Communications in Physics, Vol. 36, No. 1 (2026), pp. 1-8
DOI: https://doi.org/10.15625/0868-3166/23939

Unparticle effects on dark matter production from photon and axion-like

Ha Huy Bang[1] **and Truong Minh Anh**[2,†]

[1]*Faculty of Physics, VNU University of Science,*
Vietnam National University, Hanoi, 334 Nguyen Trai Street, Thanh Xuan Ward, Hanoi, Vietnam
[2]*Faculty of Engineering Physics, Hanoi University of Science and Technology,*
1 Dai Co Viet Street, Hanoi, Vietnam

E-mail: [†]anh.truongminh@hust.edu.vn

Received 11 December 2025
Accepted for publication 29 December 2025
Published 5 March 2026

Abstract. *In this work, we study the effects of vector unparticle on the* $a\gamma \to \chi\bar{\chi}$ *process, where* χ *is a dark matter fermion. Our numerical results show that the cross-section takes values from* 8.23×10^{-15} *barn to* 5.12×10^{-14} *barn. Consequently, the cross-section with unparticle effect should be about* 10^{26}–10^{28} *times larger that obtained via pure photon exchange. This enhancement could be important for searching for dark matter, as well as unparticle.*

Keywords: unparticle; axion-like; heavy axion-like particles.
Classification numbers: 95.35.+d; 12.60.-i; 14.80.-j.

1. Introduction

As is well known, Dark Matter (DM) makes up most of the mass of galaxies and galaxy clusters, and is responsible for the way galaxies are organized on grand scales. Fermion dark matter is a type of DM candidate made of spin–$1/2$ particles which are neutral under gauge interactions and possess gravitational effects but interact weakly with Standard Model particles. Therefore, it becomes very important to consider the interactions between DM and ordinary particles.

Noteworthy, unparticle physics were proposed by Howard Georgi [1] as a way to describe a scale invariant "hidden sector" that interacts with the Standard Model. Unlike ordinary particles, unparticles have a continuous mass spectrum rather than a discrete mass. They cannot be observed directly but must be inferred from their effects on Standard Model particles.

In the last few years, we have investigated unparticle effects on Bhabha scattering [2] and on axion-like particles production in e^+e^- collisions [3].

In this paper, we consider dark matter production from photon and axion-like via unparticle exchange.

2. The cross sections and the creations of dark matter from photon and axion-like via unparticle and photon exchange

The above-mentioned process is described by the Feynman diagram presented in Fig. 1.

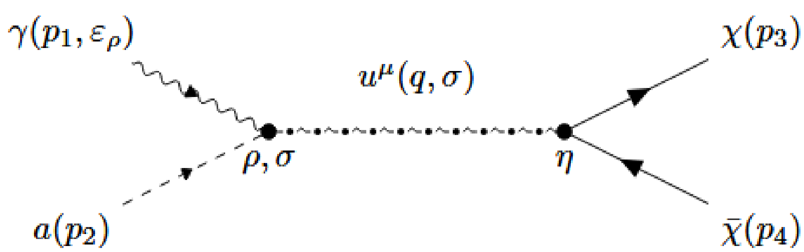

Fig. 1. The Feynman diagram for $a\gamma \to \chi\,\bar{\chi}$ process via radion.

The effective Lagrangian of describing photon (γ), axion-like (a) and dark matter fermion (m_χ) interaction is given by [4]

$$\mathscr{L}_{\text{int}} = \frac{C_3}{\Lambda_U^{d_u}}\,\phi_a F_{\mu\nu}\,\partial^\mu O_u^\nu + \frac{C_4}{\Lambda_U^{d_u}}\,\phi_a \tilde{F}_{\mu\nu}\,\partial^\mu O_u^\nu. \tag{1}$$

By setting

$$A = \frac{C_3}{\Lambda_U^{d_u}} \qquad B = \frac{C_4}{\Lambda_U^{d_u}}\,, \tag{2}$$

we get the interaction vertex of $\gamma(p_1,\rho) - a(p_2) - u(q,\sigma)$ as follows

$$A\left[-(p_1\cdot q)\,\delta_\sigma^\rho + p_{1\sigma}q^\rho\right] + B\,\varepsilon_{\sigma\mu\alpha\beta}\,p_1^\alpha g^{\rho\beta} q^\mu\,. \tag{3}$$

