Electron drag by resonant-frequency light

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The effect of discrete atomic excitations on the drag current arising from photoionization of gas atoms or from inverse-bremsstrahlung absorption of light by electrons in a weakly ionized plasma is investigated. It is shown that this leads to resonance behavior and repeated changes in direction of the drag current in a specific energy range. The effect on the drag current of the Ramsauer minimum in the cross section for electron scattering by atoms is examined. The gas atoms chosen for study were argon and xenon.

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1. When investigating the absorption of light in the low-energy part of the spectrum one usually neglects the momentum of the photon and treats the process in the dipole approximation. It has been repeatedly shown,[1-5] however, that when the photon momentum is taken into account the angular distribution of the electrons that have absorbed photons becomes asymmetric with respect to the propagation direction of the light, the electrons moving preferentially in a direction parallel (or antiparallel) to the direction of the photon momentum. This asymmetry gives rise to a current in the gas—the drag current. The strength of the drag current can vary between wide limits—from $10^{-12}-10^{-5}$ A/cm^2 for the case of photoionization of gas atoms or the case of inverse-bremsstrahlung absorption of light by the electrons of a weakly ionized plasma,[2,3] up to 10^6-10^{10} A/cm^2 for the case of inverse-bremsstrahlung absorption by the electrons of a laser plasma.[4]

In the present work we investigate the drift current generated by the photoionization of gas atoms and by the inverse-bremsstrahlung absorption of light by the electrons of a weakly ionized plasma for the case of incident radiation frequencies close to or coinciding with characteristic frequencies of the atoms. At such frequencies, the amplitudes for those processes are of resonance type, and since the strength of the drift current is proportional to the amplitudes of the processes, it is natural to expect to find resonances in the drift current, too. The present work is devoted to the study of drift-current resonances.

2. One of the processes that gives rise to a current in a gas is the photoionizatioon of the gas atoms. A detailed theoretical study of the current that arises in this case was given in an earlier paper.[2] There it was shown that the drift-current density due to the photoionization of an atom from the nl shell is given by the formula

$$\mathbf{j}^{\mathrm{ph}}(\omega)=-\frac{1}{3}|e|W\varkappa\frac{\sigma^{nl}(\omega)}{\sigma_a(\varepsilon)}\gamma^{nl}(\omega), \tag{2.1}$$

where e is the electron charge, W is the flux density of the incident photons, $\sigma^{nl}(\omega)$ is the total cross section for photoionization of the atom from the nl shell, $\sigma_a(\varepsilon)$ is the cross section for elastic scattering of the photoelectrons by the gas atoms, $\gamma^{nl}(\omega)$ depends on the dipole and quadrupole photoionization amplitudes and the phases of the electron wave functions for the continuum,[2] and $\hbar\varkappa$ is the photon momentum. It is evident from Eq. (2.1) that resonances in $\sigma^{nl}(\omega)$ or $\gamma^{nl}(\omega)$ will be accompanied by resonances in the drag current.

In this section we shall investigate the behavior of the drag current in a frequency region x in which auto-ionizing states of the atom are excited, and in which, therefore, $\sigma^{nl}(\omega)$ and $\gamma^{nl}(\omega)$ are of resonance type. We shall begin by expressing the dipole and quadrupole amplitudes for photoionization of the atom from an outer nl shell in the form[6]

$$R_i(\omega)=r_i(\omega_s)+\frac{r_s(\omega_s)\Gamma_{si}(\omega_s)}{\hbar\omega-E_s+i\Gamma/2}. \tag{2.2}$$

Here r_i is the nonresonant part of the amplitude for photoionization of the atom from the nl shell to the continuum state i, r_s is the amplitude for discrete excitation to the resonance level s, $E_s=\hbar\omega_s$ is the excitation energy of the resonance, Γ_{si} is the amplitude for decay of the resonance level s to the continuum state i, and Γ is the total width of the resonance.

