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Features of the Transition Radiation Generated by Weakly-Relativistic Electrons in the Regime of Grazing Escape from a Flat Target

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Abstract—Features of the transition radiation (TR) generated in the vacuum ultraviolet range by weakly-relativistic electrons escaping from a target at small (grazing) angles have been theoretically studied. A significant (more than tenfold) increase in the angular density of TR with decreasing escape angle is predicted. It is established that the spectral and angular distribution of the TR intensity significantly depends on the target permittivity and the electron energy and escape angle.

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Investigation of the angular distribution of the intensity of transition radiation (TR) generated by a nonrelativistic charged particle crossing the medium–vacuum interface [1] showed that the ratio of the real ($\varepsilon'(\omega)$) and imaginary ($\varepsilon''(\omega)$) parts of the complex dielectric permittivity strongly influences the magnitude and position of the maximum in the angular profile under consideration (ω is the TR quantum energy). It was established [1] that, for $\varepsilon''(\omega) = 0$, this maximum exactly coincides corresponds to the angle of total internal reflection of light from the interface and the TR intensity at the maximum is greater than that in the case of $\varepsilon''(\omega) \neq 0$. In the general case, the position of maximum in the angular distribution of TR for nonrelativistic charged particle depends only on $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$.

A much more interesting situation is observed for weakly relativistic electrons. In this case, the Coulomb field of the radiating particle is deformed and the angular distribution of TR becomes sensitive to not only $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$, but also to the particle energy. The most interesting phenomena can be expected in the vacuum ultraviolet (VUV) spectral range, where the ratio of $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ can exhibit considerable variations that would lead to sharp changes in the spectral and angular characteristics of the TR.

The results of investigation [2] of the TR of relativistic electrons in the soft X-ray range at small (grazing) angles of electron incidence on the medium–vacuum interface showed the possibility of increasing the TR yield in cases where the relativistic particle moves at an angle on the order of the angle of total internal reflection of the TR from the interface. Below, the possibility of sharply increasing the angular density of TR for the grazing escape of weakly-relativistic electrons from the target is demonstrated and it is shown that the mechanism of this growth is different from that considered in [2]. The predicted effect can provide for a more than tenfold increase in the TR density in the 10–100 eV range, which is of considerable interest for the development of effective VUV radiation sources.

The spectral and angular distribution of the TR of an electron crossing the medium–vacuum interface in the response plane determined by the vectors of the electron velocity (V) and the normal (n) to the target surface can be described by the following equation:

$$\omega\frac{dN}{d\omega d\Omega} = \frac{e^2}{\pi^2}\frac{\chi'^2+\chi''^2}{((1-V\cos(\varphi)\sin(\Theta))^2-V^2\sin(\varphi)\cos^2(\Theta))^2}\frac{V^2\sin(\varphi)\cos^2(\Theta)}{(1-V\cos(\varphi)\sin(\Theta)-V\sin(\varphi)\beta')^2+V^2\sin(\varphi)\beta''^2}$$

$$\times\frac{(V\sin(\varphi)(\sin(\Theta)-V\cos(\varphi))\beta'-\sin(\Theta)(1-V^2\sin^2(\varphi)-V\cos(\varphi)\sin(\Theta)))^2+V^2\sin^2(\varphi)(\sin(\Theta)-V\cos(\varphi))^2\beta''^2}{((1+\chi')\cos(\Theta)+\beta')^2+(\chi''\cos(\Theta)+\beta'')^2}, \quad (1)$$

$$\beta' = \frac{1}{2}\sqrt{\sqrt{(\cos^2(\Theta)+\chi')^2+\chi''^2}+\cos^2(\Theta)+\chi'},$$

$$\beta'' = \frac{1}{2}\sqrt{\sqrt{(\cos^2(\Theta)+\chi')^2+\chi''^2}-\cos^2(\Theta)-\chi'},$$

where Θ is the observation angle (measured relative to the outer normal to the surface of the medium) and φ is the angle of electron escape from then medium (measured from the surface plane of the medium, and $\chi = \chi' + i\chi''$ is the complex susceptibility.

