Active remote detection of radioactivity based on electromagnetic signatures

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A proposed new concept uses laser radiation and a probe beam to detect electromagnetic signatures in the vicinity of radioactive material and enables standoff detection at distances greater than 100m.

Sources of naturally occurring radioactivity range from rocks to bananas. Man-made radioactivity can be found in nuclear power plants and nuclear weapons. Moderate doses of radioactivity can be useful, for instance, in medicine and technology. At high doses, however, radioactivity is dangerous to biological entities, and it is important to have a robust means for its detection. A prominent example of this is the wrecked Fukushima Daiichi power plant in Japan. Another example is illicit transportation of radioactive materials. Other applications of methods for detecting radioactive materials include security and verification of compliance with arms control treaties. The most common type of radioactivity detector is the so-called Geiger-Müller tube: the sensing element of the familiar Geiger counter, which emits a click on detecting a particle of ionizing radiation. Useful as they are, existing techniques are passive, which results in limited sensitivity. They also have a very limited range (less than a few meters). Yet detection at extended range is critical, for example, in the case of illicit activities.

We previously proposed a radioactivity detection concept based on a high-power terahertz (THz) pulse that induces avalanche (collisional) breakdown and spark formation in the vicinity of the radioactive material. We have since observed that laser sources have the potential for longer standoff detection distances compared with THz sources. Here, we propose an alternative concept using laser radiation and a probe beam (e.g., millimeter beam) to detect electromagnetic signatures in the vicinity of radioactive material (see Figure 1). Studies we and others carried out between 2002 and 2008 analyzed propagation of short laser pulses in the atmosphere. These studies indicate the feasibility of propagating laser beams in the atmosphere as probes for the purpose of detection.

Figure 1. Schematic of active remote radioactivity detection concept. Laser radiation (frequency ω) photodetaches electrons from superoxide (O$_2^-$) ions, providing electrons for an avalanche (collisional) ionization process that increases the electron density, which modulates the frequency of a probe beam (e.g., millimeter beam).

The working principle is as follows. Radioactive materials emit gamma rays that ionize the surrounding air. The ionized electrons rapidly attach to oxygen molecules, forming superoxide (O$_2^-$) ions. The elevated population of O$_2^-$ extends several meters around the radioactive material. Electrons are photodetached from O$_2^-$ ions by laser radiation and initiate avalanche ionization, which results in a rapid increase in electron density. The rise in electron density induces a frequency modulation on a probe beam, which becomes a direct signature for the presence of radioactive material. Gamma rays emitted by radioactive material will increase the free electron density as well as the O$_2^-$ density. Our proposed concept makes use of laser beams to photoionize the O$_2^-$, thus providing the seed electrons for air breakdown.

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The rate of change of electron density is given by $\frac{\partial N_e}{\partial t} = (1 + \alpha_{\text{rad}})Q_{\text{rad}} + S_e - L_e$, where $\alpha_{\text{rad}}$ is the radiation enhancement factor (a measure of the amount of radioactive material) and $Q_{\text{rad}} = 20$ disintegrations/cm$^3$ is the ambient (background) radiation level, $S_e$ represents the various electron source terms, and $L_e$ is the electron loss terms. In the absence of radioactive material, $\alpha_{\text{rad}} = 0$. Figure 2 shows the radiation enhancement factor $\alpha_{\text{rad}}$ as a function of distance from the radioactive source, for 1 and 10mg of $^{60}$Co (cobalt-60).

A probe beam of frequency $\omega_0$ propagating in a time-varying electron density will undergo a frequency change that is given by $\Delta \omega(t, z) = (2\omega_0)^{-1} \left[ \omega_p^2(t) - \omega_p^2(t - z/c) \right]$, where $\omega_p(z, t) = \left[4\pi q^2 N_e(z, t)/m\right]^{1/2}$ is the plasma frequency, $q$ is the elementary electric charge, and $m$ is the electron mass.

As an example of this method of detection, we consider the case where the ionizing laser has a peak intensity of 160GW/cm$^2$ and pulse duration of 1ns. The probe beam is a millimeter wave source of frequency 94GHz. In the absence of radioactive material there is no frequency modulation of the probe. For $\alpha_{\text{rad}} = 10^3$ and a probe-beam interaction distance of 10cm, the fractional frequency modulation is significant, ~5%, which is readily detectable (see Figure 3). In other words, the frequency shift is the sought-for electromagnetic signature of radioactive material and can be measured.

In summary, we have proposed and analyzed a concept for active remote detection of radioactive materials. The frequency modulation on a probe beam is a signature of the radioactive material. Our analysis indicates that a measurable frequency shift can be expected for relatively small amounts of radioactive material. Proof-of-concept experiments are underway at the University of Maryland.

Figure 2. Radiation enhancement factor ($\alpha_{\text{rad}}$) versus distance from source. $M_{\text{rad}}$: Mass of radioactive material. $^{60}$Co: Cobalt-60.

Figure 3. Fractional frequency shift $\Delta \omega/\omega_0$ (%) versus time in the presence of radioactive material and a 1ns ionizing laser pulse. $L$: Probe-beam interaction distance.

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