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Decay of Z boson into photon and unparticle

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Abstract

We study the decay of the standard model Z boson into unparticle plus a single photon through a one-loop process. As in the anomaly type decay, only the axial-vector part of the Z coupling matching with the vector unparticle and/or the vector part of the Z coupling matching with the axial-vector unparticle can give a nonzero contribution to the decay. We show that the photon spectrum terminates at the end point in accord with Yang's theorem. Existing data on single photon production at LEP I is used to constrain the unparticle sector.

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1. Introduction

It is well known that the Poincaré symmetry group can be enlarged to the group of conformal symmetry in any number of spacetime dimension D. From the structure of the conformal algebra we learn that conformal symmetry implies scale invariance, while scale invariance in general does not necessarily imply conformal symmetry. It is widely believed that a local quantum field theory that is scale invariant will also be conformal invariant for any D. Although a formal proof is still lacking, no counterexample has been found. For $D = 2$ it was first conjectured in [1] and later shown in [2] that scale invariance does imply conformal symmetry under broad conditions.[1] One of the most important consequences of scale invariance is that the single particle state must be either massless or have a continuous mass spectrum. An obvious example for the former case is pure QED, where the photon is exactly massless. Minimal coupling of the photon to charged particles in a gauge invariant fashion guarantees the photon remains massless to all orders in the perturbation series. However, particles with continuous mass distributions have been largely ignored in particle physics due to lack of experimental evidence.

Recently, an interesting physical possibility for scale invariant stuff with continuous mass distribution was pointed out by Georgi [4], who coined the term unparticle[2] to describe a possible scale-invariant hidden sector sitting at an infrared fixed point at a high scale $\Lambda_{\mathcal{U}}$. If the hidden sector carries Standard Model (SM) quantum numbers, it would be highly constrained by existing experimental data. In Georgi's scheme [4], the hidden sector communicates with the SM content via a messenger sector characterized by a high mass scale M. At energy below M, one can integrate out the messenger sector and end up with the effective operator suppressed by inverse powers of M of the following form

$$\frac{1}{M^{d_{\rm SM}+d_{\rm UV}-4}}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm UV}, \tag{1}$$

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[1] However, a counterexample in the two-dimensional theory of elasticity without unitarity was demonstrated in [3].

[2] We use the term "unparticle" as an uncountable noun, so just like water, it has no distinct plural.

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where $\mathcal{O}_{\rm SM}$ and $\mathcal{O}_{\rm UV}$ represent local operators of the SM and hidden sector with scaling dimensions $d_{\rm SM}$ and $d_{\rm UV}$, respectively. As one scales down the theory from M, the hidden sector may flow to an infrared fixed point at the scale $\Lambda_{\mathcal{U}}$ which, for example, can be generated by quantum effects via dimensional transmutation. At the fixed point where the hidden sector becomes scale invariant, the above operator (1) has to be replaced by a new set of operators of similar form

$$C_{\mathcal{O}_{\mathcal{U}}}\frac{\Lambda_{\mathcal{U}}^{d_{\rm UV}-d_{\mathcal{U}}}}{M^{d_{\rm SM}+d_{\rm UV}-4}}\mathcal{O}_{\rm SM}\mathcal{O}_{\mathcal{U}}, \tag{2}$$

where $\mathcal{O}_{\mathcal{U}}$ is the unparticle operator with a scaling dimension $d_{\mathcal{U}}$ and $C_{\mathcal{O}_{\mathcal{U}}}$ is the unknown coefficient. Because the underlying theory is a scale invariant interacting theory, the scaling dimension $d_{\mathcal{U}}$ need not have a canonical value of integer or half-integer, unlike the free boson or free fermion cases. The unparticle operator $\mathcal{O}_{\mathcal{U}}$ can be characterized as scalar, vector, tensor, spinor, etc., according to its Lorentz group representation. One prototype [4] hidden sector that can give rise to unparticle is the weakly interacting Banks–Zaks [5] theory. Another possibility is the strongly interacting magnetic phase of certain supersymmetric QCD theories [6], as pointed out in [7]. A third possibility would be the hidden valleys model which can be viewed as an unparticle sector with a large mass gap [8].