We shall assume that the atom has dipole and quadrupole resonances lying close together. Then, after calculating σ^{nl} and γ^{nl} from the dipole and quadrupole transition amplitudes as given by Eq. (2.2), we obtain the following expression for the drag current in the vicinity of the resonance:

$$j^{\mathrm{ph}}(\omega)=j_0(\omega_s)+\sum_{n=1}^{2}a_n\frac{\varepsilon_n+b_n}{\varepsilon_n^2+1}+\frac{\varepsilon_1+\varepsilon_1\varepsilon_2+\varepsilon_2+c}{(\varepsilon_1^2+1)(\varepsilon_2^2+1)}. \tag{2.3}$$

Here j_0 is the current that would flow in the absence of auto-ionization; $\varepsilon_n=(\hbar\omega-E_n)/(\Gamma_n/2)$ is the relative detuning from the resonance (Γ_n and E_n are the width and excitation energy, respectively, of the dipole or quadrupole resonance); and a_n, b_n, and c are certain constants. The second term in (2.3) represents the sum of the contributions from the individual dipole and quadrupole resonances, and the third term represents the interference between them. We note that Eq. (2.3) admits in principle, the possibility of a change in sign, and therefore of a change in the direction of the current, depending on the frequency of the radiation.

In this section we shall investigate the drag current due to photoionization of the argon atom from the $3p^6$ shell in the region in which there is only excited the $3s3p^64p$ auto-ionizing resonance ($E_s=26.6$ eV, $\Gamma=0.08$ eV),[7] which decays to the $3p^5\varepsilon s$ and $3p^5\varepsilon d$ continua. In this case Eq. (2.3) simplifies, taking the form

$$j=j_0+a\frac{\varepsilon+b}{\varepsilon^2+1}. \tag{2.4}$$

The results of a calculation[8] of the drag current in the

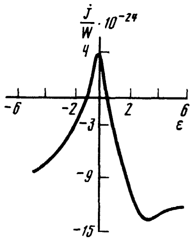

FIG. 1. The drag current in the vicinity of the excitation of the first $3s3p^64p$ auto-ionizing state in the photoionization of argon atoms. The ordinates give the ratio of the drag current density j (A/cm^2) to the incident-photon flux density W (cm^{-2} $\times$sec^{-1}).

random phase approximation with exchange is presented in Fig. 1; these results show how substantially the auto-ionizing states of an atom affect the drag current.

3. Now let us consider the drag current due to the inverse-bremsstrahlung absorption of light by electrons in the fields of the neutral atoms in a weakly ionized plasma. The drag-current density arising in this case is determined by the formula[3]

$$j^{ib}(\omega)=-\frac{1}{3}|e|WN_e\varkappa\sum_{l=0}^{\infty}\int_0^{\infty}f(v)v\frac{\sigma_{v'}^{l}(\omega)}{\sigma_a(v')}\gamma^l(v,v')dv. \tag{3.1}$$

Here N_e is the electron concentration in the plasma, $\sigma_a(v')$ is the cross section for elastic scattering of electrons by the atoms, v and v' are the velocities of an electron before and after absorbing a photon, $\gamma^l(v, v')$ is determined by a relation analogous to the corresponding relation for the photoionization case, $f(v)$ is the velocity distribution function for the plasma electrons, normalized to unity, and $\sigma_{v'}^l(\omega)$ is the usual inverse-bremsstrahlung partial cross section[9]:

$$\sigma_{k'}^{l}(\omega)=\frac{8}{3}\pi^4\frac{m^2e^2\omega}{\hbar^3k'k^3c}\{(l+1)R_{l+1}^2+lR_{l-1}^2\},\ [\mathrm{cm}^4\cdot\mathrm{sec}], \tag{3.2}$$

where the R_λ are dipole amplitudes for inverse-bremsstrahlung transitions of an electron to the continuum.

Since the strength of the drag current is inversely proportional to the cross section for elastic scattering of electrons by the atoms, all the features of the behavior of that cross section will make themselves felt in the behavior of the drag current. It is well known that for certain elements (Ar, Kr, Xe) the electron elastic scattering cross section has a deep minimum—the Ramsauer minimum—in the region of low incident-electron energies. In this section we shall investigate the inverse bremsstrahlung under these conditions.

