Search for Dark Photons with Sub-keV Sensitivity Germanium Detector at the Kou Sheng Nuclear Reactor

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In various Standard Model (SM) extensions featuring an additional $U(1)'$ gauge symmetry, the dark photon (A') naturally emerges as a highly motivated candidate for Dark Matter.The Dark photon can couple to SM sector particles through a kinetic mixing term, providing a potential portal to dark matter [1]. Compton-like scattering process serves as a straightforward and effective method to investigate the dark sector, enabling both the production and detection of dark photons through electron interactions. Understanding these interactions between dark sector particles and the SM is essential, and reactor-based experiments offer a unique platform to explore these potential connections.

The effective Lagrangian [2] for the photon and dark photon (DP) system with the kinetic mixing parameter (ϵ) is given by:

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} \\ &+ \frac{1}{2}m_{A'}^2 A'^2 - e\left(A_\mu + \epsilon A'_\mu\right)J^\mu,\end{aligned} \tag{1}$$

where $F_{\mu\nu}$ ($F'_{\mu\nu}$) is the field strength of the photon (dark photon) field A_μ (A'_μ), $m_{A'}$ is the DP mass, and J^μ is the current of electrically charged matter.

Dark Photons may be produced via photon-electron scattering. Since a nuclear reactor is a source of high-intensity MeV photons and has an abundant supply of electrons, it provides an idel platform for studying the dark photons. The majority of γ-rays generated within a reactor arise from neutron capture and the decay of fission products. Approximately 6.7 to 7.8 γ-rays are emitted per fission for isotopes like ^{235}U and ^{239}Pu, translating to about 2×10^{20} γ-rays per second in a 1 GW reactor. In this studty, we use the γ-ray flux determined for the FRJ-1 reactor core for $E_\gamma > 200$ keV [3] is approximated by:

$$\frac{dN_\gamma}{dE_\gamma} = 0.58{\times}10^{18}\left(\frac{P}{\text{MW}}\right)\exp\left(-\frac{E_\gamma}{0.91\text{MeV}}\right).$$

This formula provides approximately 1.76×10^{20} γ-rays per second for $E_\gamma > 1$ MeV. A photon produced within the reactor core may undergo Compton-like scattering with an electron, resulting in the production of a dark photon with mass $m_{A'}$ and energy $E_{A'}$. The differential flux for dark photon production inside the nuclear core is described by

$$\frac{dN_{A'}}{dE_{A'}} = \int \frac{1}{\sigma_{\text{tot}}}\frac{d\sigma_{A'}}{dE_{A'}}\frac{dN_\gamma}{dE_\gamma}\,dE_\gamma, \tag{2}$$

where σ_{tot} is the total and average cross section for photon interactions in the reactor core material. We assumed that the material is composed entirely of pure thorium (Z=90). Compton scattering dominates for photon energies between 0.8 and 10 MeV. The photon energy E_γ is constrained by following relation [4],

$$E_\gamma(E_{A'}) = \frac{-0.5m_{A'}^2 + E_{A'}m_e}{m_e - E_{A'} + \sqrt{E_{A'}^2 - m_{A'}^2}\cdot\cos\theta}, \tag{3}$$

where θ is the angle between the incident photon and the outgoing dark photon. Figure 1 illustrates the dark photon flux for a 1 GW reactor core with different masses.

The Kuo-sheng Neutrino Laboratory (KSNL) is located 28 meters from the 2.9

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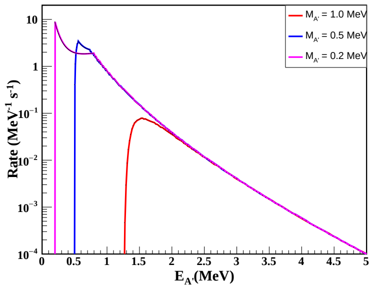

FIG. 1: The rate of dark photons emitted per second for a kinetic mixing parameter $\epsilon = 1$ from the center of a reactor with 1 GW thermal power. The reactor is modeled as a point source. The red, blue,and magenta curves correspond to dark photon masses of 1.0 MeV, 0.5 MeV, and 0.2 MeV, respectively.

GW thermal power core-1 of the Kuo-sheng nuclear power plant Taiwan, with an overburden equivalent to 30 meters of water [5]. The n-type Point Contact Germanium (PCGe) detector is surrounded by a 38.3 kg NaI(Tl) anti-Compton (AC) detector, as shown in fig 2. This setup is housed within a 50-ton shielding structure equipped with cosmic-ray (CR) veto scintillator panels. Data from the n-type PCGe detector, selected for its low threshold of 300 eV and absence of anomalous surface events, minimizes complications in the analysis. Comparing reactor ON and OFF states provides a highly sensitive approach for laboratory searches of exotic particles. If a reactor-produced dark photon is detected, it would be indicated by an excess of events with a $1/T^2$ pattern in the residual energy spectra recorded during the ON-OFF phase. A total of 124.2/70.3 kg-days of reactor ON/OFF data are used for this study [6].

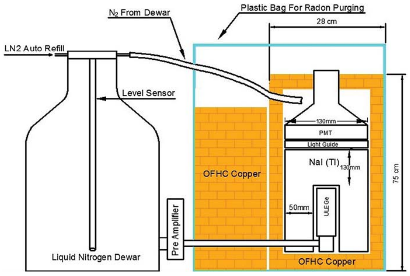

FIG. 2: PCGe and NaI(Tl) detector setup inside the 50-ton shielding house.

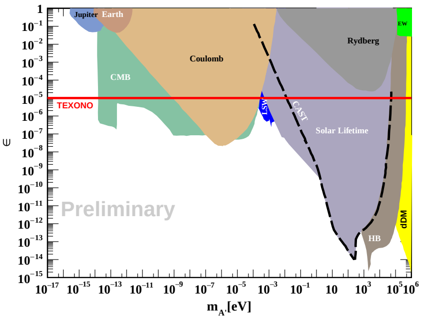

FIG. 3: Current exclusion limits on the parameter space for dark photon mass and the kinetic mixing parameter

The preliminary excluded parameter space (ϵ, $m_{a'}$) at a 90% confidence level, based on the current nPCGe data, is indicated by the red line in figure 3. This is compared with previous laboratory limits and constraints from cosmological and astrophysical models.

Acknowledgments

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