[5)]To verify the validity of the employed expression (6) in the calculation of C_{DA} we have compared the results of the calculation[24] of C_{DA} for $KNdP_4O_{12}$, obtained by formula (6) with the results of a determination of C_{DA} with the aid of the calculation of the lattice sum with summation over the nearest 14 ions. The results turned out to be close: $C_{DA}(6) = 6.8\times10^{-41}$ and $C_{DA}(\Sigma) = 6\times10^{-41}$ cm^6/sec.

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Polarization and spectral composition of the radiation of nonrelativistic electrons interacting with a rough surface

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The polarization and spectral composition of radiation produced when nonrelativistic electrons enter into a substance having a varying degree of surface roughness are measured. It is shown that at large electron entry angles, and particularly at glancing angles of incidence on the surface, the radiation is due to the surface roughnesses. The degree of polarization of radiation reaches ~40%. The spectral density of the radiation energy depends on the optical constants of the substance, on the degree of its surface roughness, and on the angle of entry of the electron into the substance. The radiation intensity at glancing entry is larger by about an order of magnitude than the intensity of transition radiation at normal incidence.

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1. The radiation produced when nonrelativistic electrons enter into a substance has been the subject of many studies.[1,20] Most experiments were undertaken to investigate transition radiation.[21] The earlier work is analyzed in a review by Frank.[22] The measurements were made mainly for the visible part of the spectrum; there are also data for the vacuum ultraviolet region.[23,24]

In the cited experiments there were analyzed the

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polarization, spectral composition, and angular distribution of the radiation, as well as the dependence of the radiation intensity on the electron energy, on the electron angle into the target, and on the optical constants of the material. The emission induced in a target by electrons is polarized, and the degree of polarization reaches ~96%. The radiation intensity increases linearly with increasing electron energy. The spectral composition of the radiation depends substantially on the optical constants of the target material.

The results of the experiments indicate that when the angle of entry of the electron into the target increases (the entry angle ψ is reckoned from the normal to the target surface) the degree of polarization decreases substantially. Next, whereas the intensity of the transition radiation should decrease with increasing entry angle, and at grazing angles ($\psi \to \pi/2$) this radiation should vanish completely, data obtained in many experiments indicate that at these entry angles the radiation not only fails to vanish, but, on the contrary, its yield becomes many times larger than the yield of transition radiation at normal incidence ($\psi = 0$). This anomaly was first observed only in silver[1,4]; it was subsequently observed also in other metals.[16,19,20] The results of our earlier experiments[16,19,20] on polished and rough targets (the degree of roughness of the target surface was not measured and was only estimated visually) indicate that the anomalous radiation is due to roughnesses present on the target surface. It was shown at the same time that the bremsstrahlung of the electrons on entering the target, as well as the excitation of the surface waves and their further transformation into spatial waves by scatterings from the roughnesses of the surface, to which some workers[1,4] attribute the anomalous radiation, make a negligible contribution and cannot account for the measurements results.[16,18,20] Nor can the anomalous radiation be attributed to undulator radiation,[25] as suggested by Gevorkyan and Krokhmazyan.[26]

At the present time it can be stated that the emission from metals under the influence of electrons consists of two types of radiation[19]—transition radiation and radiation by the surface roughnesses. At small angles of entry of the electron into the target, the bulk of the total emission consists of polarized transition-radiation photons. A small fraction of partially polarized radiation from the surface roughnesses is also present. At large entry angles, on the contrary, the total emission consists of electron-emission photons from the surface roughnesses, and the contribution of the transition radiation is negligibly small.

Even during the early stages of the investigation of these questions[16] we have pointed out that the detection of the emission of electrons entering a medium can serve as a good method of studying the surface state of the medium. This made it necessary to perform experiments with targets having a certain and known degree of roughness measured by other independent methods, so as to reveal the functional connection between the parameters describing the degree of roughness and the different characteristics of the radiation. The results of measurements of the polarization and of the spectral composition of radiation produced by electrons entering targets with different degrees of roughness are reported in the present article.

2. A detailed description of the experimental setup, of the features of the experimental geometry, of the measurement procedure, and of the reduction of the results was published by us earlier,[13,15] and we omit the details here. We note only that the measurements were made on 80-keV electrons entering the target at angles from $\psi = 0$ to $\psi = 88.5°$.

