

Comment on “Amplifying nonresonant production of dark sector particles in scattering dominance regime”

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In [M. Du *et al.*, [Phys. Rev. D **109**, 055041 (2024)]] it has been argued that production of dark photons—hypothetical massive vectors—in nuclear reactors via mixing with the visible photons is considerably enhanced (by a factor of 10) due to Compton scattering of the latter. We revisit the production of dark photons in the reactor environment and find that although the scattering of photons indeed leads to a larger number of produced dark photons, the overall enhancement is considerably smaller than what has been obtained in the above article. Our findings are validated using GEANT simulations, which take into account oscillations between ordinary and visible photons and interaction of the latter with matter. The correction to the limit on mixing parameter between dark and visible photons is expected to be below 30% for all masses. Its application must be accompanied with an update on the original spectrum of photons produced in nuclear reactions inside the nuclear reactor.

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1. Massive vector boson interacting with the Standard Model (SM) particles via mixing with photon (so-called vector portal) is predicted in many extensions of SM, providing with an interesting phenomenology being either a dark matter candidate or mediator to a hidden sector, see, e.g., [1] for a review. The relevant part of the model Lagrangian has the form [2]

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}X_{\mu\nu}^2 - \frac{\epsilon}{2}X_{\mu\nu}F^{\mu\nu} + \frac{m_X^2}{2}X_\mu^2 - eA_\mu j_{em}^\mu, \quad (1)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$ with A_μ and X_μ being the vector fields of visible (γ) and dark (X) photons, respectively. The former field interacts with the electromagnetic current j_{em}^μ ; m_X and $\epsilon \ll 1$ are model parameters.

Our subject is the production of a dark photon via its mixing with the ordinary photon [see Eq. (1)] in the medium. Specifically, we consider the hidden photon lighter than about 1 MeV. For this mass range the strongest of all bounds are the astrophysical ones, see, e.g., [3]. Still,

direct searches play an important role typically presenting more robust limits. In this respect searches for dark photons, emerged from a nuclear reactor [4–6], present an interesting avenue for these studies. Photons of energies $E \sim 1\text{--}10$ MeV, produced abundantly in the reactor core, can oscillate to dark photons if kinematically allowed. The latter then propagate freely through the reactor and its shielding to give a signal in a distant detector. The energy spectrum of ordinary photons produced in the reactor is rather complicated due to their numerous sources. In what follows we use for the high energy tail, $E \gtrsim 0.2$ MeV, of the photon spectrum the estimate presented in Ref. [7] and based on the most relevant nuclear reactions accompanying with γ -production. It has the exponentially decaying form

$$\frac{dN_\gamma}{dE} = 0.58 \times 10^{21} \times \frac{T}{\text{GW}} \times e^{-\frac{E}{0.91 \text{ MeV}}} \quad (2)$$

in units of photons/(s $\times$ MeV), with T being the reactor thermal power. Let us note that other directions of direct searches for a light dark photon include hunts for light dark photons at colliders, in particular, in future experiments [8,9].

2. Oscillations between visible and hidden photons can be described [10–12] by the following Hamiltonian

$$H = \frac{1}{2E} \begin{pmatrix} \epsilon^2 m_X^2 + m_\gamma^2 & -\epsilon m_X^2 \\ -\epsilon m_X^2 & m_X^2 \end{pmatrix}. \quad (3)$$

Here m_γ is an effective mass of photon, which the latter acquires due to its coherent forward scattering off free

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electrons in the media [13], $m_\gamma^2 = 4\pi\alpha n_e/m_e$. The effective Hamiltonian (3) is justified in the ultrarelativistic case, $E_\gamma \gg m_X, m_\gamma$. The transition probability over the distance L has the form of standard oscillations

$$P(\gamma \rightarrow X) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right), \quad (4)$$

where

$$\tan 2\theta = \frac{2\epsilon m_X^2}{\Delta m^2} \quad (5)$$

with $\Delta m^2 \equiv m_X^2 - m_\gamma^2$. Corresponding oscillation length scales with the parameters as $L_{\text{osc}} \approx 2.5 \text{ cm} \times \frac{E}{1 \text{ MeV}} \frac{(10 \text{ eV})^2}{\Delta m^2}$.

