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Real Physics of Electron Transfer (Drift) in Gas Substance: Explanation of Electron "Abnormal" Fast Transfer and Still Missed Fundamental Transfer Properties

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Abstract:
Known problem of "abnormal" fast transfer of electrons in tokamak plasma, what violates desired condition for controlled thermonuclear fusion, is explained taking into account real physics of electron transfer (drift) in gas substance. An explanation of this problem is simple: drift velocity of elastically scattered electrons in gas is significantly greater than the result of usually accepted calculation. According to conservation law for momentum of electron transfer (drift), the value of drift velocity is proportional to momentum relaxation time, which is unknown a priori. Therefore it became accepted to replace this time by electron free path time, which may be calculated and is wrongly considered as momentum relaxation time for elastically scattered electrons. However, developed theory, first based on real physics of electron drift in gas matter, gives that relaxation time is greater (from 16 to 4 times) than the electron free path time. Such wrong replacement leads to significant underestimation (16 times for thermal electrons) of calculated electron drift velocity (mobility). Obtained result is consequence of very small electron mass relative to that of gas particles and means that transfer of electrons in gas at elastic (and isotropic) scattering should be really so fast. This paper also shows that developed statistically correct theory reveals early unknown two important properties of electron transfer (drift) and heating in atomic gas under electric field force. Thus, to describe entirely the drift of electrons in gas matter, where they are scattered and so don't move freely, it is necessary use not only the mass of free electron, but also the effective mass, which is equal nearly to the mass of gas particle. The use of effective mass concept, which is well known for solid state physics but never used for the gas phase, first reveals true relation of electron drift velocity with electron velocity distribution function and indicates significant anisotropy of this function for hot electrons, which are heated by transfer in strong fields.

Keywords:
Real Physics of Electron Drift in a Gas, "Abnormal" Fast Electron Transfer, Tokamak Problem, Missed Fundamental Properties of Electron Transfer

1. Introduction

Revealed transfer (drift) of electrons in tokamak plasma occurs much faster (more than an order of magnitude) than expected from accepted calculation, and therefore this phenomenon was called as electron "abnormal" transfer. Such unexpectedly fast transfer of electrons leads to rapid destruction of inner wall of tokamak chamber by hot electrons and to ejection of wall matter into tokamak plasma, what violates plasma properties desired for realization of controlled thermonuclear fusion. This phenomenon created a complicated problem of wall protection from hot electron, for solution of which some different expensive efforts are used. For successful realization of controlled fusion it is necessary to reveal the reason of "abnormal" electron transfer in order to establish possible methods to suppress noted fast damage. This is important for controlled thermonuclear fusion realization as at now effected in France ITER (International Thermonuclear Experimental Reactor) project and at future DEMO project, both of which are based on tokamak for plasma confinement at controlled fusion.

An explanation of the reason of "abnormal" (unexpectedly fast) transfer of electrons is given on the base of developed theory of electron transfer and heating under electric field force in atomic gas [1,2,3]. This theory is based on momentum and energy conservation laws and for the first time takes into account real physics of forced transfer (drift) of electrons in the gas: appearance of momentum of directed transfer as of drifting electrons and also of gas particles (atoms) due to transference to them some directed momentum from drifting electrons at theirs scattering. At that, transfer of drifting electrons should be considered with the use of the concept of electron effective mass, which value is near the mass of gas particles (atoms). Results of the theory are confirmed by known experimental date for electron transfer in rare gases [4,5,6]. With the use of conservation law for transfer momentum of drifting electrons it is shown [7] that electron drift velocity (and mobility) in the atomic gas phase for elastically scattered electrons is much faster (from 16 to 4 times) than the value of accepted calculation.

The reason of such "abnormal" fast electron transfer in gas phase is rather simple, and it is not linked with any physical effect since it is caused by theoretical blunder. At calculation of electron drift velocity, the value of which is proportional to relaxation time of electron transfer momentum, it is generally accepted to substitute this time, which is not known a priory, by electron free path time, which may be calculated using known cross sections of electron scattering. Developed theory [1-3] gives that relaxation time of electron transfer momentum at elastic (and isotropic because of small electron mass) scattering is significantly larger (in interval from 16 to 4) than the electron free path time [7]. Such decrease of time difference (from 16 to 4) occurs due to forced heating of drifting electrons above their thermal energy at theirs transfer under the force of strong electric field. This result is directly confirmed by analyses [5,6] of specific features of field dependence of electron drift velocity in dense rear gases [4] and means that such substitution leads to significant underestimation of the value of electron drift velocity. Thus, electron drift velocity in gas phase should be really so "abnormal" fast. Accepted wrong substitution of the relaxation time of electron transfer momentum by electron free path time is caused, as it was noted in [8,9], by misunderstanding of the real physics of electron transfer in gas phase. Namely, it should be understand that under the action of electric field force an appearance of electron transfer momentum takes place, which should obey to

momentum conservation law and which should be carefully evolved from electron thermal momentum, which has no influence on electron forced transfer (drift).

