

Observation of Resonant Diffusive Radiation in Random Multilayered Systems

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Diffusive radiation is a new type of radiation predicted to occur in randomly inhomogeneous media due to the multiple scattering of pseudophotons. This theoretical effect is now observed experimentally. The radiation is generated by the passage of electrons of energy 200 KeV–2.2 MeV through a random stack of films in the visible light region. The radiation intensity increases resonantly provided the Čerenkov condition is satisfied for the average dielectric constant of the medium. The observed angular dependence and electron resonance energy are in agreement with the theoretical predictions. These observations open a road to application of diffusive radiation in particle detection, astrophysics, soft-x-ray generation, etc.

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Introduction.—Several types of radiation mechanisms are possible for a charged particle moving through a dielectric medium. In the optical region, well-known mechanisms are the isotropic luminescence, Čerenkov radiation (CR), bremsstrahlung, and transition radiation (TR). Bremsstrahlung is related to the changing of particle velocity due to the collisions with the atoms of the medium. In the optical region it is negligible compared to other mechanisms. CR is produced when the particle velocity exceeds the phase velocity of the radiation in the medium and is emitted under a certain angle $\cos\theta = c/v\sqrt{\varepsilon}$, where v is the velocity of the particle and ε is the dielectric constant of the medium; see, for example, [1].

A charged particle uniformly moving in a randomly inhomogeneous medium is known [2] to be radiating electromagnetic waves due to the fluctuations of dielectric constant. The origin of the radiation can be explained as follows. Each charged particle creates an electromagnetic field around it which is not yet a photon but a pseudophoton. These pseudophotons scatter on the inhomogeneities of dielectric constant and convert into real photons. The main issue here is accurately to take into account the pseudophoton multiple scattering effects. The effect was studied both for three-dimensional (3D) [3] and one-dimensional randomness (1D) [4]. It was shown that the radiation intensity consists of two terms. One is caused by the single scattering of pseudophotons and the other by their multiple scattering. When the conditions for multiple scattering are fulfilled, its contribution to the radiation intensity strongly dominates. Single scattering contribution actually is the TR from the randomly spaced interfaces.

Random multilayered systems are an example of a medium with 1D randomness of dielectric constant. They are of significant interest due to the possibility of employing them in high energy particle detection [5]. Recently multi-

layered systems have been considered as possible sources for soft-x-ray radiation [6,7]. The CR and TR mechanisms were explored for the above mentioned purposes. Here we demonstrate the possibility of experimental generation of a *new* diffusive radiation (DR) mechanism in these systems. DR strictly differs from the other radiation mechanisms by its angular distribution, dependence of intensity on particle energy, etc.

For a given energy of electron the luminescence and CR photon yields depend on the length of electron path in the medium and is not related to the layered structure of the medium. Therefore, to reveal the stack effect we compare the photon yields from the stack and a continuous medium with the same thickness of material, see below.

Theory.—Considering the radiation from a charged particle uniformly moving in a system of randomly spaced parallel films, it was shown [4] that the multiple scattering of pseudophotons leads to the diffusion and its contribution to the spectral-angular intensity is given by the formula

$$I(\omega, \theta) = \frac{5e^2\gamma_m^2(\omega)L_z l_{\text{in}}(\omega)\sin^2\theta}{2\varepsilon(\omega)c l^2 |\cos\theta|}, \quad (1)$$

where $\varepsilon = \varepsilon_0 + na(\varepsilon_f - \varepsilon_0)$ is the average dielectric constant of the system, n is the concentration of films, a is their thickness, ε_f and ε_0 are the dielectric constants of film and medium, respectively, $\gamma_m = (1 - \frac{v^2\varepsilon}{c^2})^{-1/2}$ is the Lorentz factor of the particle in the medium, l and l_{in} are elastic and inelastic mean free paths of pseudophoton. The Eq. (1) is correct provided that $|\cos\theta| \gg (\lambda/l)^{1/3}$ and conditions for pseudophoton multiple scattering $\lambda \ll l \ll l_{\text{in}} < L_z$, where L_z is the system size in the z direction, are fulfilled. It is assumed that the z axis is the normal to the films and the particle is moving in that direction. The formula Eq. (1) has a clear physical meaning [8]. The quantity $e^2\gamma_m^2 L_z/c$ is the total number of pseudophotons in the medium, $1/l$ is