The amplitude for this process is

$$\begin{aligned} iM = \varepsilon_\rho &\left\{A\left[-(p_1\cdot q)\,\delta_\sigma^\rho + p_{1\sigma}q^\rho\right] + B\,\varepsilon_{\sigma\mu\alpha\beta}\,p_1^\alpha g^{\rho\beta} q^\mu\right\}\frac{iA_{d_u}}{2\sin(d_u\pi)}(-g^{\sigma\eta}) \\ &\times\left(-q^2 - i\varepsilon\right)^{d_u-2}\bar{u}(p_3)\left(C_1\gamma_\eta + C_2\gamma_\eta\gamma_5\right)\frac{1}{\Lambda_u^{d_u-1}}\,v(p_4)\,. \end{aligned} \tag{4}$$

Hence, we obtain the total squared amplitude

$$\begin{aligned} |M|^2 = -D^2\Big\{ & 4\Big[|A|^2\big(2(|C_1|^2+|C_2|^2)\big) + 2|B|^2\big(|C_1|^2-|C_2|^2\big)\Big]\big[(q\cdot p_1)(p_1\cdot p_3)(q\cdot p_4) \\ & + (q\cdot p_1)(p_1\cdot p_4)(q\cdot p_3)\big] - 12|A|^2|C_2|^2(q\cdot p_1)^2(p_3\cdot p_4) \\ & - 8\Big[|A|^2\big(|C_1|^2+|C_2|^2\big) + |B|^2\big(|C_1|^2-|C_2|^2\big)\Big]s(p_1\cdot p_3)(p_1\cdot p_4)\Big\}, \end{aligned} \tag{5}$$

here

$$D = \frac{-A_{d_u}}{2\sin(d_u\pi)}(-1)\left(-q^2 - i\varepsilon\right)^{d_u-2}\frac{1}{\Lambda_u^{d_u-1}}\,, \tag{6}$$

and

$$A_{d_u} = \frac{16\pi^2\sqrt{\pi}}{(2\pi)^{2d_u}}\,\frac{\Gamma\left(d_u+\frac{1}{2}\right)}{\Gamma(d_u-1)\,\Gamma(2d_u)}\,. \tag{7}$$

In the center of mass frame, four-momenta of particles are defined

$$p_1 = (E_1,\vec{p}), \qquad p_2 = (E_2,-\vec{p}), \qquad p_3 = (E,\vec{k}), \qquad p_4 = (E,-\vec{k}), \tag{8}$$

$$E_1 \simeq E, \qquad E_2 \simeq E, \tag{9}$$

and

$$s = (p_1+p_2)^2 = (p_3+p_4)^2 = q^2 = 4E^2, \tag{10}$$

$$|\vec{p}| = \frac{\sqrt{s}}{2}\sqrt{1-\frac{4m_a^2}{s}}, \qquad |\vec{k}| = \frac{\sqrt{s}}{2}\sqrt{1-\frac{4m_\chi^2}{s}}, \tag{11}$$

where s is the center of mass energy, m_a and m_χ are axion-like mass and DM fermion mass, respectively.

From these, we have

$$p_1\cdot p_2 = \frac{s}{2}\left(1-\frac{2m_a^2}{s}\right), \tag{12}$$

$$p_3\cdot p_4 = \frac{s}{2}\left(1-\frac{2m_\chi^2}{s}\right), \tag{13}$$

$$p_1\cdot p_3 = p_2\cdot p_4 = \frac{s}{4}\left[1-\sqrt{\left(1-\frac{4m_a^2}{s}\right)\left(1-\frac{4m_\chi^2}{s}\right)}\cos\theta\right], \tag{14}$$

$$p_1\cdot p_4 = p_2\cdot p_3 = \frac{s}{4}\left[1+\sqrt{\left(1-\frac{4m_a^2}{s}\right)\left(1-\frac{4m_\chi^2}{s}\right)}\cos\theta\right], \tag{15}$$

$$q\cdot p_1 = \frac{s}{2}\left(1-\frac{2m_a^2}{s}\right), \qquad q\cdot p_3 = q\cdot p_4 = \frac{s}{2}, \tag{16}$$

with θ is the angle between $\vec{p}$ and $\vec{k}$.

