

Reply to “Comment on ‘Amplifying nonresonant production of dark sector particles in scattering dominance regime’”

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We thank the authors of Ref. [1] for their careful reanalysis of reactor dark-photon production and for highlighting several important aspects of the problem. In this paper, we address their comments point by point, indicating where we agree with their conclusions and where our interpretation differs. Throughout this reply, we refer to our original work as Ref. [2].

Reference [1] revisits the impact of Compton scattering on the dark-photon flux in a reactor environment and finds that, while secondary photons from Compton scattering do enhance the produced dark-photon flux, the enhancement is modest (at the level of a factor of a few in the low-energy part of the spectrum) and becomes negligible at higher energies. This conclusion is supported by an analytic treatment based on density-matrix evolution and by a Geant simulation. We agree that, once realistic (energy-dependent) interaction lengths are used, the enhancement is smaller than what was presented in Ref. [2]. We also clarify below which aspects modify the numerical results and which do not affect the underlying formalism.

I. ABSORPTION MODEL AND ENERGY DEPENDENCE

We agree with Ref. [1] regarding the energy dependence of photon interaction lengths and the dominance of absorption

processes over Compton scattering at sub-MeV energies in heavy elements (e.g., U/Th). As noted in Ref. [1], the photon absorption cross sections exhibit strong energy dependence, with photoelectric absorption dominating for photon energies below ~ 1 MeV, pair production becoming the dominant process above ~ 5 MeV, and Compton scattering being the primary interaction in the intermediate energy range of $1 \text{ MeV} \lesssim E \lesssim 5 \text{ MeV}$. This is clearly illustrated in Fig. 1 of Ref. [1].

In our work [2] we adopted a simplified parametrization for the photon absorption input in our benchmark medium, following the treatment used in Ref. [3]. We thank Ref. [1] for emphasizing that a realistic, energy-dependent absorption cross section is required for a quantitative prediction in the present setup, and we therefore update our calculation using XCOM [4].

We acknowledge that this simplification leads to an overestimate of the enhancement in certain energy ranges. However, this affects only the numerical magnitude of the enhancement and does not alter the physical structure of the collisional enhancement mechanism. Secondary photons produced via scattering can enhance the sterile-state yield solely by increasing the number of conversion attempts before photon absorption occurs. Thus, while a more realistic treatment of energy-dependent absorption modifies the size of the effect, it does not change the underlying physics or the qualitative conclusions of our work.

II. VALIDITY OF THE SCATTERING-DOMINANCE CRITERION AND WHAT REMAINS TRUE

We agree with Ref. [1] regarding the photon interaction lengths in large- Z media (e.g., U/Th) at sub-MeV energies, specifically that photon absorption typically dominates over Compton scattering, as expressed by

$$\sigma_{\text{abs}}(E) \gtrsim \sigma_C(E), \quad (1)$$

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and that Compton scattering preferentially produces lower-energy secondary photons. This observation indicates that the assumption used for an analytic estimate in Ref. [2], namely $\Gamma_{\text{sca}} \gg \Gamma_{\text{abs}}$ (or equivalently $\lambda_{\text{sca}} \ll \lambda_{\text{abs}}$), does not hold uniformly across the full energy range in such materials.

Indeed, the parametric scaling identified in Ref. [2] can be formulated more generally. In the nonresonant regime relevant here, the conversion probability per “active photon segment”—after averaging over rapid oscillations—depends only weakly on the precise damping rate. The enhancement instead originates from the cumulative effect of multiple photon segments generated prior to true absorption terminating the active-photon history. When a photon undergoes successive scattering interactions in a medium, the total production probability can be organized schematically as

$$P_{\text{tot}} \sim \sum_{\text{segments}} P_{\gamma \rightarrow A'}(\text{segment}) \Rightarrow P_{\text{tot}} \propto N_{\text{seg}}, \quad (2)$$

where the number of segments N_{seg} is controlled by the competition between scattering processes, which regenerate photons, and absorption processes, which permanently remove them.

Consequently, whenever Γ_{sca} is comparable to (or larger than) Γ_{abs} in a given energy window, one generically expects an enhancement of order

$$\mathcal{E}(E) \sim \frac{\Gamma_{\text{tot}}(E)}{\Gamma_{\text{abs}}(E)} = 1 + \frac{\Gamma_{\text{sca}}(E)}{\Gamma_{\text{abs}}(E)}, \quad (3)$$

up to corrections associated with spectral reshaping from Compton energy losses. This conclusion is fully consistent with Ref. [1], which finds that in high- Z materials $\Gamma_{\text{sca}}/\Gamma_{\text{abs}}$ reaches at most $\mathcal{O}(1)$, implying a modest—but parametrically well defined—enhancement rather than its absence.