the probability of the photon scattering, and l_{in}/l is the average number of the pseudophoton scatterings in the medium. As it is seen from Eq. (1) the maximum of photon yield is achieved at the resonant point $\gamma_m^{-2} = 0$. Note that if one takes into account the absorption of photons or finite sizes of the system then the radiation intensity also will be finite although still large. Close to the resonant point γ_m^2 is substituted by the factor d^2/λ^2 , where $d \equiv \min[L, l_{\text{in}}]$, λ is the photon wavelength and L is the characteristic size of the system. The resonance condition $\gamma_m^{-2} = 0$ is the Čerenkov condition for the average dielectric constant. Hence one can say that the resonance diffusive radiation (RDR) has its origins from the interaction of two processes. The Čerenkov condition $v\sqrt{\epsilon}/c = 1$ creates a resonantly large number of pseudophotons and multiple scattering converts them into real photons. It should be emphasized that in the 3D random case the resonant factor γ_m^2 enters to the radiation intensity as $\ln\gamma_m$ [3]; therefore, 1D randomness is more preferable for getting larger photon yield.

It should be emphasized that the Eq. (1) is correct provided that $v\sqrt{\epsilon}/c \leq 1$. Note that the resonant velocity $c/\sqrt{\epsilon}$ is much larger than the Čerenkov threshold velocity for the material $c/\sqrt{\epsilon_f}$, because $\epsilon \ll \epsilon_f$. Preliminary estimations show that for electron energies far above the resonant energy DR is suppressed as compared to CR.

Above we have taken into account absorption of pseudophotons in the random medium. However, already formed real photons also will be absorbed in the medium. Therefore, to know what part of already created real photons will escape the system one should take into account the absorption of real photons in the medium. Suppose that we are interested in the photon yield from the depth z in the material. Using Eq. (1) and adding an exponential decay factor which takes into account the difference of paths of real photons with different emitted angles, one has

$$\frac{dI}{dz} = \frac{5e^2\gamma_m^2(\omega)l_{\text{in}}(\omega)\sin^2\theta}{2\epsilon(\omega)c^2|\cos\theta|} \exp\left(-\frac{z}{l_{\text{in}}|\cos\theta|}\right). \quad (2)$$

Here $\frac{dI}{dz}$ is the spectral-angular radiation intensity per unit length of electron path in the medium. Note the suppression of radiation intensity at very large angles. The real DR photons are formed in the effective size $(ll_{\text{in}})^{1/2}$. Therefore, when finding the total radiation intensity one should cut the integral in the lower limit on this length. After integration over the electron path, for the total spectral-angular intensity, we have

$$I = \frac{5e^2\gamma_m^2(\omega)\sin^2\theta l_{\text{in}}^2}{2\epsilon(\omega)c^2} \exp\left[-\left(\frac{l}{l_{\text{in}}}\right)^{1/2} \frac{1}{|\cos\theta|}\right]. \quad (3)$$

So as one could expect the absorption of real DR photons leads to the cutoff of radiation intensity at large angles and maximum lies at medium angles.

Experiment.—In the present work, we report the experimental observation of the DR generated by electrons passing through a random mylar stack. A schematic representation of the experimental setup is shown in Fig. 1.

The setup allows us to detect the photons in the wavelength range 300 nm–600 nm and obtain their angular distribution in the region $\theta = 50^\circ$ – 75° . The angular distribution is provided by the movement of the photomultipliers $P1$, $P2$ along the horizontal axis of the setup.

We use the following targets for generation of DR: a low-density mylar stack consisting of 45 films with thickness $4.5 \mu\text{m}$ and average spacing $55 \mu\text{m}$, a dense mylar stack with 50 films of thickness $3 \mu\text{m}$ and average spacing $6.8 \mu\text{m}$, and a polystyrene stack of 50 films with thickness $3 \mu\text{m}$ and average distance between films $76 \mu\text{m}$. The diameter of all targets is 50 mm. For each stack it has been made a continuous version with the same thickness of material as in the stack. As a source of charged particles the radioactive Sr^{90} giving electrons of energy 0.2–2.2 MeV is used. In order to interrupt the electron beam a lead Pb stopper placed between source and target is used. Electrons pass through the target reach the scintillation detector and are absorbed there. The radiation formed in the target is reflected and focused to the photomultipliers $P1$, $P2$. The photomultipliers have sensitivity in the wavelength region 300 nm–600 nm. The mirrors have a form of truncated cone with reflecting aluminum coating on the inner surface. The optical scheme of the setup allows us to detect the radiation in both forward and backward directions. The direction of movement of electrons is assumed as a forward one. The photon yields in both directions have been detected in the conventional electron-photon coincidence technique. During the experiment the photomultipliers $P1$, $P2$ were moved step by step to the target from the most distant position, which corresponds to minimal detection angle $\theta = 50^\circ$. The photon yields have been registered after each step of movement. The number of steps, their lengths, and registration time were given by programmed instruction. The number of steps (3.4 mm in lengths) in the angle range of 50° – 75° was 80; that means at least 3 steps per degree. The data were analyzed by LabView program package, collected by CAMAC and transferred to a PC by National Instruments GPIB card.