At $\psi = 0$ the radiation was detected in a direction making an angle 52.5° with the surface of the target. In this case the transition radiation reaches its maximum precisely in the region of these observation angles. At entry angles different from zero, the radiation was detected in directions close to normal (in the range 1.5–7.5°). In the experiment we detected the spectral energy density of the radiation in the wavelength interval from 300 to 600 nm.

We investigated in the experiment targets of Al, Ag, and Ge. The Ge targets were thin germanium plates whose surface was worked mechanically, ground with a free abrasive, and washed carefully in various alcohols and ethers to remove any contamination. The aluminum and silver targets were layers of metal $\lesssim 0.15\ \mu$m thick coated by vacuum sputtering on the end of steel cylinders subjected to similar mechanical grinding and cleaning. A film of this thickness is already opaque to the investigated spectral interval.

The surface of the target is not ideally flat, and one can speak only of some degree of approximation of the surface by a plane. Usually the roughness of a surface is specified in terms of the probability distribution density of the heights of the points of the surface above the zero surface within the limits of the chosen base line. In the course of production, the surface is formed as a result of joint and additive action of many independent factors, so that by virtue of the central limit theorem it can be assumed that the distribution of the surface-roughness heights is most likely to obey the normal law; this is confirmed by existing experimental data.

The degree of surface of the roughness of the targets used in the experiment was measured by a commercial profilometer-profilograph, model 201 of the "Kalibr" plant. The obtained profilograms make it possible to plot the distributions as well as determine the average and mean squared values of the different parameters that characterize the degree of roughness. In the description of the roughness we shall follow the presently valid standard GOST-2789-73, but out of all the numerous parameters characterizing the degree of roughness, we shall use only two for the interpretation of the experimental data, the arithmetic mean R_a of the absolute values of the deviations of the profile from the average line within the limits of the base length, and the average distance S between the peaks of the profile roughnesses.

For convenience, the investigated interval of the val-

ues of R_a was divided into the 10 groups represented in the table, and the numerical values of the limits of the interval in each group, in microns, were chosen from the set suggested in GOST 2789-73. Referred to GOST 2789-59, which is no longer valid today, group 1 corresponds to the 14th class of surface finish, group 2 to the 13th, etc. and group 10 to the 5th. The limits of the measured values of S for each group are also given in the table (the numerical values of the limit, in millimeters, were also chosen from the set suggested in the standard). It should be noted that when aluminum or silver is sputtered on a steel base, the degree of roughness was measured both before and after the sputtering. The measured values of R_a and S for the two cases differed insignificantly.

3. We measured in the experiments the spectral density of the radiation polarized in two mutually perpendicular planes. One of them, usually called parallel, is the plane made up of the line of sight and the normal to the target surface, i.e., the plane in which the transition is polarized. The second component of the radiation is customarily called perpendicular. The degree of polarization of the radiation is defined by the ratio

$$p=(W_\omega^{\parallel}-W_\omega^{\perp})/(W_\omega^{\parallel}+W_\omega^{\perp}).$$

The results of the measurements for targets of Al, Ag, and Ge are given in Fig. 1. We note that, other conditions being equal, no regularity whatever is observed in the variation of the degree of polarization from one substance to another. Further, the data on Fig. 1 are plotted not in the form of points, as would be customary, since their number reaches 2000, but the points are grouped, in accordance with a definite attribute, into three different regions. Region 1 corresponds to normal entry ($\psi = 0$) of the electrons into targets of group 1. Region 2 corresponds again to normal entry, but for targets of group 2. The data for the targets of the remaining groups at all entry angles, including $\psi = 0$, as well as the data for targets of group 1 and 2 at entry angles $\psi \gtrsim 45°$ are gathered into region 3.

It follows from Fig. 1, first, that the investigated radiation is in all cases polarized in the parallel plane, i.e., the sign of the polarization of the radiation detected in the experiment agrees with the sign of the polarization transition radiation. Second, the degree of polarization of the radiation is more readily independent of the photon wavelength in the spectral region from 300 to 600 nm.

Next, the degree of polarization approaches unity (p

TABLE I.