We shall use a method discussed by Firsov and Chibisov[10] to describe the inverse-bremsstrahlung absorption of light by low-energy electrons. This method is based on the idea that at low electron energies it is sufficient to take into account only the s phase shifts in the wave functions of the incident and scattered electrons. In addition, since contributions from large distances are important in the expressions for the matrix elements, we express the electron wave functions in the form

$$P_{kl}(r)=(-1)^l\left(\frac{2}{\pi}\right)^{1/2}\frac{r^{l+1}}{k^l}\left(\frac{d}{r\,dr}\right)^l\frac{\sin[kr+\delta_l(k)]}{r}. \tag{3.3}$$

In this approximation the matrix elements for the dipole and quadrupole transitions take the forms

$$R_{01}=\frac{4}{\pi}\frac{k'^2\sin\delta_0(k)}{(k'^2-k^2)^2},\quad D_{02}=\frac{16}{\pi}\frac{k'^3\sin\delta_0(k)}{(k'^2-k^2)^3}. \tag{3.4}$$

Calculations using the matrix elements (3.4) yield the following expressions for the inverse-bremsstrahlung cross section and the drag current:

$$\sigma_{k'}^{0}(\omega)=\frac{8}{3}\pi^2\frac{e^2\hbar}{m^2c\omega^3}\left(\frac{k'}{k}\right)^3\sin^2\delta_0(k), \tag{3.5}$$

$$j^{ib}(\omega)=-\frac{16}{5}\pi|e|WN_e\left(\frac{e\hbar}{mc}\right)^2\frac{1}{\omega^3}\int_0^{\infty}f(k)\frac{E'^2\sigma^s(k)}{\sigma_a(k')}dk, \tag{3.6}$$

where ω is the photon energy and

$$\sigma^s(k)=\frac{4\pi}{k^2}\sin^2\delta_0(k)$$

is the cross section for elastic scattering of an electron with initial momentum $\hbar k$.

Let us use this approximation to investigate the drag current for the case of neutral Ar and Xe atoms, whose elastic scattering cross sections exhibit the Ramsauer minimum at scattered-electron energies[11] of 0.3 and 0.7 eV, respectively. We shall consider a weakly ionized plasma at the temperature $T = 300°$K, which corresponds to a thermal energy of ~0.03 eV for the electrons. We recall that the strength of the drag current depends on the electron concentration N_e in the plasma. In our case, however, as follows from the well-known Saha equation,[12] the gas is virtually non-ionized. As was pointed out by Zel'dovich and Raĭzer,[13] however, one can produce the required electron concentration in the gas by introducing a small admixture of a material having a low ionization potential: the admixture will be strongly ionized in the laser beam, thereby producing the necessary electron concentration N_e. Since our treatment of the drag current is for the case of an ideal plasma, which is defined by the inequality $N_e^{1/3}e^2 \ll T$, we shall assume that $N_e = 10^{14}$ cm^{-3}.

The results of calculating the drag current under the above assumptions are presented in Fig. 2. The figure shows that the drag current has a maximum, beyond which it falls off rather sharply, decreasing by a factor of 25 – 30 as the scattered-electron energy changes by only 0.7 eV. This is a consequence of the decrease in the drag current beyond the Ramsauer minimum as a result of the increases in both the photon frequency and the elastic scattering cross section.

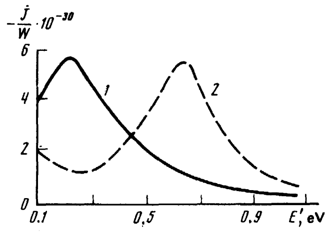

FIG. 2. Effect of the Ramsauer minimum in the elastic scattering cross section for electrons by atoms on the drag current arising from the inverse-bremsstrahlung absorption of light in an argon plasma (curve 1) and a Xenon plasma (curve 2). W and j have the same meanings as in Fig. 1, and $E' = \omega + \hbar^2k^2/2m$.

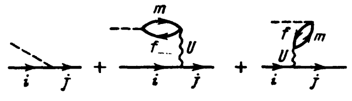

FIG. 3.

