Electron scattering near the focus of a laser

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Scattering of 7—15 eV electrons passing near the focus of a Q-switched ruby laser is observed. The dependence of the scattering probability on the electron impact parameter is investigated. The experimental data are compared with calculations performed by the averaging method.

In connection with the development of lasers, the possibility has arisen of the experimental investigation of the interaction of an intense optical beam with free electrons. Thus the well-known effect of electron scattering by standing light waves (the Kapitza-Dirac effect) has recently been subjected to experimental verification. This effect had been predicted in 1933.[1-5]

In the present work, the scattering of slow electrons passing near a focused beam of a Q-switched ruby laser has been studied. S. P. Kapitza has shown that elastic scattering of a nonrelativistic electron under the action of force gradients is possible in the focal plane of such a laser. The calculation was carried out by the method of averaging the classical motion of an electron in a rapidly oscillating electromagnetic field.[7,8] It is proposed to apply this method below to the study of the intensity distribution of the electromagnetic field near the focus of a laser. The researches of[9-18] have been devoted to this and similar questions.

Recently, the stimulated Compton scattering of light has attracted attention in connection with the problem of the heating of a plasma to thermonuclear temperatures by means of laser radiation.[17] The scattering of electrons passing near the focus of the laser can also be treated as a stimulated Compton effect by using a plane-wave expansion of the field near the focus.

THEORETICAL ESTIMATES

Let us consider briefly the fundamental results of the classical calculation of electron scattering near the focus of a laser and the conditions for its validity. The problem is solved under the assumption that the motion of the electron in the field of the laser can be described in a classical manner.

If the electron travels a distance of the order of a light wavelength in a time that is much greater than the period of oscillation of the electromagnetic field, then we can use the method of averaging the motion of the electron in the rapidly oscillating electromagnetic field.[7,8] According to this method, the motion of the nonrelativistic electron with charge e and mass m in an electromagnetic field with intensities $\mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r})e^{-i\omega t}$ and $\mathbf{H}(\mathbf{r}, t) = \mathbf{H}(\mathbf{r})e^{-i\omega t}$ can be represented approximately as small oscillations $\mathbf{r}_i(t)$ relative to some average trajectory $\mathbf{r}(t)$. The equation of averaged motion can then be written down in the form

$$m\ddot{\mathbf{r}} = -\nabla U(\mathbf{r}), \quad U(\mathbf{r}) = \frac{e^2|\mathbf{E}(\mathbf{r})|^2}{4m\omega^2}, \tag{1}$$

which is valid under the conditions

$$|\mathbf{r}_i(t)| \ll R, \quad |\dot{\mathbf{r}}_i(t)| \ll c, \tag{2}$$

where R is the spatial dimension of the inhomogeneity of the field, c the velocity of light in a vacuum.

Thus the problem reduces to elastic scattering of the electron in a given field with potential $U(\mathbf{r})$. We assume that the beam of the laser is focused symmetrically relative to the z axis, and that the electron moves initially parallel to the x axis with constant speed v. We further assume that the energy of the incident electron $u \gg U(\mathbf{r})$ and that the scattering takes place at small angles.

S. P. Kapitza[6] has shown that for the case in which the intensity distribution of the electromagnetic field in the focal plane (z = 0) of the laser can be approximated by the Gaussian distribution

$$|\mathbf{E}(\mathbf{r})|^2 = E_0^2 \exp[-(x^2+y^2)/R^2] \tag{3}$$

(R is the effective radius of the focal region), the scattering angle of the electron in the focal plane, after passage through the focus of the laser, is determined by the relation

$$\theta = \sqrt{2}\,\theta_r \frac{y}{R} \exp\left[\frac{1}{2} - \left(\frac{y}{R}\right)^2\right] \tag{4}$$

where

$$\theta_r = 2.27(\lambda/R)^2 P/u \tag{5}$$

is the maximum value of the angle of deflection and is realized at an impact parameter $y = R/\sqrt{2}$. The radiation power of the laser P is expressed here in MW and the energy of the electron u in eV; λ is the wavelength of the laser beam.

