in the vector unparticle model with $c^l_V = -0.01$. Here $c^q_V = 1 \times 10^{-15}$ for the shortest dash-length, $c^q_V = 4 \times 10^{-14}$ for the middle dash-length, and $c^q_V = 1 \times 10^{-13}$ for the longest dash-length.](image)

![Figure 6: Same as in Fig. 5 except $c^l_V = 0.01$.](image)

In Fig. 7 and Fig. 8 we show the dependence of the branching ratio on the coupling $c^q_V$ for a very large value of $c^l_V$ ($\mp -0.05$). We can find that the vector unparticle contribution
can be dominant in both destructive and constructive cases, if \( d_U \) is large enough.

\[
B(K^+ \rightarrow \pi^+ \! + \! E) \quad \text{versus} \quad c^q_V
\]

**Figure 7:** Branching ratio versus \( c^q_V \) in the vector unparticle model with \( c^l_V = -0.05 \) and \( d_U = 1.1, 1.5, 1.7, 1.8 \) and 1.9. The dash-length increase with \( d_U \).

\[
B(K^+ \rightarrow \pi^+ \! + \! E) \quad \text{versus} \quad c^q_V
\]

**Figure 8:** Same as in Fig. 7 except \( c^l_V = 0.05 \).

The energy spectra for the charged \( \pi \) are depicted in Fig. 9 and Fig. 10 for the negative and positive values of \( c^l_V \)'s, respectively. We find that for large \( c^l_V \)'s, the spectra can be quite different from the SM spectrum in the region when the \( p\ell \)'s are hard. The spectrum is even much different from that in the scalar unparticle model, due to the much complicated mediation of the vector unparticle. If the difference in spectrum were found in the future experiments, it would be clear signature as evidence of the vector unparticle model.

5 Conclusion

In this paper we have discussed the process \( K^+ \rightarrow \pi^+ \! + \! \text{Missing Energy} \) in the unparticle models. We find that both the branching ratio and the spectrum can be very different
Figure 9: The energy spectra for the charged π in the vector unparticle model. $d_U = 1.3$, $c^q_V = 6.6 \times 10^{-14}$, $c^l_V = -0.05$ for the shortest dash-length, $d_U = 1.8$, $c^q_V = 5.0 \times 10^{-15}$, $c^l_V = -0.05$ for the middle dash-length, $d_U = 2.3$, $c^q_V = 1.0 \times 10^{-15}$, $c^l_V = -0.08$ for the longest dash-length. The solid line represents the SM spectrum.

Figure 10: Same as in Fig.9 except $c^l_V$’s are positive.

from the SM predictions. Especially an vector unparticle model can bring some complicated interference into the amplitude with the SM one.

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