Preliminarily, the setup was calibrated under a target which gives an isotropic radiation and acceptance curve of optical scheme was obtained. As a source of an isotropic

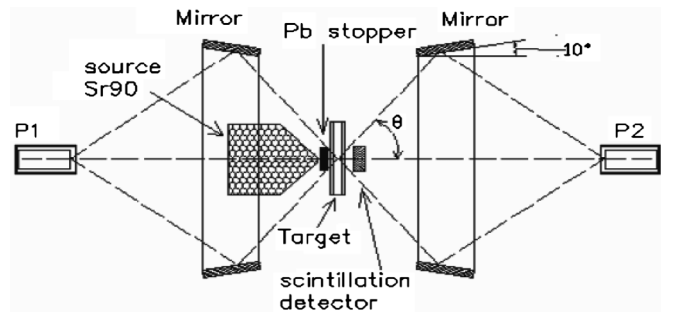


FIG. 1. Schematic of the experimental setup.

optical radiation we used a scintillation polystyrene film with the same thickness as that of targets. Then all obtained curves of radiation yield have been normalized to the acceptance curve.

The intensity of the radiation yield in the optical range of spectra can be represented as a sum of the following constituents: luminescence, DR, Čerenkov radiation (CR), and transition radiation. The luminescence contributes the essential part of the radiation yield and spreads both in the forward and backward directions. The DR according to Eqs. (1)–(3) is also the same for the backward and forward directions. The CR has strictly forward direction for a continuous target and for stack, because of the multiple scattering of real CR photons, spreads both in forward and backward directions. The TR yield is negligible as compared to the other constituents. The number of optical TR photons per one electron is $1/137$ per one interface, see, for example, [9], hence their number in our system is less than unity, $\sim 100/137$. Therefore, the TR photons cannot contribute to the electron-photon coincidence events.

The number of luminescence photons for a given energy of electron ought to be the same for the stack and the corresponding continuous target with the same thickness of material. Therefore, to reveal the DR photons from the stack photon yield we extract the photon yield of a continuous medium with the same thickness of the material.

The obtained angular distribution of the low-density mylar stack and the corresponding continuous target are shown in Fig. 2 and 3. The photon yields from the stacks are considerably higher than that of continuous medium. The difference of these two yields we attribute to the presence of DR radiation.

Although the number of DR photons is the same for forward and backward directions, in the experiment, the DR effect in back is seen more clearly (Fig. 2). The reason is the nonproper extraction of CR photons from the total photon yield. Apparently the number of CR photons in the

forward direction for the stack is smaller than that for continuous target due to displacing of some photons from forward to back. Therefore, the difference curve in Fig. 3 provides underestimated values for DR photons. On the other hand, the difference curve for backward direction (Fig. 2) provides overestimated values for DR photons because of existence of CR photons in backward for the stack. The ratio of DR and CR intensities is of order $\lambda\gamma_m^2/l$ [8]. This ratio is large near the electron resonance energy. Therefore, the DR photons give the dominant contribution to the difference curve.

Suppose that there is no DR mechanism. In this case the photon yield in the forward direction from the continuous target should be larger than the yield from the stack because of the loss of some forward photons due to reflections on the interfaces. Remember that the number of possible TR photons in the stack is negligible.

The observed angular dependence of emitted DR photons in backward direction (Fig. 2) is in good agreement with the theoretical relation Eq. (3). The maximum of DR intensity is achieved approximately at 55° . One obtains the same value from Eq. (3) provided that $l/l_{in} \sim 0.2$. If the parameter l/l_{in} is smaller, then the maximum moves to the region of larger angles. We observed this phenomenon by checking as a target the polystyrene stack for which the maximum is located at 65° . In the polystyrene the photon absorption is weaker and correspondingly l_{in} is larger. Photon elastic mean free path l in the geometrical optics region $\lambda \ll a$ we are interested in is of order of average distance between films [4].

We attempted to measure the energy of those electrons that radiate DR photons. The adjacent averaged energy distributions for different mylar targets (low-density stack, dense stack) and electron source are presented in Fig. 4. The source and low-density mylar stack distribution functions are normalized to the same total number of electrons. They have maximum at the same energy interval

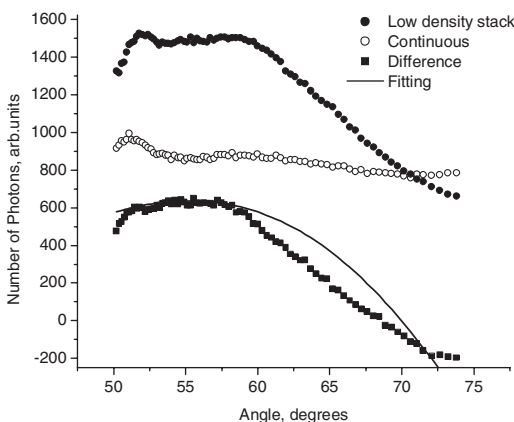


FIG. 2. Angular distribution of photons in the backward direction.