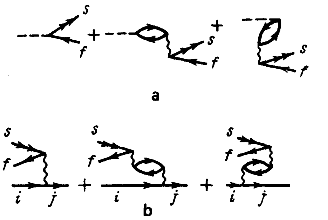

FIG. 4.

4. Now let us consider the drag current resulting from the inverse-bremsstrahlung absorption of light with photon x energies in the vicinity of the ionization potential I of the atom. As has been repeatedly shown,[14-17] in treating inverse-bremsstrahlung processes taking place in the field of an atom one must treat the atom as a dynamical system. In the first order of perturbation theory, this is equivalent to taking the diagrams shown in Fig. 3 into account in calculating the inverse-bremsstrahlung amplitude. In these diagrams a dashed line represents a photon, a wavy line represents the Coulomb interaction (including exchange), and a full line with a narrow pointing to the right (left) represents a particle (hole). The letters at the lines represent sets of quantum numbers specifying the state of the corresponding particle or hole.

According to the usual rules,[18] the inverse-bremsstrahlung amplitude has the following analytic expression:

$$R_{ij}(\omega)=\langle j|d|i\rangle+\sum_{f,m}\left(\frac{\langle m|d|f\rangle\langle fj|U|mi\rangle}{\hbar\omega-E_m+E_f}-\frac{\langle f|d|m\rangle\langle mj|U|fi\rangle}{\hbar\omega-E_f+E_m}\right), \tag{4.1}$$

where d is the operator for the interaction of the electron with the radiation, U is the operator for the Coulomb interaction (including exchange) between electrons, and the summation is taken over all occupied and unoccupied states of the atom and includes an integration over the continuum.

At photon energies corresponding to excitation of the atom from the state f to one of the possible discrete states $m=s$, i.e. for $\hbar\omega=E_s-E_f$, the denominator of the first term in parentheses vanishes and the inverse-bremsstrahlung process has a resonance. Taking the resonant part of this term out of the sum over intermediate states and taking account of the total width Γ of the resonance level s associated with all possible decay channels for that level, we can express the inverse-bremsstrahlung amplitude in the following form analogous to Eq. (2.2):

$$R_{ij}(\omega)=r_{ij}(\omega_s)+\frac{r_s(\omega_s)\Gamma_{si}^{j}}{\hbar\omega-\mathscr{E}_s+i\Gamma/2}, \tag{4.2}$$

in which r_{ij} is the nonresonant inverse-bremsstrahlung amplitude defined by Eq. (4.1), from which, however, the resonance term has been deleted; $\mathscr{E}_s=E_s-E_f$; ω_s is the frequency of the radiation at resonance; and the amplitudes r_s and Γ_{si}^{j} are given in the first order of perturbation theory by the formulas

$$r_s=\langle s|d|f\rangle,\qquad \Gamma_{si}^{j}=\langle fj|U|si\rangle, \tag{4.3}$$

and in higher orders are represented by the diagrams in Figs. 4a and 4b, which do not contain the resonance in the intermediate state.

We note that the process can be qualitatively regarded as taking place in two stages: first the atom actually absorbs a photon, and then it is de-excited by plasma electrons. This can be represented by the scheme

$$A+\hbar\omega\rightarrow A^*,\quad A^*+e(E)\rightarrow A+e(E+\hbar\omega),$$

in which E is the initial energy of the electron.

Using Eq. (4.2), we can derive the following formula for the inverse-bremsstrahlung cross section at the l-th partial wave of the electron near the resonance:

$$\sigma_l(\omega)=\sum_j\sigma_{l,j}^{(0)}(\omega_s)\frac{[(\varepsilon+q_j)^2+1]}{\varepsilon^2+1}, \tag{4.4}$$

where $q_j=2r_s\Gamma_{si}^{j}/r_{ij}\Gamma$, $\sigma_{l,j}^{(0)}$ is the nonresonant inverse-bremsstrahlung cross section taken at the resonance and determined by the amplitude r_{ij}, and the summation is taken over all possible transitions in the continuum. This expression is equivalent to Fano's well-known parametric formula for an auto-ionization resonance in the photoionization cross section.[19] The behavior of the drag current in this case is determined by formulas analogous to Eqs. (2.3) and (2.4).