This simple oscillation picture becomes more complicated when incoherent interactions of photon with the media are taken into account.¹ For the relevant photon energy range the most important processes include [14] a photoelectric absorption, a pair production and Compton scattering. The first two of them lead to photon disappearance (i.e., absorption by the media), while the Compton scattering results in the production of a secondary photon, which propagates with a lower energy. Figure 1 shows the absorption lengths for each of these processes for uranium² U^{238} media calculated using Ref. [16]. As we see, the Compton scattering is important in the photon energy range 0.7–4.5 MeV, where $\Gamma_{\text{sca}}/\Gamma_{\text{abs}}$ (with Γ_{sca} and Γ_{abs} being inverse scattering and absorption lengths, respectively) can reach a large factor of few (up to about 5). However, outside this energy range photon absorption processes noticeably dominate.

The energy spectrum of Compton-scattered photons has the following form (see, e.g., [17])

$$\frac{d\Gamma_{\text{Comp}}}{dE'}(E, E') \propto \frac{E}{E'} + \frac{E'}{E} + \left(\frac{m_e}{E'} - \frac{m_e}{E}\right)^2 - 2\left(\frac{m_e}{E'} - \frac{m_e}{E}\right), \quad (6)$$

where E and E' are the initial and final photon energies, respectively. The energy range of scattered photon reads

$$\frac{E}{1 + 2E/m_e} \leq E' \leq E. \quad (7)$$

Analyzing Eqs. (6) and (7) we see that the secondary photons produced by the primary ones having relatively

¹We stress that Eq. (2) corresponds to energy spectrum of the *primary* photons, i.e., photons emitted in nuclear reactions and radioactive decays in the reactor.

²Reference [15] takes thorium as a dominant element of the reactor active zone. But the ratio $\Gamma_{\text{sca}}/\Gamma_{\text{abs}}$ for uranium and thorium are almost the same.

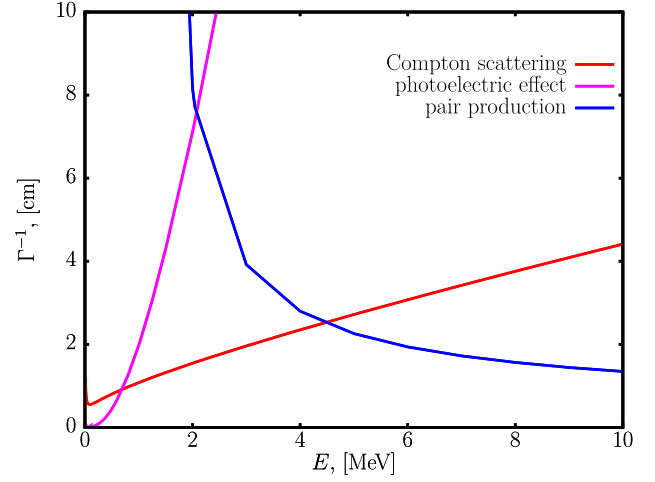


FIG. 1. Photon interaction lengths for Compton scattering, atomic photoelectric effect and pair production processes in uranium matter. Data are taken from [16].

large energies, i.e., $E \gg m_e$, exhibit energy spectrum strongly peaked at lower part of the energy range (7). Increasing energy of the primary photon results in further flattening of the flat part and further raising of the peak part of the photon spectrum in the reactor, see Fig. 2 for illustration.

3. Early calculations [5] of dark photon production in a reactor took into account photon absorption processes only. In this case the produced dark photon has the same energy as the parent visible photon and conversion probability has the form [10]

$$P = \epsilon^2 \times \frac{m_X^4}{(\Delta m^2)^2 + E^2 \Gamma_{\text{abs}}^2} \quad (8)$$

for distances much larger than Γ_{abs}^{-1} . The authors of [15] estimated the impact of secondary photons on the dark photon production. Their line of reasoning is as follows. Photon scattering represents an act of measurement in which the pure state $a|\gamma, E\rangle + b|X, E\rangle$ collapses into the mixed state described by the density matrix $\hat{\rho} = |a|^2|\gamma, E'\rangle\langle\gamma, E'| + |b|^2|X, E\rangle\langle X, E|$ with $|b|^2 \sim \mathcal{O}(\epsilon^2)$. The secondary photon having lower energy E' has a chance to scatter again, resulting in the production of a dark photon with energy E' . This evolution proceeds until photon absorption or until $E' < m_X$. Therefore, the total number of produced dark photons is enhanced by a factor of order of number of photon scatterings before absorption, which is of order $\Gamma_{\text{sca}}/\Gamma_{\text{abs}}$.