The numerators in the first and second factors in the right-hand side of Eq. (1) determine the maxima of the angular distribution of the TR, which appear due to a transformation of the Coulomb field of the radiating particle in the vacuum and medium, respectively. The denominator of the second term for $\chi'(\omega) > 0$ has a resonant character, which determines the position of the maximum in the spectral and angular distribution of the Vavilov–Cherenkov radiation intensity. The denominator of the third term in Eq. (1) determines the maximum of the angular distribution of radiation that is related to the total internal reflection of the radiation quanta from the medium–vacuum interface, which is described in detail in [1].

Since only the third term of Eq. (1) enters into the expression for the spectral and angular distribution of the TR of nonrelativistic electrons ($V \ll 1$), the shape of the angular distribution is determined entirely by the $\chi'(\omega)$ and $\chi''(\omega)$ values:

$$\omega\frac{dN}{d\omega d\Omega} = \frac{e^2}{\pi^2}(\chi'^2+\chi''^2) \times \frac{V^2\sin^2(\varphi)\cos^2(\Theta)\sin^2(\Theta)}{((1+\chi')\cos(\Theta)+\beta')^2+(\chi''\cos(\Theta)+\beta'')^2}. \tag{2}$$

The maximum in the angular distribution occurs near the total internal reflection angle (determined by the relation $\cos(\Theta) = \sqrt{-\chi'}$) and this position is independent of the orientation of momentum of the radiating particle.

As the electron energy increases, the Coulomb field of the radiating particle exhibits transformation and the shape of the spectral and angular distribution of the TR becomes dependent not only on the permittivity of the medium, but on the electrum momentum as well. The maxima in the angular distribution of the TR of a weakly-relativistic electron are determined by two mechanisms. According to the first mechanism, which is related to the transformation of the Coulomb field of the electron, the maxima are observed for $|\chi'| \ll 1$ and

$$\varphi \gg \arccos\left[\frac{1}{4}(V+\sqrt{V^2+8})\right]$$

near the angles

$$\Theta \approx \frac{\pi}{2} - \varphi \pm \arccos\left[\frac{1}{4}(V+\sqrt{V^2+8})\right].$$

The second mechanism is related to the total internal reflection and the corresponding maxima are near the angles

$$\Theta \approx \pm\arccos(\sqrt{-\chi'}).$$

As a rule, the maxima determined by the two mechanisms are independent. However, at a certain angle of electron incidence on the interface, these positions may coincide and then the angular density of TR will significantly increase.

Figure 1 shows the angular distributions of TR with a fixed quantum energy ω for various angles φ of electron incidence on the interface, which were calculated for experimentally determined susceptibility components $\chi'(\omega)$ and $\chi''(\omega)$ for carbon [4] and an electron energy of $\varepsilon = 0.5$ MeV. The position of maximum in the optimum case (curve *3*) corresponds to the total internal reflection angle.

Figure 2 shows the energy dependence of the ratio of the maxima of the angular distributions for the normal and grazing incidence:

$$G = \omega\frac{dN^{\text{grazing}}}{d\omega d\Omega}\bigg|_{\max} \Big/ \omega\frac{dN^{\text{normal}}}{d\omega d\Omega}\bigg|_{\max}$$