In concluding this section we note that the expressions derived for the drag current and the inverse-bremsstrahlung cross section should, strictly speaking, be averaged over the energy distribution of the plasma electrons. However, such averaging would have no substantial effect on the resonance behavior of the current, since the current is determined only by the photon energy, and not by the energy of the dragged electron.

5. In this section we present the results of a calculation of the drag current that arises in an argon plasma at a temperature of ~1.2 eV as a result of inverse-bremsstrahlung absorption by plasma electrons of photons of energy close to the $3p^6\rightarrow 3p^5 3d$ excitation energy of the argon atom ($\hbar\omega\approx 11.8$ eV). In these calculations we used the following approximations and assumptions: The amplitude r_{ij} was calculated in the approximation discussed in Sec. 3, and the amplitude r_s and Γ_{si}^{j} were calculated in the Hartree-Fock approximation. The concentrations N_a and N_e of neutral atoms and electrons in the plasma were taken as 10^{19} and 10^{16} cm^{-3}, respectively. The width of the excited $3d$ level was assumed to be equal to its radiative width[20] $\Gamma\approx 2\times 10^{-7}$ eV; this seems reasonable since our estimates indicate that the broadening of the level due to collisions with electrons amounts to ~10^{-9} eV, and that due to collisions with atoms, to 10^{-8} eV.

The results of a calculation under the above assumptions are presented in Fig. 5. It is evident from the figure that the drag current changes direction. The drag current is six orders of magnitude stronger at resonance than off resonance.

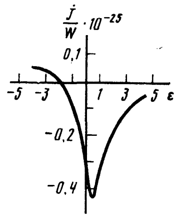

FIG. 5. The drag current arising from the inverse-bremsstrahlung absorption of light by an argon plasma in the vicinity of the $3p^6 \to 3p^5 3d$ excitation of the argon atom. The notation and units are the same as in Fig. 1.

In concluding this section we shall show that the drag current j^a due to inverse-bremsstrahlung absorption at neutral atoms is greater than the drag current j^i due to inverse-bremsstrahlung absorption at the plasma ions, despite the fact that the degree of ionization of the plasma is not low. If we assume that when an electron absorbs a photon it acquires the photon's momentum we can derive the following very rough formula for estimating the drag current:

$$j \approx -\mu W N_e N v \sigma^{ib}(\omega), \tag{5.1}$$

in which μ is the electron mobility and N is either the concentration N_a of neutral atoms or N_i of ions in the plasma. From (5.1) we obtain

$$j^i/j^a = N_i \sigma_i^{ib} / N_a \sigma_a^{ib}. \tag{5.2}$$

To estimate the cross section for inverse bremsstrahlung in the field of an ion we use the formula

$$\sigma_i^{ib}(\omega) = \frac{16\pi^2}{3}\frac{e^2}{\hbar c}\frac{e^4}{m^2\omega^3 v'^2}\ln\left(\frac{2mv'^2}{1.78e^2\omega}\right), \tag{5.3}$$

which was used earlier[3] and is valid provided the condition $mv'^3/e^2 \gg \omega$ is satisfied, as it is in our case. We used formula (3.5) to estimate the cross section for inverse bremsstrahlung in the field of an atom. Using the numbers $N_a = 10^{19}$ cm^{-3} and $N_e = 10^{16}$ cm^{-3} together with our estimate of ~3 for the ratio $\sigma_i^{ib}/\sigma_a^{ib}$ we obtain $j^i/j^a \sim 10^{-3}$; thus, $xj^i \ll j^a$ even outside the resonance.

6. In the work reported here we discovered resonances in the drag current that lead to amplification of the current in the energy region concerned. We demonstrated this by studies of the drag current in the vicinity of the Ramsauer minimum in the elastic scattering cross section, where the drag current increased by a factor of 25 – 30, and in the vicinity of an inverse bremsstrahlung resonance. The possibilities of amplifying the drag current thus revealed can obviously play a decisive part in the experimental study of that current. But the experimental study of the drag current itself, together with other experiments to determine, for example, the total and differential cross sections for absorption of light etc., make it possible to investigate various phenomena associated with the absorption of light by atoms and may prove to be useful for testing atomic models. In connection with this we call attention to the fact that the expression for the drag current contains quadrupole transition amplitudes. This makes it possible actually to make direct measurements of such amplitudes, measurements that it would be virtually impossible to make otherwise at low photon energies.