Target group	R_a, μm	S, mm	Target group	R_a, μm	S, mm
1	0.01	0.0060	6	0.16 0.32	0.0125 0.0160
2	0.01 0.02	0.0060 0.0080	7	0.32 0.63	0.0125 0.0160
3	0.02 0.04	0.0080 0.0100	8	0.63 1.25	0.0160 0.0200
4	0.04 0.08	0.0080 0.0100	9	1.25 2.50	0.0200 0.0250
5	0.08 0.16	0.0100 0.0125	10	2.50 5.00	0.0250 0.0320

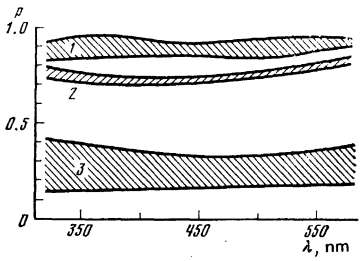

FIG. 1. Polarization of radiation.

$\approx 0.84-0.96$) for the smoothest surfaces, and only at normal entry of the electrons into the target (region 1). It should be noted here that it is precisely for region 1 that the experimental data agree with good accuracy with the conclusions of the theory of transition radiation, both with respect to the absolute value of the intensity and with respect to the different functional dependences.

However, a very slight increase of the degree of roughness of the surface (targets of group 2, region 2) leads to a decrease of the degree of polarization of the radiation to $p \approx 0.7-0.85$, and for all the remaining target groups the degree of polarization does not exceed the level $p \approx 0.15-0.42$ even at normal entry of the electrons into the target. At $\psi \gtrsim 45°$ (region 3) the degree of polarization turns out to be low for all the targets, including the smoothest ones. This is understandable, since the surface roughness should be more strongly felt with increasing entry angle.

Thus, the source of the unpolarized part of the radiation in practically all the experiment performed to date becomes clear. The magnitude of the unpolarized part of the radiation varies from experiment to experiment, since different targets are used and these are most likely to have different degrees of surface roughness.

The spectral distributions of the radiation for targets of certain groups, made of aluminum, silver, and germanium, are shown in Figs. 2 and 3. These figures show the sum $W_\omega^{\parallel} + W_\omega^{\perp}$ of the parallel and perpendicular components of the radiation, with curves *1–7* corresponding to seven different electron entry angles: *1*) $\psi = 88.5°$, *2*)87°, *3*) 84°, *4*) 81°, *5*) 75°, *6*) 45°, *7*) 0.

The first conclusion that follows from the data of Figs. 2 and 3 is that the smallest radiation yield occurs at normal entry of the electrons (curves 7) into the targets of all groups (some small deviations are observed only for targets of the first group); in this case the radiation intensities for targets of different groups differ by a factor 1.5–2. The theory of transition radiation predicts an intensity at the level of curves *7*). However, we can state only for the target of the first group that this is transition radiation, since the degree of polarization in this case is quite high. For the remaining groups of targets the degree of polarization is low. Calculations recently performed by Bagiyan and Ter-Mikaelyan[27] show that in fact, owing to the surface roughness, the transition radiation, first, becomes depolarized and second, the radiation yield can be larger than the yield of the transition radiation for a flat boundary. No detailed comparison of the experi-