For a quantum-mechanical consideration of this problem, the electromagnetic field is introduced in classical fashion and the motion of the electron is described by the Schrödinger equation. Just as in the classical calculation, the problem for the nonrelativistic electron can be materially simplified by means of the method of averaging over the period of oscillation of the electromagnetic field, as is done in[13-18]. The time-averaged wave function of the electron is the solution of the stationary Schrödinger equation in which the Hamiltonian of the electron with charge e and mass m, situated in an external electromagnetic field with vector potential **A** (div **A** = 0), is described by the relation

$$\hat{H} = -\frac{\hbar}{2m}\Delta + U(\mathbf{r}), \quad U(\mathbf{r}) = \frac{e^2|\mathbf{A}(\mathbf{r})|^2}{4mc^2}, \tag{6}$$

where ħ is Planck's constant. For the case of a monochromatic field with frequency of oscillation ω, the potential $U(\mathbf{r})$ is identical with the potential (1) of the classical gradient forces.

Thus, just as in the classical case, the application of the averaging method allows us to reduce the given problem to the study of the scattering of an electron in a given constant field with a potential $U(\mathbf{r})$ which is defined in the relation (6).

The quantum analysis allows us to determine the condition for the validity of the classical scattering at angle θ. This condition can be written in the form

$$\theta \gg \hbar / p\rho, \quad (7)$$

where ρ is the impact distance of an electron with momentum p.

The problem of electron scattering by standing light waves[13-17] usually reduces to a solution of the one-dimensional stationary Schrödinger equation with the potential $U(z) = U_0 \cos(2\pi z/\lambda)$, where λ is the wavelength, of light propagating along the z axis. Here the classical condition (7) is not satisfied and one can use the Born approximation for calculation of the scattering cross section.

In the case of electron scattering near the focus of the laser, it is necessary to solve the three-dimensional Schrödinger equation, since the potential $U(\mathbf{r})$, in accord with (6), depends on all three coordinates. The problem is simplified if it is assumed that the scattering takes place in a central field. We consider the case in which the intensity distribution of the electromagnetic field near the focus of the laser can be approximated by a three-dimensional Gaussian distribution with effective radius R, which corresponds to a spherically symmetric diverging beam. For a real optical system, such an approximation can evidently be applied to the case of the focusing of the beam of a multi-mode laser by means of a lens with a large aperture, when the transverse and longitudinal effective dimensions of the focal plane become comparable.

Using the laws of conservation of energy and momentum in a central field, we obtain the result that the angle of classical scattering of the electron is determined in first approximation by the relation (4), where it is necessary to replace y by r. For a value of the impact parameter $r = R/\sqrt{2}$, we obtain the classical scattering at the maximum angle θ_r, which is determined by the relation (5).

Applying the method of partial waves in the quasi-classical approximation, we can show that the quasi-classical effective differential scattering cross section in the unit solid angle $d\Omega$ near the angle θ is determined by the relation[20]

$$\frac{d\sigma}{d\Omega} = (k_0 R \theta_r)^{1/3} \left(\frac{R}{\theta}\right)^2 |v(t)|^2, \qquad t = (k_0 R \theta_r)^{2/3} \frac{\theta - \theta_r}{2^{1/2}\theta_r}, \quad (8)$$

where $k_0 = 2\pi/\lambda_0$, λ_0 is the Debye wavelength of the electron, and v(t) is the Airy function.

At a scattering angle $\theta < \theta_r$, which corresponds to the values $t < 0$, the function v(t) oscillates about its mean value; substitution of this mean value in Eqs. (8) yields the classical scattering cross section. At $t > 0$, the function v(t) decays exponentially with increase in t, which corresponds to scattering at the classically forbidden angle $\theta > \theta_r$.

We note that the scattering of electrons that pass near the focus of a laser can be treated as a stimulated Compton effect.[17] We expand the electromagnetic field in the focal plane of the beam in a Fourier integral in plane monochromatic waves. In quantum electrodynamics, each such wave is set in correspondence with phonons of momentum $\hbar\mathbf{k}$ and energy $\hbar\omega$, where $\mathbf{k}$ is the wave vector and ω the frequency of the corresponding plane wave. We consider two-quantum stimulated Compton scattering, as a result of which the electron absorbs a photon with momentum $\hbar k_1$ and energy $\hbar\omega_1$ from one plane wave, accompanied by simultaneous stimulated emission of a second photon with momentum $\hbar\mathbf{k}_2$ and energy $\hbar\omega_2$ into another wave. Here the laws of conservation of energy and momentum are formally identical with the laws of conservation for the ordinary Compton effect, with this one difference that the values of $\mathbf{k}_2$ and ω_2 are governed by the stimulating radiation.