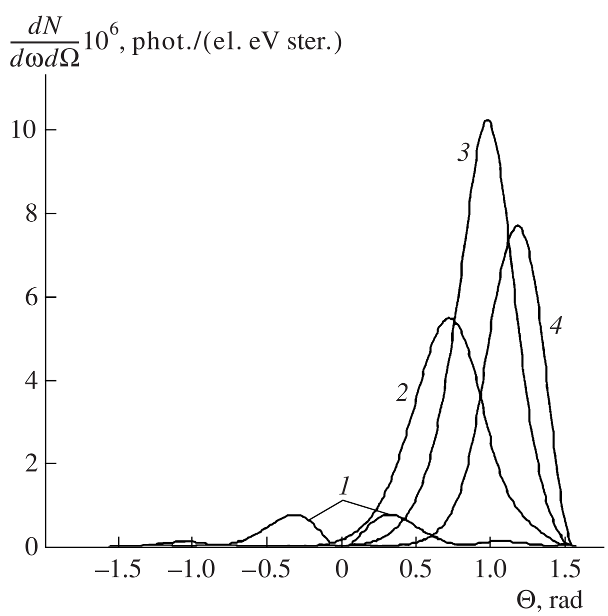

Fig. 1. Increase in the angular density of TR at $\omega = 50$ eV for electrons with an energy of $\varepsilon = 0.5$ MeV incident on the medium–vacuum interface at various angles $\varphi = \pi/2$ (*1*), 0.7 (*2*), 0.45 (*3*), and (*4*) 0.2.

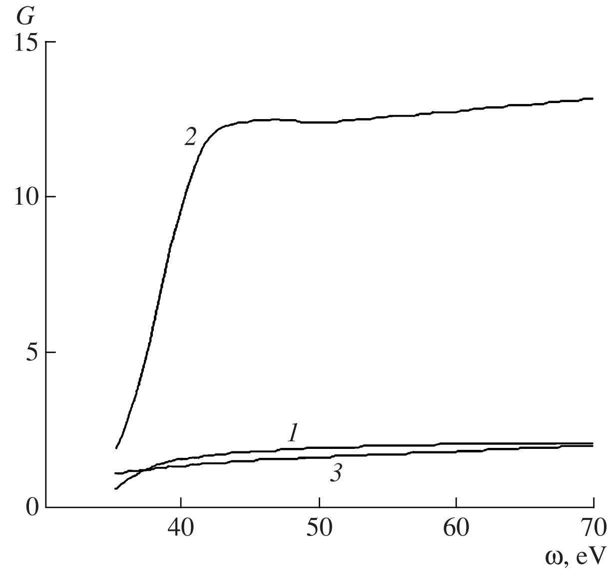

Fig. 2. Suppression of the effect of increase in the angular density of TR as manifested by the ratio G of the TR intensities at the maxima of angular distributions for the grazing (optimum φ) and normal incidence angles at an electron energy ε of (*1*) 0.05, (*2*) 0.5, and (*3*) 5 MeV.

(for the grazing geometry, φ was selected equal to the aforementioned optimum value), where curves *1* and *3* correspond to the nonrelativistic and relativistic cases, respectively. An insignificant increase in the angular density of TR in the nonrelativistic case is explained by a weak dependence of the shape of the angular distribution on the orientation angle as described by Eq. (2). In the weakly relativistic case (described in [2]), the angular distribution of TR is determined primarily by the degree of transformation of the Coulomb field of the radiating particle. In the region of manifestation of the phenomenon under consideration (i.e., for $\chi'' = 0$ in the limit as $\gamma \longrightarrow \infty$, where γ is the Lorentz factor of the radiating electron), the ratio G of the TR intensities at the maxims of angular distributions for the grazing and normal incidence is about 4.

Thus, the results of this investigation predict the possibility of significantly increasing the spectral and angular density of the TR of weakly relativistic electrons crossing the medium–vacuum interface at a grazing angle. A more than tenfold increase in the TR intensity is manifested near the angle of total internal reflection of the radiation quanta from the interface ($\Theta \approx \arccos(-\sqrt{\chi'})$) at an electron energy on the order of 100 keV. The increase in the angular density is most pronounced at 10–100 eV range in the case where the position of maximum in the angular distribution of TR (formed due to the transformation of the Coulomb field of the radiating electron) is close to the angle of the total internal reflection of TR from the medium–vacuum interface. It should be emphasized that this effect is not manifested for nonrelativistic and ultrarelativistic electrons.

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