This paper, besides explaining the reason of “abnormal” fast electron transfer, shows that developed statistically correct theory reveals still missed two important properties of electron transfer (drift) and hearting in gas substance (in atomic gas) under electric field force. Firstly, to describe entirely the drift of electrons in the gas, where they not move freely (since are scattered), it is necessary use not only the mass of free electron, but also the effective mass, which is equal nearly to the mass of atom. Secondly, the use of effective mass concept, which is well known for solid state physics but never used for the gas phase, at the first time reveals true relation of electron drift velocity with electron velocity distribution function and indicates significant anisotropy of this function for heated electrons in strong fields.

Obtained results shows, that for correct explanation of any physical processes it is necessary understand their real physics and then use for their explanation known fundamental laws of physics. Known three conservation laws of classical physics and all principles of quantum mechanics (based on the value of Planck’s constant), as was recently shown [10], have their true materialistic substantiation, since they (including Planck’s constant value) are determined by observed features of cosmic microwave background radiation produced by dark matter thermal motion at temperature 2.7K.

2. Real Physics of Electron Forced Transfer (Drift) in Gas Phase Under Electric Field Force

For correct calculation of electron drift velocity (V_d), which, being experimentally measured, reveals real properties of the process of electron transfer, it is necessary take into account real physics of electron transfer (drift) in the gas phase. As clear, under the action of the electric field strength (E) the electron transfer momentum $P_E=mV_d$, where m is the mass of the electron, is formed, which value is statistically averaged over all drifting electrons [1,2,3]. Accurate calculation of $V_d(E)$ dependence on the base of conservation law for electron transfer momentum $P_E=mV_d$ with the use the concept of P_E relaxation time (τ_p) and comparing this result with experimental date for $V_d(E)$ dependence in atomic gas allows reveal real properties of the electron transfer (drift) in the gas phase. Application of such approach to calculation of $V_d(E)$ for the case of dense gas of rear atoms [5,6] let revealed the reason of "abnormal" fast electron transfer [7], which is observed in the tokamak and at well-known D. Bohm’s diffusion.

Main idea of such approach [5,6,7] is to take into account a quantitative relationship of $P_E=mV_d$ relaxation time τ_p with usually calculated electron free path time (τ):

$$\tau_p=Z\tau \quad (1)$$

As clear, in equation (1) a number Z must be larger than 1. This quantitative relationship between τ_p and τ is logical, since the relaxation (dissipation) of P_E occurs only at the scattering of electrons in the substance with frequency, which is determined by the value of τ. The knowledge of Z value let obtain τ_p value, which is needed for correct (V_d) calculation, with the use of τ value, which may be found in considered substance by common calculations using known cross-sections of electron scattering. As may be shown, the value of V_d, according to the conservation law for the transfer momentum $P_E=mV_d$, is proportional to τ_p, namely, $V_d=eE\tau_p/m$, where e is the electron charge, [1-3]. Indeed, since the rate of the growth of momentum P_E is

equal to the force eE, acting on the electron, whereas the rate of dissipation (relaxation) of P_E is generally determined with the use of the relaxation time as P_E/τ_p, then at stationary drift of electrons the equality of these two rates gives namely such equation:

$$V_d=eE\tau_p/m \quad (2)$$

For correct calculation of V_d with the use of equation (2), besides calculated value of τ, a value of Z is desired since $\tau_p=Z\tau$. To determine Z value, it should be taken into account that, according to equation (2), a stationary electron transfer momentum is

$$P_E=mV_d=eE\tau_p=eEZ\tau \quad (3)$$

Since the increase of P_E in the direction of the electric field force for each time τ is $eE\tau$, so for stationary electron transfer the same value $eE\tau$ must be backscattered (against the direction of the electric field force) for this time τ. It means that for each time τ, during which all drifting electrons are scattered isotropically, according to equation (3) exactly Z^{-1} part of $P_E=eEZ\tau$ must be backscattered. Calculation of the part of $P_E=eEZ\tau$, which is backscattered each time τ, as is shown [7], gives that at weak electric field, when the contribution of electron thermal velocities is significant, Z=16, and for strong electric field, when the contribution of thermal velocities of electrons is negligible, Z=4.