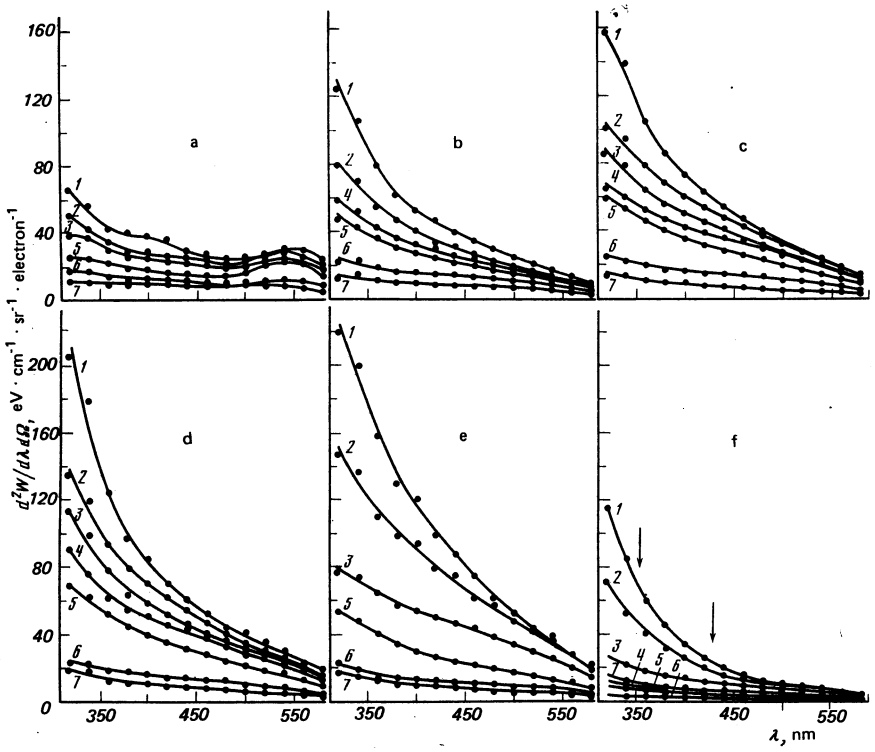

FIG. 2. Spectral distributions of radiation for aluminum targets: a) $R_a = 4.6$ μm, $S = 30$ μm; b) $R_a = 1.11$ μm, $S = 18.5$ μm; c) $R_a = 0.24$ μm, $S = 12.5$ μm; d) $R_a = 0.15$ μm, $S = 11$ μm; e) $R_a = 0.032$ μm, $S = 8.9$ μm; f) $R_a \lesssim 0.01$ μm, $S \lesssim 6$ μm.

mental data with the formulas of Ref. 27 was made, since this was not the purpose of the present paper, nor were estimates made to show that the degree of polarization observed in experiment is lower than predicted by the theory.[27]

In the general case of oblique incidence of the electron, a perpendicular component of the transition radiation appears in addition to the parallel components. Under the conditions of the experiment in question $W^{\perp} \ll W^{\parallel}$. In addition, $W^{\perp}$ is much less than the experimental noise level, so that only the parallel component of the radiation should be detected in the experiment. With increasing entry angle, the intensity of the transition radiation should decrease like $\sim\cos^2\psi$, while as $\psi \to \pi/2$ the transition effect vanishes. However, as follows from the data of Figs. 2 and 3, for practically all groups of targets the spectral energy density of the radiation, on the contrary increases with increasing entry angle and reaches a maximum value at glancing entry of the electrons into the target. In individual cases the radiation yield at $\psi = 88.5°$ (curves *1*) exceeds the yield at $\psi = 0$ (curve *7*) by more than an order of magnitude. It is characteristic that in cases when transition radiation is observed (targets of group *1*, curves *7*), the spectral energy density of the radiation first decreases with increasing entry angle, as does transition radiation, but then begins to increase again.

The largest radiation yield was observed for aluminum. The absolute value of the radiation intensity depends most likely on the optical constants of the target material. Next, the intensity of the radiation depends on the degree of roughness of the target surface, i.e., on the quantity R_a. It reaches a maximum value in the region where $R_a \approx 0.04$–0.16 μm. This was to be expected, inasmuch as for the investigated spectral interval this is precisely the region where $R_a \sim \lambda$. In addition, it should be noted that if the radiation intensity does depend on S at all it does so weakly.

For aluminum and germanium targets the spectral energy density of the radiation in the long-wave part of the spectrum is much less than in the region close to ultraviolet. The spectral curves have a general form $\propto \lambda^n$ where $n \approx 2$–5 depending on R_a, the electron entry angle into the target, and the wavelength.

The radiation spectra for silver differ little in the long-wave part from the radiation spectra for aluminum and germanium, except that for targets of the sixth and eighth groups they are more gently sloping (cf., e.g., curves *2*, *4*, *5* of Fig. 3a and 3b with curves *2*, *4*, and *5* of Figs. 2b and 2c). However, for silver targets of all groups the spectral density of the radiation energy decreases sharply in the region $\lambda \lesssim 350$ nm, leading to formation of a broad maximum in the spectral curves. The widths of these maxima and the value of the spectral energy density of the radiation at the maximum depend on the degree of roughness of the target and the electron entry angle.