Even though the scale invariant sector remains unspecified, the 2-point function [4] and the Feynman propagator [9,10] of the unparticle field operator $\mathcal{O}_{\mathcal{U}}$ can be determined by scale invariance. We note if special *conformal invariance* is imposed it is shown in a recent paper [11] that the form of vector and tensor unparticle propagators should be modified. Consequently, the polarization sum of the vector and tensor unparticle have to be modified as well. However, the new form of the polarization sum does not allow one to impose transversality of the vector unparticle unless the scaling dimension $d_{\mathcal{U}}$ equals to 3. Many groups have pursued phenomenological studies of unparticle physics [4,7–83], while more theoretical aspects of unparticle were explored by others [84–91]. Unparticle does not have a fixed invariant mass, but instead has a continuous mass spectrum. Thus, like a massless particle, the unparticle has no rest frame. This implies that real unparticle is stable and cannot decay. Direct signals of unparticle can nevertheless be detected in the missing energy and momentum distributions carried away by the unparticle once it is produced in a process [4], while virtual unparticle effects can be probed via interference with SM amplitudes [9,10].

In a previous note [73], Li and two of us studied the decay of a SM Higgs (H) into vector unparticle plus a single photon. We showed that the photon energy spectrum for the process is continuously smeared out near its end point and its branching ratio is comparable to that of the discovery mode of $H\to\gamma\gamma$ for an intermediate mass Higgs. In this note, we study the rare decay of the Z boson into unparticle plus a single photon, $Z\to\mathcal{U}\gamma$, via a triangular loop of SM fermions.[3] As in the Higgs decay, the energy spectrum of the photon would have been monochromatic had the unparticle had a fixed mass. However, due to the nature of the continuous mass spectrum of the unparticle, the resultant photon energy spectrum is also continuous and the shape depends sensitively on the scaling dimension $d_{\mathcal{U}}$. But unlike the case of $H\to\mathcal{U}\gamma$, and many other previously studied cases, the end point of the photon energy spectrum in the decay $Z\to\mathcal{U}\gamma$ goes to zero as governed by Yang's theorem.

[3] The decay of Z boson into photon plus a scalar unparticle was considered in [31].

2. Decay rate of $Z\to\mathcal{U}\gamma$

The interaction of spin-1 unparticle $\mathcal{U}$ with a SM fermion f can be parameterized by a term in the effective Lagrangian [4, 10]

$$\mathcal{L}_{\rm eff}\ni\frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}\bar f\left(\lambda_1^f\gamma_\mu-\lambda_1'^f\gamma_\mu\gamma_5\right)f\,O_{\mathcal{U}}^\mu \tag{3}$$

where λ_1^f and $\lambda_1'^f$ are the unknown vector and axial-vector couplings. Here we assume the transversality of unparticle operator $\partial_\mu O_{\mathcal{U}}^\mu=0$ is satisfied and $O_{\mathcal{U}}^\mu$ has both vector and axial-vector couplings to the SM fermions. The process $Z\to\mathcal{U}\gamma$ is induced at one-loop level with the standard model fermions circling in a triangle loop diagram. The photon always has vector-type interactions with SM fermions. Possible types of interactions for the Z–$\mathcal{U}$–γ vertex are either AVV or VAV, where $V(A)$ denotes vector (axial-vector) interaction. The other two possibilities of VVV and AAV vanish due to Furry's theorem. Note that the vector couplings of the Z boson are much smaller than the axial-vector couplings (at least true for u, d and e), but we consider both types of couplings for the Z–$\mathcal{U}$–γ vertex.