However, as we see from Fig. 1, the total number of photon scatterings can hardly be quantified by the $\Gamma_{\text{sca}}/\Gamma_{\text{abs}}$ because the latter has very strong energy dependence. Figure 1 clearly demonstrates that the Compton scattering in a reactor may indeed have a noticeable effect for the photons having $E \lesssim 4.5$ MeV, while for larger energies one does not expect any perceptible contribution to dark photon

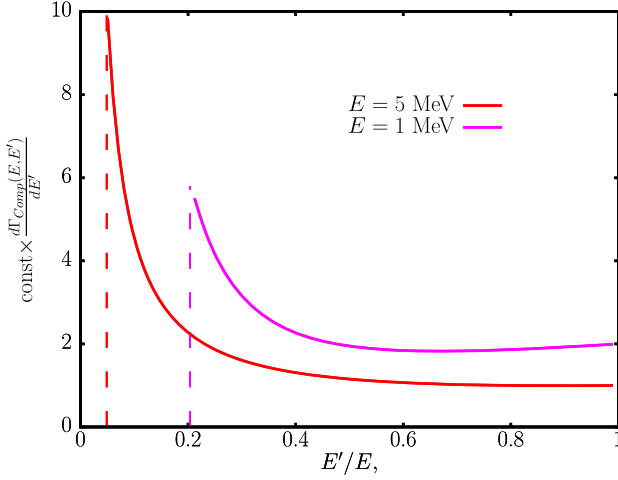


FIG. 2. Energy spectrum of outgoing photon after Compton scattering for a set of initial photons energies.

production from the secondary photons. This conclusion appears in a sharp contrast with the results of Ref. [15] where an enhancement of order 2 due to the photon scattering was observed already for $E \approx 5$ MeV, see Fig. 3 in Ref. [15]. Next, the energy spectra of Compton-scattered photons shown in Eqs. (6), (7) and Fig. 2 hint that average photons with $E \gtrsim 1$ MeV lose considerable amount of energy in a single scattering event and therefore quickly degrade to very small energies. Furthermore, given the exponentially decaying with growing energy spectrum of reactor photons [see Eq. (2)], a tenfold increase in the dark photon spectrum from Compton scattering observed in [15] is highly improbable, as the number of high-energy photons available for scattering is itself exponentially smaller.

The resolution of the problem relies on the observation made long ago [18,19], that the picture where interaction acts as a measurement described above (which can be extended not only to the scattering but also to the absorption processes) is not entirely accurate. As it is well known it indeed leads to a correct description if the rate of the measurement is taken to be *one half* of the interaction frequency of the visible photon. Such a description is widely used, for instance, for calculations of sterile neutrino production in a hot plasma (see, e.g., [20]). The authors of Ref. [15] considered absorption and scattering processes on different footing: while their expression for absorption probability is in agreement with the above description, their consideration of scattering process follows the incorrect interpretation of scattering as a measurement which completely collapses the wave function, so the factor of one half is lost. It is more appropriate to consider both absorption and scattering processes in the same way that allows one to calculate correctly the dark photon production in both absorption and scattering dominated regimes.

4. Having the arguments presented above we revisit the dark photon production in the reactor media by performing

an accurate calculation. We consider the density matrix of the visible-hidden photon system

$$\rho(E) = \begin{pmatrix} \rho_{11}(E) & \rho_{12}(E) \\ \rho_{12}^*(E) & \rho_{22}(E) \end{pmatrix}, \quad (9)$$

which obeys the following equation [21]

$$\frac{d\rho}{dr} = -i[H, \rho] - \frac{1}{2}\{G_{\text{abs}}, \rho\} + \frac{1}{2}G_{\text{prod}}. \quad (10)$$

Here we neglect irrelevant Bose enhancement and introduce $G_{\text{abs}} = \text{diag}(\Gamma_{\text{tot}}, 0)$ with $\Gamma_{\text{tot}} \equiv \Gamma_{\text{abs}} + \Gamma_{\text{sca}}$, $G_{\text{prod}} = \text{diag}(Q_{\text{prod}}, 0)$ where

$$Q_{\text{prod}}(E) = \int_E^\infty dE' \frac{d\Gamma_{\text{Comp}}}{dE}(E', E) \rho_{11}(E') \quad (11)$$

describes the contribution of secondary Compton-scattered photons. According to Eq. (10), the evolution equations for components of the density matrix read