An analysis of the data shows that a similar behavior of the spectral curves for silver depends on the optical constants of this material. Indeed, an analogous behavior was observed already for transition radiation,[12,15] namely, whereas for many metals (Al, Au, Cu, In, Pt) the emission spectra revealed no such singularities and their form is close to $\propto \lambda^2$, as is the case for transition radiation without allowance for the disper-

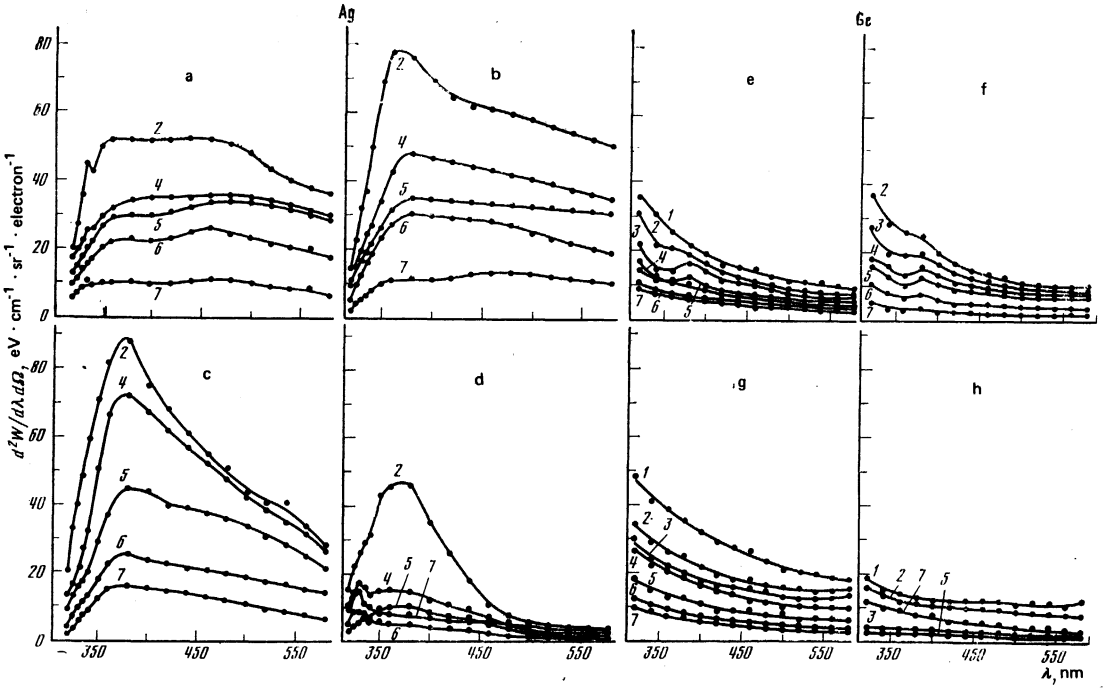

FIG. 3. Spectral distributions of radiation for silver targets: a) $R_a = 0.98$ μm, $S = 20$ μm; b) $R_a = 0.32$ μm, $S = 12.4$ μm; c) $R_a = 0.067$ μm, $S = 9.7$ μm; d) $R_a \lesssim 0.01$ μm, $S \lesssim 6$ μm; and Ge: e) $R_a = 0.482$ μm, $S = 13.8$ μm; f) $R_a = 0.140$ μm, $S = 11$ μm; g) $R_a = 0.035$ μm, $S = 8.9$ μm; h) $R_a \lesssim 0.01$ μm, $S \lesssim 6$ μm.

sion for the medium, the emission spectra for silver at a sharp peak at $\lambda \approx 330$–340 nm; in Fig. 3 this peak is observed for targets of group 1. The reason is that silver has a transparency point precisely in the region $\lambda \approx 325$–340 nm, and the values of the optical constants in this region determine the form of the emission spectra. The same was observed also in the region of the vacuum ultraviolet ($\lambda \approx 80$–100 nm) for Al and In.[23,24]

To our knowledge, there are no theoretical papers dealing with the radiation of electrons as they enter into a medium with a specified degree of roughness of the surface at various angles. We note here that the calculations of Bagiyan and Ter-Mikaelyan[27] can predict only the change of the characteristics of the transition radiation, and furthermore at relatively small entry angles (at large entry angles, and all the more at glancing entry, these calculations are not valid). We are therefore unable to compare directly the obtained experimental data with those expected from any concrete theory.