The amplitude square for $Z\to\mathcal{U}\gamma$ can be adapted from an earlier calculation in a different context [92]

$$\sum_{\rm pol}|\mathcal{M}|^2=\frac{1}{2\pi^4}z(1-z)^2(1+z)|\mathcal{A}|^2m_Z^2, \tag{4}$$

where $z=P_{\mathcal{U}}^2/m_Z^2$. The loop amplitude $\mathcal{A}$ is given by

$$\mathcal{A}=-\frac{e^2}{\sin\theta_{\rm w}\cos\theta_{\rm w}}\frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}\times\sum_f N_C^fQ_f\left(g_A^f\lambda_1^f+g_V^f\lambda_1'^f\right)\mathcal{I}(z,\eta_f), \tag{5}$$

where the color factor $N_C^f=3(1)$ for f being a quark (lepton), $g_V^f=T_{3f}/2-Q_f\sin^2\theta_{\rm w}$ and $g_A^f=T_{3f}/2$ are the vector and the axial-vector couplings of the Z boson to the fermion f, respectively, Q_f is the electric charge of the fermion f and $\eta_f=m_f^2/m_Z^2$. The loop function $\mathcal{I}(z,\eta)$ is given by

$$\mathcal{I}(z,\eta)=\frac{1}{1-z}\left\{\frac12+\frac{\eta}{1-z}\left[F(\eta)-F\left(\frac{\eta}{z}\right)\right]-\frac{1}{2(1-z)}\left[G(\eta)-G\left(\frac{\eta}{z}\right)\right]\right\}, \tag{6}$$

where

$$F(x)=\begin{cases}-2\left(\sin^{-1}\sqrt{\frac{1}{4x}}\right)^2 & \text{for } x\geqslant\frac14,\\ \frac12\left(\ln\frac{x^+}{x^-}\right)^2-\frac{\pi^2}{2}-i\pi\ln\frac{x^+}{x^-} & \text{for } x<\frac14,\end{cases}$$

and

$$G(x)=\begin{cases}2\sqrt{4x-1}\sin^{-1}\sqrt{\frac{1}{4x}} & \text{for } x\geqslant\frac{1}{4},\\ \sqrt{1-4x}(\ln\frac{x^+}{x^-}-i\pi) & \text{for } x<\frac{1}{4},\end{cases}$$

with

$$x^{\pm}=\frac{1}{2}\pm\sqrt{\frac{1}{4}-x}.$$

The amplitude square vanishes in the limit $z\to 0$ as governed by Yang's theorem.

The differential decay width for $Z\to\mathcal{U}\gamma$ is

$$d\Gamma=\frac{1}{2m_Z}\overline{\sum}|\mathcal{M}|^2\,d\Phi, \tag{7}$$

where $\overline{\sum}|\mathcal{M}|^2=\frac{1}{3}\sum_{\rm pol}|\mathcal{M}|^2$ and the phase space factor $d\Phi$ is

$$d\Phi=\frac{A_{d_\mathcal{U}}}{16\pi^2}\left(m_Z^2\right)^{d_\mathcal{U}-1}z^{d_\mathcal{U}-2}(1-z)\,dz \tag{8}$$

with

$$A_{d_\mathcal{U}}=\frac{16\pi^{5/2}}{(2\pi)^{2d_\mathcal{U}}}\frac{\Gamma(d_\mathcal{U}+\frac{1}{2})}{\Gamma(d_\mathcal{U}-1)\Gamma(2d_\mathcal{U})}. \tag{9}$$

Collecting all the pieces, we have

$$\frac{d\Gamma}{dz}=\frac{e^4}{192\pi^6\sin^2\theta_{\rm w}\cos^2\theta_{\rm w}}A_{d_\mathcal{U}}m_Z\left(\frac{m_Z^2}{\Lambda_\mathcal{U}^2}\right)^{d_\mathcal{U}-1}\times\left|\sum_f N_C^f Q_f\left(g_A^f\lambda_1^f+g_V^f\lambda_1'^f\right)\mathcal{I}(z,\eta_f)\right|^2\times z^{d_\mathcal{U}-1}(1-z)^3(1+z). \tag{10}$$

Integrating the above expression over z from 0 to 1, we obtain the partial width of the channel $Z\to\mathcal{U}\gamma$.