Finally, we emphasize that a realistic reactor core contains a mixture of materials (including moderate- Z components and water shielding), for which the relative importance of Compton scattering and absorption can differ. In such a case, a material- and geometry-dependent treatment is required to quantify the net enhancement reliably.

III. “FACTOR OF ONE-HALF” ISSUE

Reference [1] emphasizes that in a quantum-kinetic description the damping of off-diagonal density-matrix elements enters with a factor of $1/2$ in the Lindblad-like term [see their Eq. (10)], and argues that treating scattering as an instantaneous projective measurement may miss this factor.

We agree that there should be one additional factor when we consider the oscillation probability in a medium. In the following, we clarify how this factor arises in the regime relevant for Ref. [2].

One key point is that in the heavy dark-photon regime relevant for Ref. [2], the oscillation length is parametrically

much shorter than the interaction length. As a consequence, coherence between interaction eigenstates is less relevant, and the system is more appropriately described in the mass-eigenstate basis. In this regime, dark photons are produced dominantly through incoherent scattering processes rather than through coherent oscillations subject to partial decoherence.

Concretely, in such limit one has

$$\sigma_{\gamma+e^- \rightarrow A'+e^-} \simeq \epsilon^2 \sigma_C, \quad (4)$$

where σ_C is the Compton scattering cross section. From the definition of a cross section, the dark-photon flux produced after a photon propagates a distance L is

$$\begin{aligned} \Phi_{A'} &= \frac{1}{1 + \epsilon^2} (1 - e^{-\Gamma_{\text{tot}} L}) \frac{\sigma_{\gamma+e^- \rightarrow A'+e^-}}{\sigma_{\text{tot}}} \Phi_{\gamma} \\ &\approx (1 - \epsilon^2) (1 - e^{-\Gamma_{\text{tot}} L}) \frac{\epsilon^2 \sigma_C}{\sigma_{\text{tot}}} \Phi_{\gamma}, \end{aligned} \quad (5)$$

where the $1/(1 + \epsilon^2)$ comes from the rotation from interaction eigenstates to mass eigenstates. Therefore, the oscillation probability in a medium is expected to be ϵ^2 . However, the oscillation probability given by the vacuum oscillation is $2\epsilon^2$. Therefore, an additional one half factor is needed.

In our calculation, we use the oscillation probability given in Eq. (2) in Ref. [2]. In the large- $m_{A'}$ limit [where the denominator in Eq. (2) in Ref. [2] is dominated by $m_{A'}^4$], one finds that, after averaging over a small energy interval,

$$P_{\gamma \rightarrow A'} \simeq (1 + e^{-\Gamma L}) \epsilon^2, \quad (6)$$

where L is the propagation length. Consequently, the probability adopted here is larger than that in the mass eigenstate formalism, and an additional compensating factor must be included to align our result with the mass eigenstate calculation.

Moreover, a more accurate expression for the photon survival probability after a regeneration via photon scattering than that used in Eq. (5) of Ref. [2] is

$$P_s = (1 - P_{\gamma \rightarrow A'}) (1 - e^{-\Gamma_{\text{tot}} L}) \frac{\sigma_C}{\sigma_{\text{tot}}}, \quad (7)$$

where $1 - P_{\gamma \rightarrow A'}$ is the probability that the photon does not convert into a dark photon during propagation over the length L , and $1 - e^{-\Gamma_{\text{tot}} L}$ is the probability that the photon undergoes at least one interaction in the medium, with the total interaction rate Γ_{tot} . The factor $\sigma_C/\sigma_{\text{tot}}$ then selects the subset of those interactions that are Compton scatterings (as opposed to absorptive processes), so that the photon is scattered and effectively regenerated.

Combining these expressions, if we consider the scattering as an projective measurement, the dark-photon flux can

be written as

$$\Phi_{A'} \approx P_{\gamma \rightarrow A'}(L) P_s \Phi_\gamma, \quad (8)$$

Taking the propagation length L to be equal to the interaction length, the dark-photon flux is expected to be about $1 + e^{-1}$ larger than that calculated in the mass eigenstates.

If we do not consider the scattering as a measurement, after the coherent photon-dark photon state interacts with matter, a fraction of the photon component undergoes scattering. Such scattering processes modify the quantum state of the photon and thereby produce a new quantum state. In contrast, dark photons do not participate in these interactions and thus remain unaffected by the scattering. As a result, the dark photon component retains its coherence with the unscattered photon component, and this coherent superposition continues to evolve subsequently, where the oscillation probability is given by Eq. (2) in Ref. [2]. Then, when the state get out of the medium, if the medium is thick enough, the oscillation probability in Eq. (8) will be

$$P_{\gamma \rightarrow A'}(L \gg \Gamma^{-1}) \approx P_{\gamma \rightarrow A'}^a \approx e^2, \quad (9)$$

where $P_{\gamma \rightarrow A'}^a$ is given in Eq. (3) in Ref. [2]. Then, Eq. (8) is consistent to the result given by the mass eigenstate. Therefore, in the following calculation, we will use $P_{\gamma \rightarrow A'}^a$ as the oscillation probability instead of $P_{\gamma \rightarrow A'}$.