For simplicity, we assume that the laser radiation is strictly monochromatic with frequency ω. Then the frequencies of the photons are equal: $\omega_1 = \omega_2 = \omega$; consequently, the electron energy u does not change. It is then easy to deduce from the momentum conservation law that the angle of electron scattering θ is determined by the relation

$$\sin\frac{\theta}{2} = \frac{\hbar k}{p} \sin\frac{\vartheta}{2}, \quad (9)$$

where ϑ is the angle between the directions of the momenta of the photons, and $k = |\mathbf{k}_1| = |\mathbf{k}_2|$.

For an angle $\vartheta = \pi$, the relation (9) determines the angle of scattering of the electron by a standing sound wave.[1] Here all the vectors of the momenta of the interacting particles lie in one plane. For the case $\vartheta = 0$, we get, in accord with (9), the result that the scattering angle of the electron is $\theta = 0$. This corresponds to the case of interaction of the electron with a single plane wave, which is forbidden by the conservation laws.

THE EXPERIMENTAL SETUP

The problem under consideration has much in common with the scattering of electrons by standing light waves; therefore, in the experimental setup, we have used essentially the same methods which were employed for the observation of the Kapitza-Dirac effect.[2,5] Thus, for the observation of small electron-scattering angles we used the electron-optical analog of the Schlieren method, which was used by Takeda and Matsui.[5] In recording the scattered electrons, we used a scintillation detector, just as in[2,5]. The basic difference between the setup of this experiment and those of the cited researches is the use of discriminators, of coincidence circuits that feed scaler circuits, and of other pulse apparatus generally used in experiments on nuclear physics. The application of such apparatus made it possible to take better advantage of the pulsed operating regime of the laser. Here we succeeded in separating the useful signal from the scattered electrons against the interference background, the level of which exceeded the amplitude of the useful signal.

In experiments on the observation of the Kapitza-Dirac effect, the characteristic dimension of the spatial inhomogeneity of the field is equal to the wavelength λ of the laser radiation; therefore, passage through the region of standing waves is always accomplished by a comparative wide beam of electrons with dimension $R_0 \gg \lambda$. In the given experiment, the characteristic dimension of the inhomogeneity of the field is the effective radius of the focal region $R \gg \lambda$, which makes it possible to use a comparatively narrow beam of electrons of width $R_0 \lesssim R$, and to study the dependence of the scattering angle on the impact parameter of the electrons.

Besides the high angular resolution, the given experiment requires high sensitivity of the apparatus, since the electron scattering takes place only during the short laser pulse. For example, for a beam current $I = 0.1$ μA and a laser pulse duration $\tau_0 = 50$ nsec we get for the number of electrons that interact with the laser radiation the value $N = I\tau_0 \approx 3 \times 10^4$. As is easy to show, the number of electrons recorded by the detector is only a small fraction of the total number of interacting electrons N.

In focusing the laser beam by means of a lens with aperture $\vartheta_0 \ll 1$, the effective size of the focal region along the direction of the optic axis of the lens is $R_z \sim R/\vartheta_0 \gg R$, where R is the effective radius of the intensity distribution in the focal plane of the lens. Here, to increase the sensitivity of the apparatus, one can carry out a probing of the focal region of the laser by a ribbon beam of electrons with dimension $z_0 \lesssim R_z$ in the region of interaction with the laser beam.