3. Numerical results

If we ignore the fermion masses as we take $z\to 0$, then the relevant factor in Eq. (10) scales as $z^{d_\mathcal{U}-1}(1+\ln z)$, where the factor $(1+\ln z)$ comes from $\mathcal{I}(z,0)$ [92]:

$$\mathcal{I}(z,0)=\frac{1}{2(1-z)}\left(1+\frac{\ln(z)}{1-z}\right). \tag{11}$$

The photon energy E_γ is given by $m_Z(1-z)/2$. At $z=0$, the photon energy reaches its end point and the unparticle behaves like a massless particle. Thus, as long as $d_\mathcal{U}>1$ the photon energy spectrum vanishes at $z=0$ in accord with Yang's theorem. It is worth mentioned that since λ_1^f and $\lambda_1'^f$ are viewed as effective couplings in Georgi's scheme, the following combination

$$\sum_f N_C^f Q_f\left(g_A^f\lambda_1^f+g_V^f\lambda_1'^f\right) \tag{12}$$

needs not vanish when summed over SM fermions in contrast with the anomaly-induced decay of $Z'\to Z\gamma$ in E_6 models studied in [92]. In Fig. 1, we plot the spectrum $d\Gamma/dz$, where $z=P_\mathcal{U}^2/m_Z^2$, for a range of $d_\mathcal{U}=1.1$–2.0 (from top to bottom)

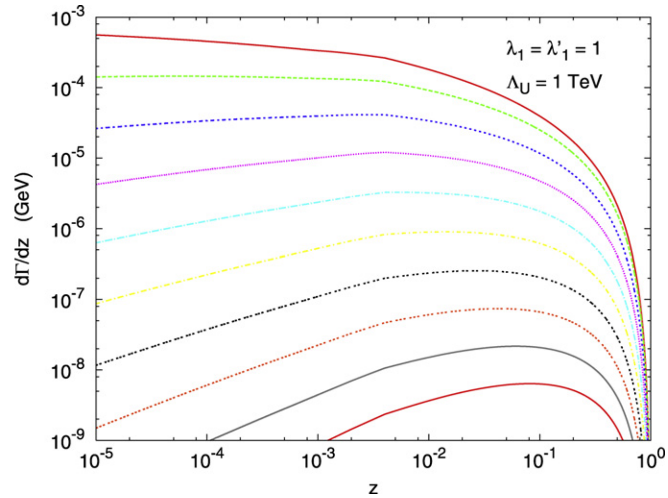

Fig. 1. Spectrum $d\Gamma(Z\to\mathcal{U}\gamma)/dz$, where $z=P_\mathcal{U}^2/m_Z^2$, with $\lambda_1^f=\lambda_1'^f=1$ and $\Lambda_\mathcal{U}=1$ TeV for $d_\mathcal{U}=1.1$–2.0 (from top to bottom).

Table 1
Partial width of $\Gamma(Z\to\mathcal{U}\gamma)$ for $\lambda_1^f=\lambda_1'^f=1$ and $\Lambda_\mathcal{U}=1$ TeV for $d_\mathcal{U}=1.1$–2.0

$d_\mathcal{U}$	$\Gamma(Z\to\mathcal{U}\gamma)$ (GeV)
1.1	1.4×10^{-5}
1.2	8.5×10^{-6}
1.3	3.8×10^{-6}
1.4	1.5×10^{-6}
1.5	5.5×10^{-7}
1.6	1.9×10^{-7}
1.7	6.5×10^{-8}
1.8	2.2×10^{-8}
1.9	7.0×10^{-9}
2.0	2.3×10^{-9}

with the democratic assumption of $\lambda_1^f=\lambda_1'^f=1$ for all SM fermions and $\Lambda_\mathcal{U}$ is set to be 1 TeV. In Table 1, the partial width for $Z\to\mathcal{U}\gamma$ is tabulated with the same input parameters. The partial width is only sizable for $d_\mathcal{U}\leqslant 1.4$.

On the other hand, as the fermion mass inside the loop becomes infinitely heavy, one has the following expansion for the loop function $\mathcal{I}(z,\eta)$ valid for $\eta\to\infty$,

$$\mathcal{I}(z,\eta)\approx\frac{1}{24\eta}+\frac{(1+2z)}{360\eta^2}. \tag{13}$$

Thus the loop amplitude $\mathcal{A}$ in Eq. (5) is vanishingly small and the heavy fermion decouples in this limit unlike the cases in the Higgs decay of $H\to\gamma\gamma$, $Z\gamma$ and $\mathcal{U}\gamma$.