Finally, we get

$$|M|^2 = -D^2\,\frac{s^3}{2}\Bigg\{2\big(|A|^2+|B|^2\big)\big(|C_1|^2-|C_2|^2\big)\left(1-\frac{2m_a^2}{s}\right)+6|A|^2|C_2|^2\,\frac{m_\chi^2}{s} - \big[|A|^2\big(|C_1|^2+|C_2|^2\big)+|B|^2\big(|C_1|^2-|C_2|^2\big)\big] \times\left[1-\left(1-\frac{4m_a^2}{s}\right)\left(1-\frac{4m_\chi^2}{s}\right)\cos^2\theta\right]\Bigg\}. \tag{17}$$

From (17) we find the differential cross section

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\,\frac{|\vec{k}|}{|\vec{p}|}\,\overline{|M|^2} = \frac{1}{192\pi^2 s}\,\frac{\sqrt{1-\frac{4m_\chi^2}{s}}}{\sqrt{1-\frac{4m_a^2}{s}}}\,|M|^2, \tag{18}$$

where

$$\overline{|M|^2} = \frac{1}{3}|M|^2. \tag{19}$$

Next, we obtain the total cross section

$$\sigma = \frac{s^2}{384\pi}\,\frac{\sqrt{1-\frac{4m_\chi^2}{s}}}{\sqrt{1-\frac{4m_a^2}{s}}}\,\frac{A_{du}^2}{\sin^2(d_u\pi)}\,s^{2d_u-4}\,\frac{1}{\Lambda_u^{4d_u-2}} \times\Bigg\{\big[-|C_3|^2\big(2|C_1|^2+|C_2|^2\big)+2|C_4|^2\big(|C_1|^2-|C_2|^2\big)\big]\left(1-2\frac{m_a^2}{s}\right) +3|C_3|^2|C_2|^2\left(1-2\frac{m_a^2}{s}\right)\left(1-2\frac{m_\chi^2}{s}\right) +\big[|C_3|^2\big(|C_1|^2+|C_2|^2\big)+|C_4|^2\big(|C_1|^2-|C_2|^2\big)\big]\left[1-\frac{1}{3}\left(1-4\frac{m_a^2}{s}\right)\left(1-4\frac{m_\chi^2}{s}\right)\right]\Bigg\}. \tag{20}$$

Taking $C_1 = C_2 = 1/\sqrt{2}, C_3 = C_4 = 1$ as input parameters [5–7], we have

$$\sigma = \frac{s^2}{384\,\pi}\,\frac{\sqrt{1-\frac{4m_\chi^2}{s}}}{\sqrt{1-\frac{4m_a^2}{s}}}\,\frac{A_{d_U}^2}{\sin^2(d_U\,\pi)}\,s^{2d_U-4}\,\frac{1}{\Lambda_U^{4d_U-2}}\left(\frac{4m_a^2}{s}+\frac{m_\chi^2}{s}+2\,\frac{m_a^2}{s}\,\frac{m_\chi^2}{s}\right). \tag{21}$$

In the same way above mentioned, we have determined the interaction vertex of $\gamma(q_1,\rho) - \gamma(q_2,\sigma) - a(p)$ as follows

$$-\frac{1}{2}\,g_{a\gamma}\,\varepsilon_{\rho\sigma\mu\alpha}\,q_1^\mu q_2^\alpha. \tag{22}$$