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[1]A. A. Grinberg, Zh. Eksp. Teor. Fiz. 58, 989 (1970) [Sov. Phys. JETP 31, 531 (1970)].

[2]M. Ya. Amus'ya, A. S. Baltenkov, A. A. Grinberg, and S. G. Shapiro, Zh. Eksp. Teor. Fiz. 68, 28 (1975) [Sov. Phys. JETP 41, 14 (1975)].

[3]M. Ya. Amus'ya and A. S. Baltenkov, Zh. Eksp. Teor. Fiz. 69, 547 (1975) [Sov. Phys. JETP 42, 279 (1975)].

[4]P. P. Pashinin and A. M. Prokhorov, Pis'ma v Zh. Eksp. Teor. Fiz. 26, 687 (1977) [JETP Lett. 26, 526 (1977)].

[5]P. P. Pashinin and M. F. Fedorov, Zh. Eksp. Teor. Fiz. 75, 454 (1978) [Sov. Phys. JETP 48, 228 (1978)].

[6]M. Ya. Amus'ya, V. K. Ivanov, and M. Yu. Kuchiev, in: Avtoionizatsionnye yavleniya v atomakh (Auto-ionization phenomena in atoms), M., MGU, 1976, p. 68.

[7]R. P. Madden, D. L. Ederer, and K. Codling, Phys. Rev. 177, 136 (1969).

[8]M. Ya. Amusia and N. A. Cherepkov, Case Studies Atom. Phys. 5, 50 (1975).

[9]I. I. Sobel'man., Vvedenie v teoriyu atomhykh spektrov (introduction to the theory of atomic spectra), Nauka, 1977, p. 619 [Engl. Transl., Translation Division, Wright Patterson Air Force Base].

[10]O. B. Firsov and M. I. Chibisov, Zh. Eksp. Teor. Fiz. 39, 1770 (1960) [Sov. Phys. JETP 12, 1235 (1961).]

[11]D. E. Golden and H. W. Bandel, Phys. Rev. 149, 58 (1966).

[12]B. M. Smirnov, Fizika slaboionizovannogo gaza (Physics of a weakly ionized gas), Nauka, 1978, p. 92.

[13]Ya. B. Zel'dovich and Yu. P. Raizer, Zh. Eksp. Teor. Fiz. 47, 1150 (1964) [Sov. Phys. JETP 20, 772 (1964)].

[14]V. M. Buĭmstrov and L. I. Trakhetenberg, Zh. Eksp. Teor. Fiz. 69, 108 (1975) [Sov. Phys. JETP 42, 54 (1975)].

[15]M. Ya. Amus'ya, A. S. Baltenkov, and A. A. Paiziev, Pis'ma v Zh. Eksp. Teor. Fiz. 24, 366 (1976) [JETP Lett. 24, 332 (1976)].

[16]M. Ya. Amus'ya, A. S. Baltenkov, and V. B. Gilerson, Pis'ma Zh. Tekh. Fiz. 3, 1105 (1977) [Sov. Phys. Lett. 3, 455 (1977)].

[17]V. M. Zhdanov, Zh. Eksp. Teor. Fiz. 73, 112 (1977) [Sov. Phys. JETP 46, 57 1977)].

[18]A. A. Abrikosov, L. P. Gor'kov, and I. E. Dzyaloshinskii, Metody kvantovoĭ teorii polya v statisticheskoi fizike (Methods of quantum field theory in statistical physics), Fizmatgiz., 1963 (Engl. Transl. Prentice Hall, 1963).

[19]U. Fano, Phys. Rev. 124, 1866 (1961).

[20]George M. Lawrence, Phys. Rev. 175, 40 (1968).

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