We have noted earlier[10] that an effective mechanism exists for generating radiation by an electron moving over surface roughnesses. In fact, at large entry angles, and all the more at glancing angles, part of the electron path near the entry into the target is at a small distance ($\lesssim \chi$) from the target surface, so that it can produce radiation from the roughnesses on the surface. This radiation is the analog of the radiation of an electron passing over a diffraction grating (one-dimensionally periodically arranged roughnesses), known in the literature as the Smith-Purcell radiation[28]; it was investigated experimentally in detail[29] and was theoretically explained in the conclusions of Bachheimer's papers.[30]

An electron moving over a periodically corrugated surface induces in the latter currents. If the charge moves close to the surface, then the induced currents can be reduced to motion of the image charge, i.e., a charge of the same magnitude and of opposite sign, located symmetrical to the source relative to the surface of the diffraction grating. When the electron is over a crest of the grating, the distance between the source and its image is less than when the source is located over a trough. Thus, the moving electron and its image form a dipole whose magnitude varies periodically with time. The emission of this alternating dipole is in fact identified with the radiation of an electron moving over a grating.

The radiation wavelength, the angle θ at which the photons are emitted (the angle θ is reckoned from the direction of motion of the electron), and the particle velocity are connected by Purcell's relation

$$\lambda = S(1 - \beta \cos i)/\beta n \cos\theta, \qquad (1)$$

where S is the pitch of the grating, $n = 1, 2, \ldots$ is the number of the radiation harmonic, and i is the angle between the velocity of the charge and the vector $S(i = \pi/2 - \psi)$. If the mean values of S and R_a for targets with randomly distributed roughnesses differ little from the values of the analogous parameters for a surface with ordered roughnesses, then the total radiation energy in these two cases should not differ significantly. The variable pitch S for targets with randomly distributed roughnesses causes violation of the condition (1), vanishing of the discreteness of the radiation harmonics, and smearing of the radiation energy of the discrete harmonics over the entire spectrum.

There are also other factors that can lead to different results in these two cases; nonetheless, we felt it appropriate to compare our experimental results for aluminum with data obtained on the Smith-Purcell radiation of electrons of energy 130 keV,[29] moving in a grating with an aluminum coating at glancing angles $i = 0.2–1.0°$. The electrons move perpendicular to the lines of the grating, and the radiation in the vicinity of $\lambda \approx 400$ nm is detected in a plane containing the normal to the surface and the direction of electron motion.

Figure 4 shows plots of the spectral density of the radiation energy for two harmonics ($n = 4$ and 5), measured at $i = 0.57°$ for a grating with $S = 8.2 \times 10^{5}$ cm. For each harmonic there is observed, at a definite angle, a coherent radiation peak at $\lambda = 400$ nm with a width $\Delta\lambda \approx 10–15$ nm. Also observed is an "amorphous" part of the radiation, due apparently to fluctuations of the grating pitch, and also to roughnesses present on the surface of the grating in addition to the lines. The amorphous part of the radiation contains also a perpendicular component, which reaches 10–25% of the parallel component of the radiation. The energy of the amorphous parts of the radiation depends little on the observation angle and constitutes a substantial fraction of the total radiation; depending on the observation angle, its intensity ranges from 45 to 80% of the intensity of the total radiation.

Thus, a comparison of the obtained experimental data with the amorphous part of the radiation in Fig. 4 is not devoid of meaning. However, in the comparison it is necessary to reduce the indicated experimental data to identical conditions. With respect to the degree of the roughness, the closest to a grating is a target of group 1 (Fig. 2; the compared spectral region is indicated by the arrows). Next, the results of Fig. 4 were obtained for electrons of energy 130 keV at $i = 0.57°$, while our present data were obtained at 80 keV, and the smallest glancing angle was 2.5° (Fig. 2, curve *1*). Taking into account the dependence of the total radiation energy on the glancing angle i (Fig. 4), as well as the linear increase of the radiation intensity with increasing electron energy, we can reduce the data of both experiments to a common denominator and decide on the degree of their agreement. Such a comparison is given on the plot corresponding to $n = 4$ and $\theta = 107.2°$ (Fig. 4b). The dark circles and the solid curve in Fig. 4 corresponds to the experimental data of Ref. 29, while the light circles and the dashed curve in Fig. 2 correspond to our present data.