Hence, we have found the total squared amplitude for the proccess $a\gamma \longrightarrow \chi\bar{\chi}$ via exchange of photon

$$|M_\gamma|^2 = \frac{1}{64} g_{a\gamma}^2 \left[\frac{s^2}{2}(\mu_\chi^2 - d_\chi^2) - \frac{s^2}{2}(\mu_\chi^2 - d_\chi^2)(1 - \frac{4m_\chi^2}{s}) \cos^2\theta + 4s m_\chi^2 d_\chi^2 \right], \tag{23}$$

where, μ_χ and d_χ correspond to the magnetic dipole moment and the electric dipole moment of the dark matter fermion χ. The total cross section for this process is

$$\sigma_\gamma = \frac{g_{a\gamma}^2}{9216\pi} \left[s(\mu_\chi^2 - d_\chi^2)\left(1 + \frac{2m_\chi^2}{s}\right) + 12 m_\chi^2 d_\chi^2 \right]. \tag{24}$$

3. Numerical results and discussion

Axion-like particles (ALPs) are hypothetical particles with a vast, largely unexplored mass range, from ultra-light (eV range) to heavy (GeV–TeV), constrained by experiments. Their mass dictates how they are searched for light ALPs via helioscopes, heavier ones via colliders, and astrophysical limits cover wide spans. Therefore, we choose a wide range of axion-like masses corresponding to the medium and heavy axion-like particles. Let us present the variation of the total cross-section σ as a function of $\sqrt{s}$ with axion-like mass $m_a = 300$ GeV (Fig. 2) and $m_a = 500$ GeV (Fig. 3).

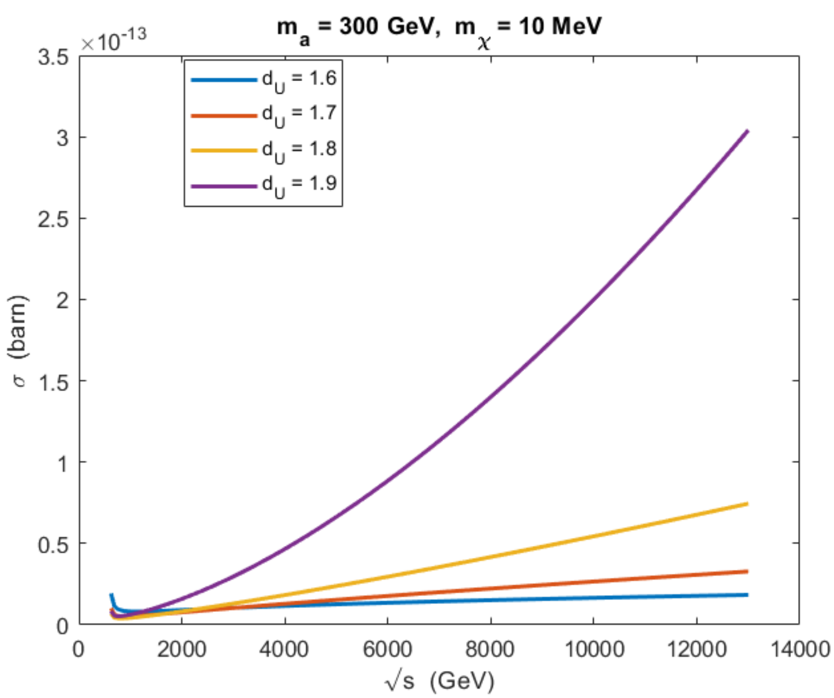

Fig. 2. (Color online) The total cross-section due to the unparticle contribution depending on the center of mass energy for $m_a = 300$ GeV. Here, we assume $m_\chi = 10$ MeV, $\Lambda_U = 1$ TeV and $d_U = 1.6,\ 1.7,\ 1.8,\ 1.9$.

