Physical nature of the angular dependence of the intensity of the excitation of bulk plasmons by fast electrons

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A theory is derived for the excitation of bulk plasmons. A common formalism is used to incorporate the transition radiation of bulk plasmons and the effect of the surface-plasmon excitation channel on the excitation of the bulk plasmons. It follows from this theory that the angular dependence of the rate of excitation of bulk plasmons is extremely sensitive to the particular parameter values of the material.

The reason for the dependence of the effective cross section for the emission of a bulk plasmon on the angle at which the fast electrons are incident on the surface of the material has remained unclear for a long time. The interpretation which we find the most plausible is that this dependence stems from two processes simultaneously: the transition radiation of bulk plasmons and the coupling of channels for inelastic scattering of a particle entering the medium.

Transition radiation leads to an increase in the cross section (σ) for the emission of a bulk plasmon as the angle (α) at which the fast particle is incident on the surface of the medium increases (the angle α is reckoned from the normal to the surface). A coupling of channels can give rise to an effect of the other sign—the cross section for the emission of a bulk plasmon, σ, may decrease with increasing α—if the excitation of the bulk plasmon is dominated in this sense by the inelastic-scattering channel involving the excitation of a surface plasmon.[1]

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In experiments in a variety of materials, at various energies of the incident particles, it has been observed that σ may either increase or decrease with increasing α; in some cases, σ has been only a weak function of α.[2–7] These results are evidence that the nature of the angular dependence, which is determined by a competition between these two physically different mechanisms, is sensitive to the values of the basic parameters of the material, on which σ depends, and also to the energy (E) of the incident electrons.

On the other hand, these two processes—the transition radiation of plasmons and the coupling of channels—are interrelated although physically distinct processes. Theoretically, this relationship is seen in the circumstance that the contribution to σ from these two processes is determined by the same Green's function (D) of the electric field of the electrons of the medium.

This Green's function (a convenient form of this function is given in Ref. 8) turns out to allow a separation of the type $D = D_B + D_S$, where the cross section for the excitation of a plasmon in the volume of the material can be found in terms of D_B, while the term D_S is used to determine the corrections to this cross section for surface effects. The function D_S in turn consists of two components: $D_S = D_{SBC} + D_{STR}$, where

$$D_{SBC} = -2e^2\pi\hbar\theta(z)\theta(z')[q\epsilon(\omega)]^{-1}\exp[-q(z+z')]. \quad (1)$$

This function describes the effect of the channel of surface-plasmon excitation on the channel associated with a bulk plasmon. The function D_{STR}, given by

$$D_{STR} = -e^2\hbar\theta(z)\theta(z')\frac{8i\pi v_F}{3\omega\epsilon(\omega)}\left(1-\frac{1}{\sqrt{\epsilon(\omega)}}\right)\exp[-q(z+z')], \quad (2)$$

describes the transition radiation of the bulk plasmons. The circumstance that D_{SBC} and D_{STR} are found from the same initial Green's function guarantees a correct description of the two processes, whose consequences may tend to cancel each other out.

Using these Green's functions, we have derived the cross section (σ) for the emission of a bulk plasmon as a function of the angle α. We simultaneously incorpo-

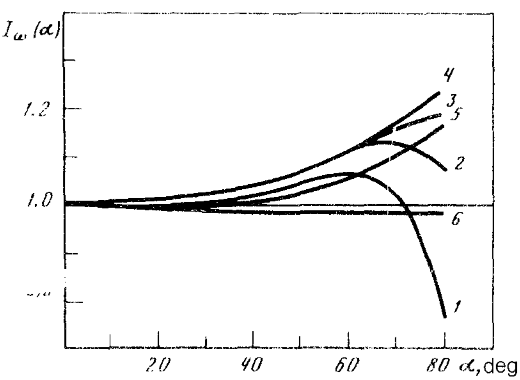

FIG. 1. Spectral intensity of the emission of bulk plasmons, $I_\omega(\alpha)$, as a function of the angle α for various energies of the incident electrons, E. 1—$E = 150$ eV; 2—300 eV; 3—500 eV; 4—1 keV; 5—4 keV; 6—100 keV. The values of the other parameters are $\mu = 0.2$, $\gamma = 0.01$, $\omega/\omega_p = 1.2$.

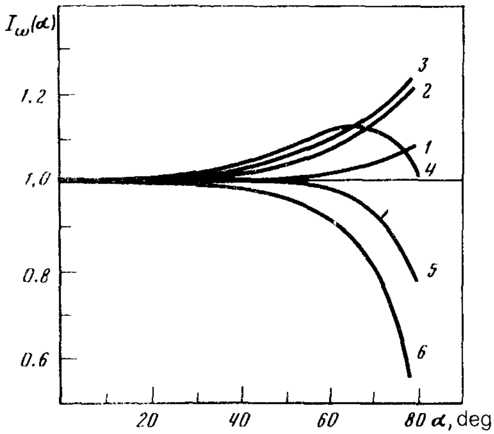

FIG. 2. The function $I_\omega(\alpha)$ for various values of the parameter μ. 1—$\mu = 0.01$; 2—0.05; 3—0.1; 4—0.2; 5—0.5; 6—0.7. $E = 250$ eV, $\gamma = 0.01$, $\omega/\omega_p = 1.2$.

rated the Čerenkov- and transition-radiation mechanisms and the channel-coupling effect. Although this function is very complicated, it is easily derived in analytic form. Figures 1–3 show its behavior for various values of the parameters.

It follows from Fig. 1 that the spectral intensity of the emission of a bulk plasmon, $I_\omega(\alpha)$ is an increasing function of the angle α when the energy of the fast particle, E, is on the order of one or a few keV. At higher and lower energies E, the channel-coupling effect outweighs the transition radiation. The nature of the angular dependence is also affected by the ratio ω/ω_p. The channel-coupling effect outweighs the transition radiation at $\omega/\omega_p < 1.2$.

The wave function of the fast particle decays exponentially with penetration into the material, with an argument $(-\mu\omega_p z/v_z)$ for the exponential function. It can be seen from Fig. 2 that values of the parameter μ on the order of 0.1–0.2 are the most favorable values for observing transition radiation.

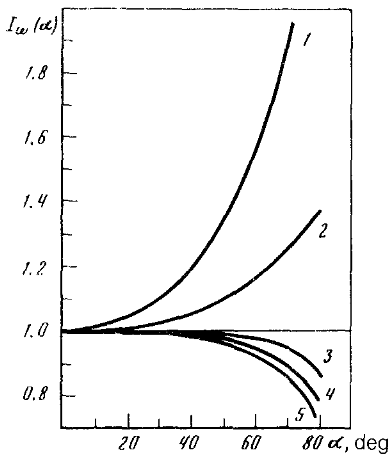

FIG. 3. The function $I_\omega(\alpha)$ for various values of the parameter γ. 1—$\gamma = 0.001$; 2—0.01; 3—0.05; 4—0.1; 5—0.3–0.5. $E = 450$ eV, $\mu = 0.2$, $\omega/\omega_p = 1.4$.

It turns out that the quantity which is the most crucial with respect to the nature of the competition between transition radiation and channel coupling is γ, which is a measure of the damping of the bulk plasmons. It can be seen from Fig. 3 that for γ between 0.01 and 0.05 there is a rather sharp transition from an increasing function $I_\omega(\alpha)$ to a decreasing function.

Finally, a comparison of the components in the plasma emission cross section representing the transition mechanism and channel coupling shows that channel coupling is generally so important that even the absence of a pronounced dependence of the bulk-plasmon emission intensity on the angle α would be possible only in the face of intense transition radiation.

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