The comparison convinces us that the suggested mechanism of radiation generation by electrons moving in a surface at glancing angles is apparently correct, and the radiation in question is due to roughnesses present on the surface of the material. Furthermore, since the radiation energy in the case of dipole radiation depends on the square of the dipole moment made up by the electron and its image,[31] and consequently this radiation energy is proportional to $\sim R_a^2$, we hope that further reduction of the experimental data will lead to the development of a new concrete and simple method of exactly determining the degree of roughness of a material surface by measuring the radiation energy detected upon entry of an electron into the material.

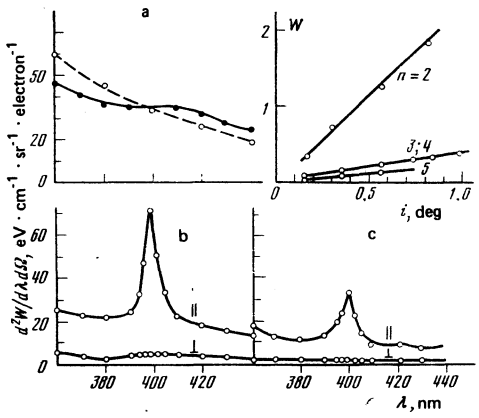

FIG. 4. Spectral distribution of Smith-Purcell radiation in accordance with the data of Ref. 29: a) see the text for an explanantion; b) $\theta = 107.2°$, $n = 4$; c) $\theta = 141.6°$, $n = 5$.

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Subradiative structure in the absorption spectrum of a two-level system in a biharmonic radiation field

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The changes of the absorption spectrum of a two-level atomic system (Cd^{113} vapor) under the influence of two quasiresonant radiation fields at arbitrary amplitudes of these fields are investigated. The frequency of one of the fields was at resonance with the atomic transition, while the frequency of the other, test field, was scanned. Within the Stark structure of the absorption spectrum, "ultranarrow" resonances that converged towards the center of the line were observed. The width of the resonances observed in the absorption was much less than the radiative line width. A theory is constructed which describes the shape of the resonances, the positions of the maxima, and the widths of the resonances. The results of the theory agree with the experimental data.

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1. INTRODUCTION

The interaction of powerful electromagnetic radiation with resonant atomic systems is the subject of numerous experimental and theoretical investigations in nonlinear optics. The variety of the energy spectrum of the atomic and molecular systems admits as a rule of a choice of a situation wherein a good approximation of a two-level system is possible provided that the radiation frequency is not at resonance with the atomic transition. The analysis of the fundamental questions of atomic spectroscopy and the investigation of the emission and absorption spectra of resonant systems are of great importance both for a better understanding of the "atom + field" quantum system, and for practical problems in laser spectroscopy, stabilization of laser frequency, diagnostics of a medium, etc.[1-3]

The spectral and energy characteristics of an atomic system in an intense monochromatic field were investigated in a number of theoretical and experimental studies,[4-9] in which the quasienergy structure of the atom in a radiation field (Fig. 1a) and its absorption and emission spectra (Figs. 1b and 1c) were established. The quasilevel concept turned out to be most useful for the interpretation of the spectral characteristics of atomic systems in strong fields. Indeed, the spectrum of the noncoherent part of the spontaneous scattering in an intense radiation field can be set in correspondence with transitions between quasienergy levels that determine the number and position of the maxima, and also the distribution of the intensity of the radiation over the spectrum (Fig. 1b).

The structure of the quasilevels manifests itself also in the investigation of the absorption spectrum of atoms placed in an intense monochromatic field ($E_0\cos\omega_0 t$), which can be obtained by scanning the frequency of a probing field ($E\cos\omega t$) near the frequency of the atomic transition. A theoretical analysis of the absorption line shape[2] has shown that at strong-field amplitudes of the order of $dE_0/\hbar \leqslant \Gamma$ (Γ is the width of the atomic line) the absorption spectrum is equivalent both to the quasienergy structure (Fig. 1c) and to the spontaneous-emission spectrum. In a more intense field ($dE_0/\hbar > \Gamma$, $f = E/E_0 \ll 1$) there appear in the vicinity of the absorption line regions of enhancement of the weak probing field in the absence of population inversion. By now there are available reliable experimental results obtained in the radio frequency and optical bands, which agree fully with the theoretical concepts.[7-9]

On going to interactions of resonant systems with intense nonmonochromatic radiation, the spectral characteristics of the absorbing media will be determined not only by the usual parameters but also by the statistics of the radiation. These phenomena are observed when the radiation source contains more than one field

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