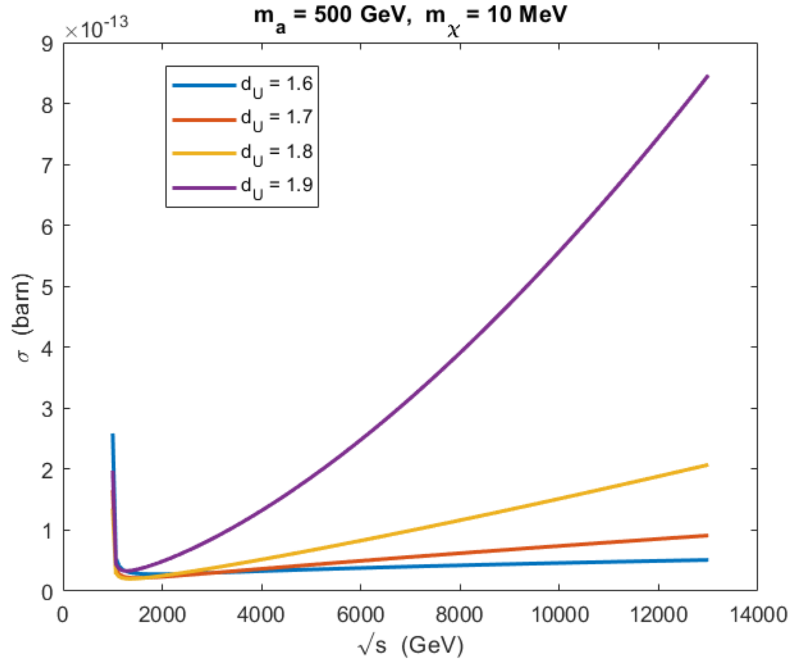

Fig. 3. (Color online) The total cross-section as a function of $\sqrt{s}$ for $m_a = 500$ GeV, $m_\chi = 10$ MeV, $\Lambda_U = 1$ TeV and $d_U = 1.6,\ 1.7,\ 1.8,\ 1.9$.

Table 1. The total cross-section with unparticle and photon effects, and their ratio σ/σ_γ at different energies for $m_a = 300$ GeV.

$\sqrt{s}$ (GeV)	σ (barn)	σ_γ (barn)	σ/σ_γ
1000	8.2304×10^{-15}	1.2906×10^{-43}	6.3774×10^{28}
2000	9.1075×10^{-15}	5.1622×10^{-43}	1.7643×10^{28}
3000	1.0428×10^{-14}	1.1615×10^{-42}	8.9785×10^{27}
4000	1.1595×10^{-14}	2.0649×10^{-42}	5.6154×10^{27}
5000	1.2625×10^{-14}	3.2264×10^{-42}	3.9132×10^{27}
6000	1.3550×10^{-14}	4.6672×10^{-42}	2.9046×10^{27}
7000	1.4393×10^{-14}	6.3273×10^{-42}	2.2762×10^{27}
8000	1.5169×10^{-14}	8.2596×10^{-42}	1.8366×10^{27}
9000	1.5892×10^{-14}	1.0454×10^{-41}	1.5202×10^{27}
10000	1.6569×10^{-14}	1.2492×10^{-41}	1.3269×10^{27}
11000	1.7207×10^{-14}	1.5166×10^{-41}	1.1019×10^{27}
12000	1.7813×10^{-14}	1.8548×10^{-41}	9.5848×10^{26}
13000	1.8389×10^{-14}	2.1810×10^{-41}	8.4311×10^{26}

As we can observe from Figs. 2 and Fig. 3, the cross-section σ strongly increases with increasing $\sqrt{s}$ for $d_U = 1.9$. In the cases of $d_U = 1.6,\ 1.7,\ 1.8$, the cross-sections much more weakly increase with $\sqrt{s}$.

Table 2. The total cross-section with unparticle and photon effects, and their ratio σ/σ_γ at different energies for $m_a = 500$ GeV.

$\sqrt{s}$ (GeV)	σ (barn)	σ_γ (barn)	σ/σ_γ
1000	–	1.2906×10^{-43}	–
2000	2.7867×10^{-14}	5.1622×10^{-43}	5.3982×10^{28}
3000	3.0104×10^{-14}	1.1615×10^{-42}	2.5919×10^{28}
4000	3.2889×10^{-14}	2.0649×10^{-42}	1.5927×10^{28}
5000	3.5535×10^{-14}	3.2264×10^{-42}	1.1014×10^{28}
6000	3.7978×10^{-14}	4.6460×10^{-42}	8.1753×10^{27}
7000	4.0351×10^{-14}	6.3237×10^{-42}	6.3643×10^{27}
8000	4.2351×10^{-14}	8.2596×10^{-42}	5.1275×10^{27}
9000	4.4320×10^{-14}	1.0454×10^{-41}	4.2397×10^{27}
10000	4.6173×10^{-14}	1.2942×10^{-41}	3.5778×10^{27}
11000	4.7925×10^{-14}	1.5166×10^{-41}	3.0690×10^{27}
12000	4.9590×10^{-14}	1.8588×10^{-41}	2.6684×10^{27}
13000	5.1177×10^{-14}	2.1810×10^{-41}	2.3464×10^{27}