The schematic diagram of the experimental apparatus is shown in Fig. 1. A single-stage ruby laser was used, with an active element 240 mm long and 16 mm in diameter. Q-switching of the laser was accomplished by a phototropic shutter. The radiation power amounted to ~10 MW in a pulse of duration ~50 nsec. Cooling of the active element was accomplished by liquid-nitrogen vapor. The working regime of the laser consisted of one pulse per minute. The laser radiation was focused by lens 8 at the center of the vacuum chamber. The effective radius of the focal region amounted to 0.1—0.2 mm. Part of the radiation was diverted by a plane-parallel quartz plate 14 to a coaxial photocell 15 of type FEK-09, which served to record the laser radiation with the oscilloscopes 19 and 25. In addition, the signal from this photocell was fed to one of the channels of the coincidence circuit 20 by means of the integrated discriminator 16 and the delay line 18. Part of the laser radiation was diverted by the plane-parallel plate 7 to the lens 13, which is identical to the basic lens 8. A movable slit 12 of width ~0.01 mm was placed in the focal region of the auxiliary lens 13. The light passing through the slit 12 falls on the photocell 11, the signal from which is recorded by a long-persistence oscilloscope. Such a system made it possible to estimate the intensity distribution in the focal region of the lens 13, which evidently differed little from the intensity distribution near the focus of the main lens 8.

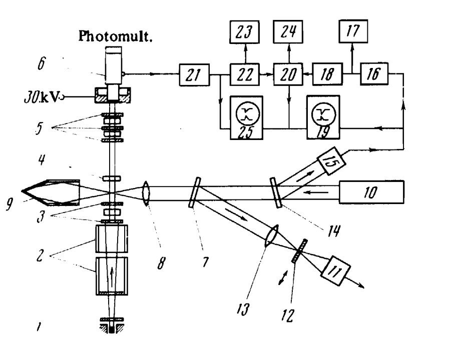

FIG. 1. Diagram of the experimental apparatus: 1 — electron beam, 2 — electron lens, 3 — diaphragm, 4 — deflecting plates of the analyzer, 5 — slits of the analyzer, 6 — electron detector, 7, 14 — beam-splitting plates, 8, 13 — lenses; 9 — light trap, 10 — laser, 11, 15 — coaxial photocells, 12 — movable slit, 16, 22 — discriminators, 17, 24 — scaler circuits, 18 — delay line, 20 — coincidence circuit, 21 — amplifier, 23 — intensity meter.

A ribbon beam of 5—30 eV electrons and a current ~0.1 μA passed near the focus of lens 8. An electron-optical system of a portable type was used to form the ribbon beam of electrons; it consisted of a cylindrical Pierce gun 1, a retarding electrostatic lens 2, and a collimating diaphragm 3. The electrostatic lens consisted of two cylinders of diameter 30 mm, and operated with a ratio of the potentials on the cylinders equal to 10—12. The collimating diaphragms were two parallel slits of width 0.1 mm, located along the beam at a distance of 20 mm from one another. Between the slits we placed deflecting plates. Such a system made it possible to obtain a beam of electrons with transverse dimensions ~0.1×1 mm in the region of interaction of the laser radiation and a beam divergence angle ~5×10^{-3} rad.

After interaction with the laser radiation, the angular distribution of the electrons in the beam was measured by means of an electrostatic analyzer, which consisted of the deflecting plates 4, a flight baseline of 100 mm, cutoff diaphragms 5, the scintillation detector 6, and the measurement apparatus. For diaphragms 5 of the analyzer we used three parallel slits of width 0.2 mm, located on the axis of the beam 12 mm apart. The entrance slit was shifted relative to the axis of the beam in the perpendicular plane by a distance of 1 mm. This was necessary to shield the photomultiplier of the detector from the scattered light of the laser. Deflecting plates were used to pass the electrons through the slit.

To record the electrons passing through the slit of the analyzer, we used the scintillation detector 6, which consisted of a scintillator, a light pipe, and an FÉU-36 photomultiplier. The advantage of such a detector is the combination of high sensitivity with high time resolution, which was necessary for the given experiment. A plastic scintillator was used, in the form of a polished disc of diameter 30 mm and thickness 5 mm. To increase the brightness of the scintillations, the electrons were accelerated to 30 keV; therefore the scintillator was at a high potential relative to the rest of the apparatus and was insulated from the cathode of the photomultiplier by a light pipe in the form of a polished Plexiglas cylinder of diameter 30 mm and length 70 mm. To increase the brightness of the scintillations and to shield the photocathode from the scattered light of the laser, a layer of aluminum of thickness about 0.2 μ was vacuum sputtered on the scintillator. The accelerated electrons passed through this layer without appreciable energy loss.