$$\frac{d\rho_{11}}{dr} = i\frac{\epsilon m_X^2}{2E}(\rho_{12}^* - \rho_{12}) - \Gamma_{\text{tot}}\rho_{11} + \Gamma_{\text{prod}}, \quad (12)$$

$$\begin{aligned} \frac{d\rho_{12}}{dr} = & -i\frac{m_\gamma^2 - (1 - \epsilon^2)m_X^2}{2E}\rho_{12} \\ & + i\frac{\epsilon m_X^2}{2E}(\rho_{22} - \rho_{11}) - \frac{1}{2}\Gamma_{\text{tot}}\rho_{11}, \end{aligned} \quad (13)$$

$$\frac{d\rho_{22}}{dr} = i\frac{\epsilon m_X^2}{2E}(\rho_{12} - \rho_{12}^*). \quad (14)$$

If one solves this system with the initial conditions

$$\rho_{11}|_{r=0} = \frac{dN_\gamma}{dE}, \quad \rho_{12}|_{r=0} = \rho_{22}|_{r=0} = 0, \quad (15)$$

then, assuming the size of the reactor active zone being much larger than the photon absorption length, the energy spectra of produced dark photons is given by

$$\frac{dN_X}{dE} = \rho_{22}|_{r \rightarrow \infty}. \quad (16)$$

Without contribution from the secondary photons (i.e., for $\Gamma_{\text{prod}} = 0$) the system (12)–(14) can be easily solved analytically order by order in ϵ resulting in

$$\frac{dN_X}{dE} = \epsilon^2 \times \frac{m_X^4}{(\Delta m^2)^2 + E^2 \Gamma_{\text{tot}}^2} \times \frac{dN_\gamma}{dE} \quad (17)$$

up to corrections of the next order in ϵ , which agrees with the use of Eq. (8) after a replacement $\Gamma_{\text{abs}} \rightarrow \Gamma_{\text{tot}}$. Alternatively, the spectrum (17) can be reproduced via

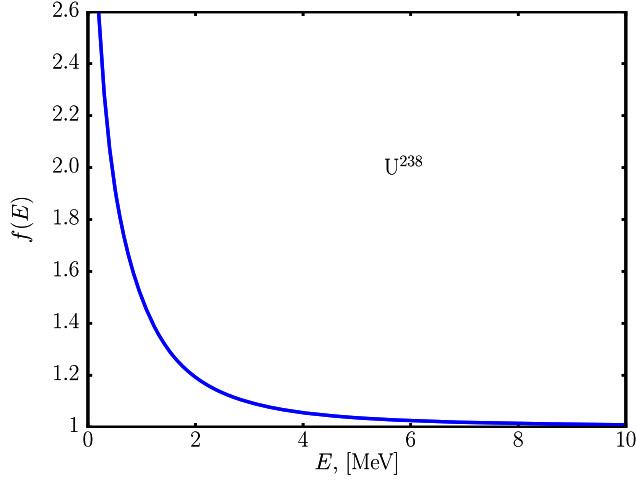


FIG. 3. Enhancement factor $f(E)$ for the dark photon production due to secondary photons from Compton scattering in media made of U^{238} .

Monte-Carlo (MC) simulation of photon propagation in which the first interaction of photon is considered as a measurement resulting in a production of dark photon with probability which is *one half* of the probability (4) while the scattered photons are neglected.

The secondary photons can be taken into account by either solving numerically Eqs. (12)–(14) with Γ_{prod} or performing MC simulation with scattered photons and with the factor *one half* in the oscillation probability. Below we follow the second approach. Direct numerical integration of the system (12)–(14) is feasible only when L_{osc} is larger than or comparable to Γ_{tot}^{-1} , which happens when m_X is close to m_γ , where we use it to check the MC simulation results. In the MC simulations we consider uranium U^{238} media and propagate photons taking into account the Compton scattering, atomic photoelectric effect as well as $e^+ - e^-$ -pair production. We define the enhancement factor $f(E)$ as the ratio of produced dark photon differential fluxes with and without secondary photons from Compton scattering. This enhancement factor is determined by the interactions of visible photon with matter and is independent of the mass of the latter. Figure 3 shows $f(E)$ obtained from the MC simulations and, independently, by direct numerical solution of Eqs. (12)–(14). We see that the effect of Compton-scattered photons is prominent at low energy part of the spectra only, in agreement with the qualitative arguments presented above. Namely, the amplification is about 20% at $E \simeq 2$ MeV and reaches about 100% at $E \sim 0.5$ MeV. Since the dark photon flux is proportional to the quartic power of mixing, the limits obtained in Ref. [5] can be improved by 30% at best and only for sufficiently light dark photons.