IV. NUMERICAL ISSUE AROUND $E \gtrsim 2$ MeV

Reference [1] correctly notes that a large enhancement at $E \gtrsim 2$ MeV is not expected on physical grounds, since photons at these energies lose a substantial fraction of their energy after Compton scattering, strongly suppressing the regeneration of hard photons (see the discussion around Fig. 2 of Ref. [1]).

To clarify the origin of the apparent discrepancy, we independently reimplemented the calculation of the dark-photon flux following exactly the physical framework of Sec. IV in Ref. [2]. The only modification is technical: instead of a Monte Carlo treatment of the photon spectrum after the i th interaction, we use an analytically controlled convolution,

$$\frac{d\Phi_\gamma^i}{dE_\gamma} = \int P_1^s \frac{d\Phi_\gamma^{i-1}}{dE'_\gamma} \frac{1}{\sigma_C} \frac{d\sigma_C}{dE'_\gamma} dE'_\gamma, \quad (10)$$

where P_1^s is the photon survival probability defined in Eq. (5) of Ref. [2], and Φ_γ^0 coincides with the prompt photon spectrum of Eq. (11) in Ref. [2]. The corresponding dark-photon flux is then given by

$$\frac{d\Phi_{A'}}{dE_{A'}} = \sum_{i=0}^n P_{\gamma \rightarrow A'}^a \frac{d\Phi_\gamma^i}{dE_\gamma}. \quad (11)$$

with $P_{\gamma \rightarrow A'}^a \approx e^2$ is given in Eq. (3) in Ref. [2].

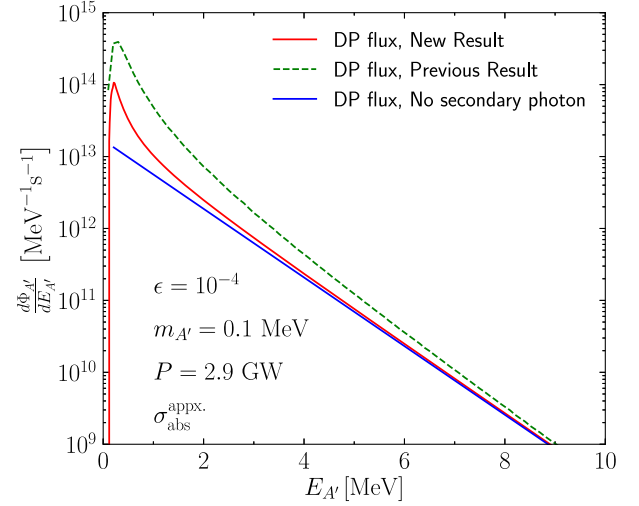


FIG. 1. Dark-photon flux recomputed using the same setup and the same (approximated) absorption cross section as in Ref. [2], adopted here intentionally to reproduce and validate our previous numerical pipeline. The parameters are $\epsilon = 10^{-4}$, $m_{A'} = 0.1$ MeV, and reactor power $P = 2.9$ GW. The green dashed curve reproduces Fig. 4 of Ref. [2], while the red solid curve shows the corrected recomputation. The previously apparent enhancement around $E \gtrsim 2$ MeV is not present after the numerical correction.

With this independent and controlled reimplementation, we find unambiguously that the enhancement previously appearing at $E \gtrsim 2$ MeV was caused by a numerical artifact rather than by any physical effect. Once the photon energy degradation inherent to Compton scattering is treated correctly and energy-dependent cross sections are used consistently, the high-energy enhancement disappears. The resulting behavior is exactly what is expected physically and is in qualitative agreement with Ref. [1].

We retain Fig. 1 below to document this numerical cross-check performed within the same setup as Ref. [2]. Importantly, the numerical correction discussed above does *not* eliminate the enhancement identified in Ref. [2]. The recalculated spectrum continues to show a pronounced enhancement in the low-energy region, though the enhancement is moderate after correcting the numerical artifact.

V. COMPARISON OF METHODS: OUR METHOD VS DENSITY-MATRIX EVOLUTION

We agree with Ref. [1] that a density-matrix evolution combined with GEANT-based photon transport provides a systematic description of photon-dark-photon propagation in a scattering and absorptive medium. However, the formalism of Ref. [2] captures the *same physical mechanism*: Compton scattering regenerates secondary photons and thereby increases the number of independent conversion opportunities before the photon is irreversibly absorbed. This mechanism is physical and formulation-independent,

and therefore cannot be invalidated by the choice of calculational method.