The analyzer of the angular distribution of the electrons in the beam can operate in the scanning or in the driven sweep mode. In the scanning regime, a sawtooth voltage synchronous with sweep voltage of the oscilloscope 25 was applied to the deflecting plates 4. The signal from the electron detector 6 was also fed to this oscilloscope through the amplifier 21. The scanning regime was used for the tuning and monitoring of the parameters of the electron beam. To study the electron scattering near the focus of the laser, we used the driven sweep mode of the analyzer. In this mode, a constant bias was applied to the deflecting plates 4, under the action of which the electron beam was deflected so that the axis of the beam passed close to one of the edges of the entrance slit 5 of the analyzer. Here a constant number of electrons fell on the electron detector. This number changed by some small amount as a result of the scattering of the beam during the time of duration of the radiation pulse of the laser; the amount was recorded by the apparatus. The measurement apparatus was designed for operation with pulses of definite polarity, which corresponded to an increase in the number of electrons passing through the slit of the analyzer; therefore, electrons were recorded whose scattering angles were of the same sign. For measurement of scattering angles of opposite sign, a shift of the electron beam to the other edge of the slit of the analyzer was carried out.

Fast and slow fluctuations of the electron beam were noted during the course of the experiment. Fast fluctuations with a characteristic time $\tau \sim \tau_0$, where τ_0 is the pulse length of the laser radiation, were recorded by the apparatus. The amplitude of the signal from the fast fluctuations was comparable with the amplitude of the signal from the scattered electrons; therefore, to separate the useful signal, we used the coincidence circuit 20 with a resolving time equal to 100 nsec. The probability of appearance of random coincidences, as control experiments showed, amounts to ~0.01. The causes of the fast fluctuations of the beam were apparently a shot effect, fluctuation of space charge and so forth. The slow fluctuations of the beam with characteristic time $\tau > \tau_0$ were not recorded by the apparatus, but led to a change in the resolving power of the system. The causes of slow fluctuations of the beam were evidently the change in the emission current of the cathode, the effect of magnetic fields, and so on. To decrease the effect of slow fluctuations of the beam on the statistics of the experimental data, a control measurement of the parameters of the electron beam was carried out after every 100 pulses of radiation of the laser. For this purpose, calibrated pulses were applied to the deflection plates 4 of the analyzer.

To calibrate the sensitivity of the apparatus, all of the electron beams were deflected by a definite angle. This was accomplished with the aid of a bias voltage which was applied to the deflecting plates 4, located near the region of interaction of the electrons of the beam with the laser radiation. Here the minimum threshold angle of deflection of all electrons with energies 15–30 eV, which were recorded by the apparatus with probability ~100%, amounted to 5×10^{-5} rad. In the case of beam deflection by an angle $\sim 3 \times 10^{-5}$ rad, the recording probability fell to 50%. For a beam with electron energy equal to 7 eV, the threshold angle of deflection with probability of recording ~ 100% increases to a value of $\sim 10^{-4}$ rad, which is attributed to the broadening of the beam under the action of space charge forces.

EXPERIMENTAL RESULTS

In the given experiment, we investigated the dependence of the number of time coincidences between the fluctuations of the electron beam and the pulses of radiation of the laser on the position of the beam axis relative to the center of focus of the laser (y = 0). For impact parameters y that significantly exceed the effective radius of the focal region of the laser R, we observed only random coincidences with probability ~1%, which were due to the finite resolving time of the coincidence circuit and the loading of its channels. As the electron beam approaches the focal region, an increase was observed in the number of coincidences.

Figure 2a shows the experimental dependence of the relative number of coincidences on the impact parameter of the electrons passing near the laser focus. Here the apparatus recorded only those electrons that were

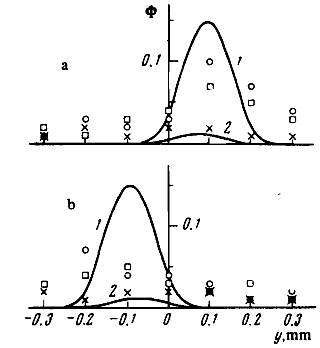

FIG. 2. Dependence of the relative number of coincidences on the impact parameter of the electrons: a – apparatus recorded electrons only with scattering angle $\theta > 0$; b – with angle $\theta < 0$; □ – electron energy 7 eV, ○ – 15 eV, × – 30 eV. The continuous curves are the calculated values; 1 – electron energy 15 eV, 2 – 30 eV.