Experimental searches for $e^-e^+\to\gamma X$, where X represents a weakly interacting stable particle, have been performed at the Z resonance [93]. No signal was found, and the 95% C.L. upper limit on the branching ratio is [93]

$$B(Z\to\gamma X)\leqslant 1\text{–}3\times10^{-6}, \tag{14}$$

who's range depends on $E_{\rm min}$, the minimum energy cut of the photon. For $E_{\rm min}$ between 30 GeV and $m_Z/2$, the branching ratio upper limit is roughly a constant of about 1×10^{-6}. It is clear from Fig. 1 that in $Z\to\mathcal{U}\gamma$, most contributions come from the region where $E_\gamma\geqslant 30$ GeV. Therefore, we use the

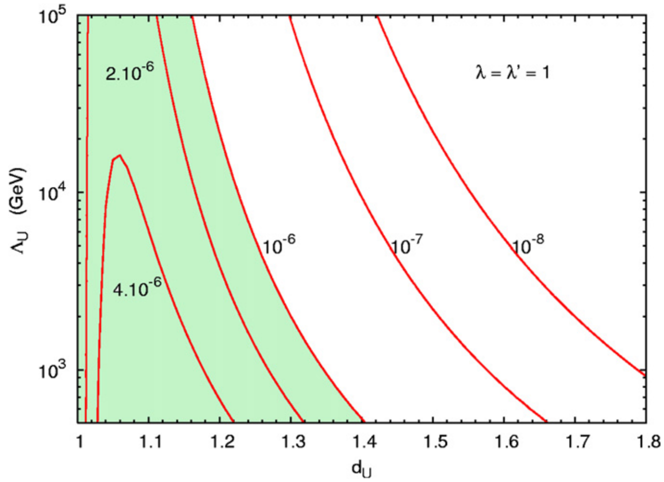

Fig. 2. Contour plot for the branching ratio $B(Z \to \mathcal{U}\gamma)$ versus $(d_{\mathcal{U}}, \Lambda_{\mathcal{U}})$ with $\lambda_1^f = \lambda_1'^f = 1$. The shaded region to the left of the contour 10^{-6} is ruled out by the 95% C.L. upper limit on $B(Z \to \gamma X) < 1 \times 10^{-6}$.

limit $B(Z \to \mathcal{U}\gamma) < 1 \times 10^{-6}$ to constrain the unparticle parameter space. In Fig. 2, we plot the contour of the branching ratio for $Z \to \mathcal{U}\gamma$ as a function of $d_{\mathcal{U}}$ and $\Lambda_{\mathcal{U}}$ assuming democratically as before that $\lambda_1^f = \lambda_1'^f = 1$ for all SM fermions. One sees that existing limits from LEP I can already place useful constraints on the hidden unparticle sector.

To recap, we have studied the rare decay of the Z boson into a single photon plus unparticle that has both vector and axial-vector couplings to the SM fermions. Existing limits from LEP I were used to constrain the parameters of the hidden unparticle sector associated with vector and/or axial-vector unparticle. Despite having a peculiar photon energy distribution in this 2-body decay, the branching ratio is rather minuscule and at best of the order of 10^{-6} for small scaling dimension $d_{\mathcal{U}} \leqslant 1.4$. For larger scaling dimension, the branching ratio is at least smaller by two orders of magnitude. Unless one can collect a very large sample of Z boson, detection of the unparticle through this mode would be quite challenging.There have been discussions on the Giga-Z option at the future linear collider [94], where the beam energies can be run at the Z pole. In a relatively short period of time a total of 10^9 Z's can be accumulated. With such a large number of Z's a branching ratio as low as 10^{-8} for $Z \to \gamma\mathcal{U}$ can be tested. It can be read from Fig. 2 that a large portion of the parameter space can be further tested at the Giga-Z.

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