One may wonder about possible contribution to the dark photon production from the secondary e^+e^- pairs. To explore this effect we turn to full Monte-Carlo simulation

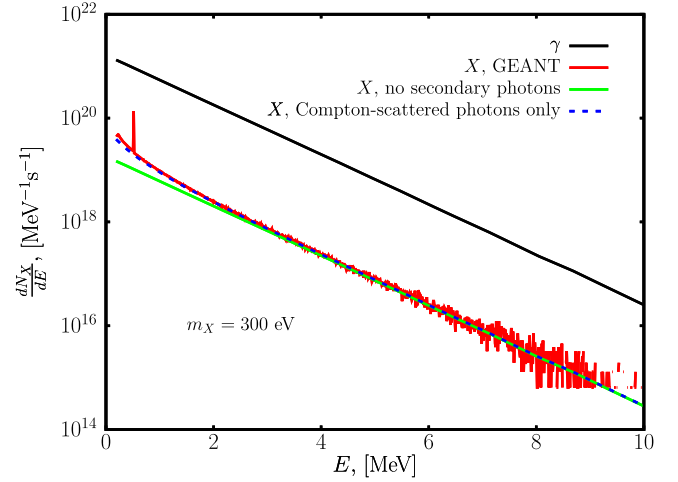


FIG. 4. The spectra of visible photons as well as dark photons calculated without scattering effect, with Compton-scattered photons and using GEANT simulation. We assume $m_X = 300$ eV, $\epsilon = 0.1$ and 2.9 GW thermal power of the reactor.

of the dark photon production in the reactor media with GEANT (version 3.21). We introduced an additional process of dark photon production to the simulation of electromagnetic processes in the GEANT code. In the simulations we adopt an U^{238} active zone of the reactor to be of a cubic geometry with a side length of 3 m surrounded by a large water shielding area. The production of hidden photons has been introduced as an additional process to the simulation of electromagnetic processes in the GEANT code, so that each time the photon interacts with the matter (via absorption or scattering) the hidden photon is produced with probability given by the vacuum oscillation formula (4) multiplied by the factor *one half* as explained above. The results are presented in Fig. 4, where we show the spectrum of photons produced by a 2.9 GW nuclear reactor as well as the expected spectrum of dark photons calculated without secondary photons [i.e., applying (17)], using the enhancement factor $f(E)$ which takes into account Compton-scattered photons only and using full GEANT simulation. Here we take $m_X = 300$ eV and $\epsilon = 0.1$ as an example. We observe that the enhancement factor $f(E)$ perfectly describes the results of GEANT simulations apart from the very low energy region where there is a sharp spike at $E \approx 0.5$ MeV which is attributed to contributions from e^+e^- annihilation process.

5. To summarize, we confirm the amplification of the dark photon production via mixing with ordinary photon due to the secondary photons. However, the overall enhancement is considerably smaller than that claimed in [15]. The enhancement is noticeable only at low energies: the amplification factor grows from 1.2 to 2.6 with energy decrease from 2 to 0.2 MeV. The enhancement due to photon scattering processes is of the same size and shape for other masses of dark photons. We expect that the sharp spike at $E \approx 0.5$ MeV observed in the expected spectrum

of dark photons can serve as a potential signature in future searches.

We conclude with a comment about the spectrum of primary photons for which in the present study (and following previous works [5,15]) we used the simple FRJ-1 research reactor model [7]. The effects, discussed in the main text, are exhibited only at low energies and numerically do not exceed a factor 2-3, which is below the accuracy of the model [7]. Even most recent calculations (see, e.g., [22]) of prompt fission γ -ray spectra (which is the main part of total photon flux) have uncertainty up to a factor of few. Moreover, the primary photon spectrum should be calculated on a case-by-case basis to ensure not only specific active zone media but also the specific changes in the latter during the working cycle of the reactor (see, e.g., Refs. [23–25]). The enhancement factor

$f(E)$ discussed in the present study can be easily found for any reactor media. However, its application for further tightening the experimental bounds on new physics models obviously requires a better knowledge of the primary reactor photon spectrum and accurate account of the matter distribution inside the reactor and in its surrounding area.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [26].

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