scattered through an angle $\theta > 0$, which corresponded to a repulsion of the electrons from the center of focus for impact parameters y > 0 and attraction to the center of focus for y < 0. For each value of the impact parameter, about 100 pulses of the laser were emitted. It is seen that as one approaches the center of focus from the impact parameters y > 0, for electrons with energies of 15 eV, an increase is observed in the relative number of coincidences Φ, which reaches a maximum $\Phi_1 = 0.1$ at a value $y_1 = 0.1$ mm. For a position of the electron beam that is symmetric relative to the center of focus y = 0, a decrease was observed in the relative number of coincidences to Φ = 0.03. For values y < 0 we obtained $\Phi \leq 0.03$.

Similar dependences of the relative number of coincidences on the impact parameter were observed in probing the focal region of the laser with a beam of 7-eV electrons (Fig. 2). Here the sensitivity of the apparatus decreased by a factor of about two, owing to broadening of the electron beam in the plane of the detector slit.

Upon passage of a beam of 30-eV electrons through the focal region, a decrease was observed in the relative number of coincidences, to a value $\Phi \leq 0.02$.

By means of calibration curves, which determined the dependence of the amplitude of the signal at the output of the detector on the angle of deflection of the electron beam, one could estimate the scattering angle of the electrons passing near the focus of the laser. In our experiment, this angle did not exceed 10^{-4} rad. It was assumed here that all the electrons of the beam were deflected through the same angle.

DISCUSSION OF THE EXPERIMENTAL RESULTS

We shall first show that to interpret the experimental results we can use calculations that have been performed with the aid of the method of averaging the motion of the electron. In the given experiment, one can regard the effective radius of the focus of the laser R as the spatial dimension of the inhomogeneity of the electromagnetic field; here, $R \gg \lambda$, where λ is the wavelength of the laser radiation. In this case, as follows from the condition (2), the method of averaging is valid for electric fields

$$|\mathbf{E}(\mathbf{r})| \ll E_m = 2\pi mc^2 / \lambda e,$$

which, for a ruby laser, amounts to $E_m \approx 5 \times 10^{10}$ V/cm. Estimates show that the maximum value of the electric field intensity at the center of the focus is $\sim 5 \times 10^6$ V/cm in the given experiment, so that the condition (2) is satisfied.

We estimate the value of the impact parameter of the electron for which the classical relations (4) and (5) for the scattering angle are valid in the given experiment. For an electron with energy 15 eV, passing near the focus of a laser with radiated power 10 MW, the intensity distribution near which is determined by the relation (3) with the effective radius R = 0.1 mm, we find that the classical condition (7) is satisfied for impact parameters 5×10^{-3} mm $< y < 0.3$ mm. Upon increase in the effective radius in the focal plane up to R = 0.2 mm, the condition (7) is satisfied for impact parameters 2×10^{-2} mm $< y < 0.5$ mm. Consequently, to interpret the experimental data given in Fig. 2, the classical relations (4) and (5) can be used for the scattering angles.

For a 15-eV electron passing in the focal plane of a laser with radiated power P = 10 MW and effective radius of the focal region R = 0.1—0.2 mm, we get the maximum scattering angle $\theta_r \approx (1.8-7.3) \times 10^{-5}$ rad. Thus, estimates show that the effect should be observed near the recording threshold of the apparatus.

As follows from the experimental data given in Fig. 2, the scattering of 15-eV electrons was not observed for every pulse of laser radiation. To explain this effect, we can assume that the scattering of the electron is described by means of the classical relations (4) and (5), but, as a result of the unstable operation of the laser, the intensity distribution near the focus differs for the different pulses of the laser radiation, which leads to fluctuations of the values of the scattering angle of the electron passing close to the focal region. We assume here, in accord with the estimate made above, that the mean value of the scattering angle of the electron lies below the threshold of operation of the measurement apparatus.

Figure 2 shows the calculated dependences of the probability of recording the scattering on the impact parameter; the curves are constructed under the assumption that the effective radius of the focus and the impact parameter are random quantities, the distribution functions of which satisfy normal laws with standard deviations equal respectively to 0.03 mm and 0.05 mm, and with a mean value of the radius of the focus 0.16 mm. It is seen that there is qualitative agreement of the experimental data with the computed curves.