Next, we give the numerical values of the total cross-section with unparticle and photon effects, and the ratio σ/σ_γ at different energies in the Tables 1, 2 for $m_a = 300$ GeV, $m_a = 500$ GeV, respectively. The input parameters are: $\Lambda_U = 1$ TeV, $g_{a\gamma} = 10^{-10}$ GeV^{-1}, $\mu_\chi = \frac{1}{8.4\times10^6}$ TeV^{-1}, $d_\chi = \frac{1}{8.7\times10^6}$ TeV^{-1}, $m_\chi = 10$ MeV, $d_U = 1.6$.

From numerical results, we have found that the cross sections are about 10-50 fb. Therefore, the effects of the unparticle on the cross-sections for the creation of heavy dark matter fermions from photon–axion-like can be very strong. If the measurement is carried out at $\sqrt{s} = 1$ TeV – 13 TeV then the σ for the process $a\gamma \to \chi\bar{\chi}$ should be detectable. Notably, if unparticle physics is disregarded, the cross-section of this process is very small. The above results show that the cross-section σ is larger than σ_γ by 26–28 orders of magnitudes. Therefore, the unparticle effect gives us hope that we can find dark matter from photon and axion-like.

4. Conclusion

Within the framework of the Standard Model, our process involving photon exchange, has a cross section of approximately 10^{-42}, which is very small. Hence, this process is undetectable. However, the situation is completely different in the same process, but through unparticle exchange. In summary, this paper shows that the interaction vertex of unparticle to photon–axion-like can give rise to observable signatures of DM fermions.

Along with recent papers on the creation of DM fermions in collisions [8,9] , our work may have important implications for dark matter searches at future colliders. Our work can be extended for other processes, for example, $e^+e^- \to \nu\bar{\nu}$ via the unparticle.

Conflict of interest

The authors have no conflict of interests to declare.

References

[1] H. Georgi, *Unparticle physics*, Phys. Rev. Lett. **98** (2007) 221601.

[2] S. T. L. Anh, H. H. Bang, N. T. Huong and T. Q. Trang, *Unparticle effects on bhabha scattering*, Can. J. Phys. **96** (2018) 268.

[3] S. T. L. Anh, H. H. Bang, N. T. Huong and T. Q. Trang, *Unparticle effects on axion-like particles production in e^+e^- collisions*, Int. J. Theor. Phys. **57** (2018) 2015.

[4] E. Izaguirre, T. Lin and B. Shuve, *A new flavor of searches for axion-like particles*, Phys. Rev. Lett. **118** (2017) 111802.

[5] S. Zhou, *Neutrino decays and neutrino–electron elastic scattering in unparticle physics*, Phys. Lett. B **659** (2008) 336.

[6] S.-X. Chen and R. Hu, *Unparticle effects on cosmic ray photon and $e^{\pm}$*, Journal of Cosmology and Astroparticle Physics **2009** (2009) 008.

[7] T. M. Aliev, S. Bilmis, M. Solmaz and I. Turan, *Scalar unparticle signals at the LHC*, Phys. Rev. D **95** (2017) 095005.

[8] A. Guha, J. Selvaganapathy and P. K. Das, *q-deformed statistics and the role of a light fermionic dark matter in the supernova SN1987A cooling*, Phys. Rev. D **95** (2017) 015001.

[9] W. Chao, J.-J. Feng and M.-J. Jin, *Direct detections of the axion-like particle revisited*, Phys. Rev. D **109** (2024) 075044.