To make this comparison explicit, we present two complementary cross-checks. Figure 1 serves as a *pipeline validation*, in which we intentionally retain the same (now recognized as oversimplified) absorption cross section used in Ref. [2]. This allows us to isolate and diagnose the numerical implementation independently of physical inputs. Once the numerical issue is corrected, the spurious enhancement previously appearing at $E \gtrsim 2$ MeV disappears.

More importantly, Fig. 2 presents our *updated* result obtained after replacing the absorption cross section with realistic, energy-dependent values from XCOM [4] and using the photon survival probability given in Eq. (7) in the limit $L \rightarrow +\infty$. With these corrected inputs and the corrected numerical implementation, the resulting dark-photon flux agrees well with the corresponding result of Ref. [1] (dot-dashed gray line). This explicitly demonstrates that, once realistic absorption is employed, the enhancement induced by Compton scattering is modest and confined to the low-energy region—precisely as expected on physical grounds and fully consistent with Ref. [1].

Finally, we note that, if one switches off the production term in their density-matrix equation [their Eq. (10)] and works consistently at leading order in ϵ^2 , the resulting solution reduces exactly to Eq. (2) of Ref. [2]. These observations make explicit that the two approaches are formally equivalent in the appropriate limit and that the methodological differences discussed here do not alter the physical interpretation or the conclusions of Ref. [2].

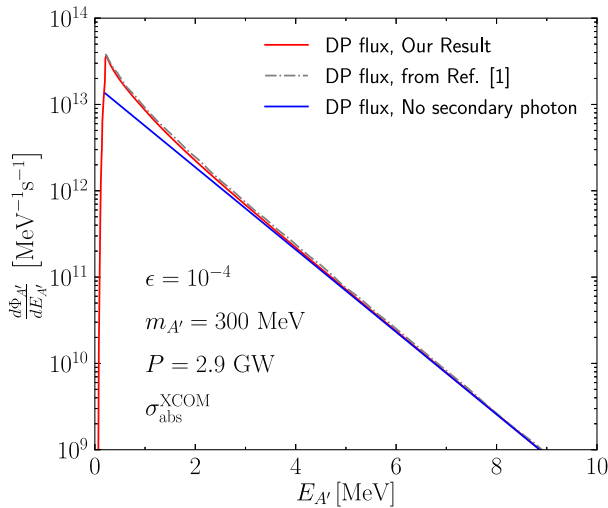


FIG. 2. Dark-photon flux using the *energy-dependent* absorption cross section from XCOM [4]. Parameters are $\epsilon = 10^{-4}$, $m_{A'} = 300$ eV, and reactor power $P = 2.9$ GW. With the corrected absorption input (and corrected numerics), our result agrees well with the flux shown in Ref. [1].

VI. PRIMARY PHOTON SPECTRUM UNCERTAINTIES

We agree with Ref. [1] that uncertainties in the *primary* reactor photon spectrum are relevant for quantitative predictions of dark-photon fluxes. As noted there, existing models of prompt fission γ spectra can differ by factors of a few, and fully realistic predictions ultimately require reactor- and fuel-cycle-dependent modeling.

These uncertainties, however, are not central to the purpose of Ref. [2]. Our work focused on identifying the physical role of scattering-induced photon regeneration and its parametric impact, rather than on precision modeling of the primary spectrum. Moreover, since the detector event rate scales as $\propto \epsilon^4$, moderate variations in the inferred photon flux translate into relatively mild shifts in the sensitivity to ϵ .

VII. SUMMARY

In light of Ref. [1], we identify two updates to Ref. [2]: (i) the absorption input used in our benchmark treatment was oversimplified (in particular, energy dependence and additional absorption channels matter in heavy elements), which led us to overestimate the enhancement in parts of the spectrum; and (ii) a numerical issue in our previous implementation produced an artificial enhancement for $E \gtrsim 2$ MeV, which disappears after correction.

At the same time, the underlying collisional-enhancement mechanism and its parametric dependence on the competition between scattering and absorption remain valid: whenever $\Gamma_{\text{sca}}/\Gamma_{\text{abs}}$ is sizeable in a given medium and energy range, secondary photons increase the total number of conversion opportunities and hence enhance the dark-photon yield. Overall, after these corrections, our updated conclusions are in good agreement with the main message of Ref. [1]: the enhancement is present but quantitatively modest (typically at the level of a few at most) and is mainly confined to the low-energy part of the spectrum, since repeated Compton scatterings degrade the photon energy and populate the lower-energy region where secondary photons accumulate.

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