We note that the excess of the relative number of coincidences over the random counts, observed in Fig. 2 when the axis of the electron beam is located near the center of focus of the laser y = 0, can also be the result of a nonuniform distribution of the density of the electron beam in the space where interaction with the laser radiation occurs.

The small excess of the relative number of coincidences over the random events when electron deflection angles $\theta > 0$ are observed (Fig. 2a) at impact parameters $y < 0$, and angles $\theta < 0$ are observed at values of $y > 0$ (Fig. 2b), can evidently be attributed to the sharp peaks or dips which have sometimes been observed in the intensity distribution of the electromagnetic field near the focus of the laser by means of the auxiliary lens 13.

It is easy to generalize the relations (4) and (5) to include the case of a nonsymmetric intensity distribution in the focal plane of the laser. We find then that, for a given radiated power of the laser, the scattering angle of the electron does not depend, in first approximation, on the effective size of the focal region along the direction of motion of the electron. The reason is that the electric field intensity in the focal region decreases with increase in this dimension, but the time of interaction of the electron with the field increases.

When plotting the calculated curves of Fig. 2, the possibility of observation of electron scattering at classically forbidden angles was not taken into account. For example, for a 15-eV electron passing near the focus of a laser with a radiated power of 10 MW, the intensity distribution near which can be approximated by a Gaussian curve with effective radius 0.2 mm, we find that the effective differential scattering cross section at the classically forbidden angle $\theta = 1.2\,\theta_r$ decreases by a factor of about 10^3 in comparison with the scattering cross section of the electron at the maximum angle θ_r. This is in accord with Eq. (8).

We note that some contribution to the observed scattering of the electrons can be made by effects due to the interaction of the electrons with the intense optical radiation in the presence of ions,[17] which are formed by the ionization residual-gas molecules by the electron beam in the vacuum chamber of the apparatus.

Our experiment was carried out with the laser operating in the pulsed mode, so that the intensity distribution near the focus changed during the pulse length of the laser. Kibble[7] has shown that in the case in which the amplitude of the field is a slowly changing function of time, a change in the energy of the electron passing near the focus of the laser is possible. However, in this experiment, the 15-eV traverses a focal region with effective radius R = 0.1 mm in a time $\tau \approx 2R/v \approx 0.1$ nsec, which is considerably less than the pulse length of the laser radiation $\tau_0 \approx 50$ nsec; therefore the effect of the pulsed mode of operation of the laser on the averaged motion of the electron near the focus can be neglected.

By regarding the phenomenon in this case as stimulated Compton scattering, it can be shown that the expansion of the field near the focus in a Fourier integral contains plane waves of sufficient intensity which pass through an angle equal to the aperture angle of the focusing lens. The interaction with these waves makes the greatest contribution to the scattering of an electron passing near the focus of the laser. For example, for a 15-eV electron passing near the focus of a lens with aperture angle 0.1 rad, we obtain (from (9)) the scattering angle $\theta \approx 8 \times 10^{-5}$ rad, which is comparable with the estimates of the scattering angle of the electron from Eq. (5). However, in such a consideration, it is necessary to take into account the interaction of the electron with all the other plane waves, an interaction that can materially change this estimate.

In the foregoing estimates, the nonmonochromaticity of the laser radiation was not taken into account. Using the energy conservation law, we can show that, for two-quantum stimulated Compton scattering, a maximum change of energy of the electron by an amount $\Delta u = \hbar\Delta\omega$ is possible, where $\Delta\omega$ is the width of the spectrum of the laser radiation. For an electron passing near the focus of a ruby laser beam with a spectrum width 1 Å, we obtain a maximum change of energy $\Delta u \approx 3 \times 10^{-4}$ eV, which is much less than the potential of the averaged field (1) at the center of the focus.

It can be shown[11] that the effect of the light pressure on the electron passing near the focus of a laser with effective radius R = 0.1 mm will be smaller by a factor $\lambda^2/r_0R \approx 2 \times 10^6$ than the effect of the gradient forces. Here r_0 is the classical radius of the electron.

Thus, it follows from the results of measurements reported in this paper that the effect of electron scattering by a focus laser beam can be assumed to be established, although quantitative interpretation of this effect is difficult at the present time.

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