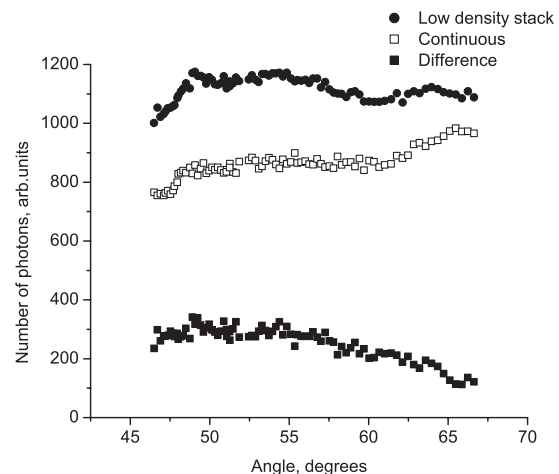


FIG. 3. Angular distribution of photons in the forward direction.

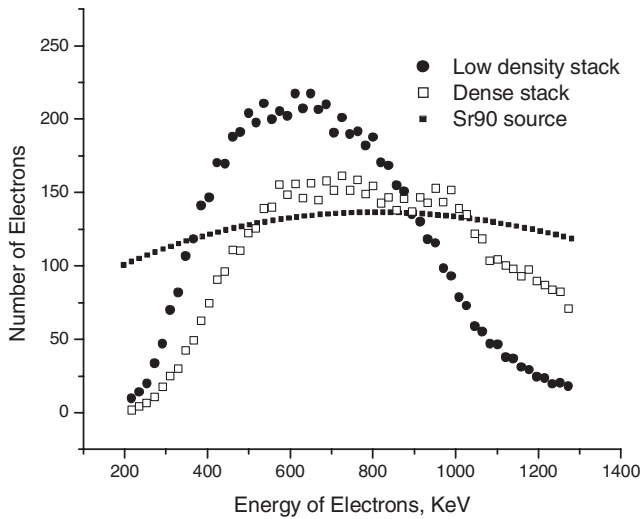


FIG. 4. Energy distribution functions of radiating electrons in electron-photon coincidence scheme. Photons are registered at 55° in forward direction.

0.6 MeV–1 MeV. However, the heights of the maximums are different. The highest maximum has the low-density stack, the second maximum has the dense stack, and both exceed the continuous mylar maximum. The coincidence of the place of peaks from different targets is explained by the fact that the energy distribution function of the electron source has a broad peak in the region 600–1000 KeV [10], Fig. 4. The DR effect intensifies the height of stack maximums compared to the continuous mylar maximum. For the low-density mylar stack with the dielectric constant $\epsilon_f = 3.12$ of films, the average dielectric constant is approximately equal to 1.17 and the corresponding resonance energy following from the condition $v^2/c^2 = 1/\epsilon$ is of order 750 KeV. This value lies in the above mentioned interval of source maximum; therefore, a resonant increase of the height of the maximum takes place. The resonance energy for the dense stack is of order 375 KeV and is far from the electron source maximum. Therefore, the increase of height of the source maximum due to the DR effect is less. Note that if the resonant factor γ_m^2 would not be in the DR intensity Eq. (3), then the yield of photons from the dense stack would be of the same order as from the low-density stack because the ratio l_{in}/l is the same for the two stacks.

Discussion.—Above, to reveal the DR photons, we subtract the photon yield of a continuous target from the stack yield, assuming that the luminescence from the stack and continuous target is the same. However, the number of escaped luminescence photons from the stack is smaller than that from the continuous target because of the stronger absorption in the stack. This is caused by the scattering on

the interfaces and therefore longer photon paths in the medium. The negative values in the difference curve (Fig. 2) are also explained by the stronger absorption in the stack. We fit the experimental data by Eq. (3), taking into account the different absorption in the stack and continuous target; for more details see [11]. As follows from Fig. 2, the agreement in the maximum region is quite good. The discrepancy at large angles between fitted and difference curves is perhaps explained by the nonproper normalization on the acceptance curve for the stack.

We have observed resonant diffusive radiation in the optical region for the first time. The resonant character of radiation is demonstrated. Angular dependence of the observed radiation and the electron resonance energy value are in agreement with the theory. The experimental confirmation of DR in the x-ray region could lead to interesting applications in high energy particle detection [12], in the soft-x-ray generation [13], etc.

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