This theoretical result is confirmed by the known experimental data for the specific $V_d(E)$ dependence in dense rare gases [4]. Developed statistically correct theory [1,2,3] with the use of Z dependence let first explain the specific effects observed for $V_d(E)$ in condensed rare gases: saturation (reaching a limiting value) of V_d in the limit of large E and a multiple increase of V_d at small additions of molecular impurities [5,6].

Thus, revealed significant underestimation of generally calculated value of V_d (at wrong assumption that $\tau_p=\tau$) let logically explain the reason of "abnormal" fast electron transfer, observed in the tokamak plasma and at known Bohm's diffusion. By the way, D. Bohm, to explain observed unexpectedly rapid transverse transfer of thermal electrons (in crossed weak enough electric and magnetic fields), obtained an enlarging factor namely 16, which is known as the Bohm's coefficient. It should be noted that such correction factor was obtained by D. Bohm by the use an idea of chaotic motion of drifting electrons due to supposed their chaotic magnetodynamical behavior. However, as clear, the use of magnetodynamics for chaotic motion of drifting electrons is unnecessary, because the isotropy of elastic scattering of drifting electrons really means their totally chaotic motion.

3. Statistically Correct Theory of Electron Forced Transfer (Drift) and Heating in the Gas of Atoms Under the Force of Electric Field

Let's consider a drift of assembly of many electrons (with the mass m and electric charge e) under a constant electric field (E) in the gas of atoms (with the mass M>>m). Observed (by measurement of electron current) stationary drift velocity (V_d) of this electron assembly means an appearance (due to electric field force eE) of directed transfer momentum $P_E=mV_d$, which value is statistically average over all drifting electrons. In order to correctly calculate V_d value it is necessary to apply the momentum conservation law to this appeared transfer momentum $P_E=mV_d$ and take into account a value of Z, which relates desired value τ_p with calculated value τ according to $\tau_p=Z\tau$. At that it should be taken into account that a growth rate of P_E is equal to electric field force eE, acting on each electron with its electric charge e, and a

dissipation rate of P_E is equal to P_E/τ_p, where τ_p is relaxation time of P_E (according to accepted concepts of physics).

Statistically correct theory is developed for the field dependence of drift velocity $V_d(E)$ and heating energy $\varepsilon(E)$ of an ensemble of non-interacting electrons (between themselves) under the action of E in a gas of atoms at theirs constant temperature T, where drifting electrons are elastically (and isotropic since M>>m) scattered on atoms [1-3]. As required values of $V_d(E)$ and $\varepsilon(E)$ are the average over the ensemble of drifting electrons, so their calculation is possible on the basis of known from statistical physics an equations of dynamic balance. These equations follow from conservation laws of momentum $P_E=mV_d$ and energy $\varepsilon(E)$ and use balance between their growth rates (dP_E^+/dt, $d\varepsilon^+/dt$) and relaxation rates (dP_E^-/dt, $d\varepsilon^-/dt$).

At stationary transfer these growth and relaxation rates should be equal to each other, so the equation of dynamic balance for P_E is such:

$$dP_E/dt=dP_E^+/dt–dP_E^-/dt=eE–P_E/\tau_p=eE–mV_d/\tau_p=eE–mV_d/Z\tau=0 \quad (4)$$

Since the electron free path time $\tau=\lambda/v_t$, where λ is the electron free path in the gas and $v_t=(2\varepsilon_t/m)^{1/2}$ is the electron average velocity determined by the total average electron energy $\varepsilon_t=\varepsilon+\varepsilon_T$, where $\varepsilon_T=3kT/2$ is the thermal energy of electron, then from equation (4) for $V_d(E)$ dependence follows such relation:

$$V_d(E)=eE\tau_p/m=eEZ\tau/m=eEZ\lambda/mv_t=eEZ\lambda/(2m\varepsilon_t)^{1/2} \quad (5)$$

As clear, when $\varepsilon<\varepsilon_T$ equation (5) gives linear $V_d(E)$ dependence what corresponds to Ohm's law.

The stationary equation of dynamic balance for the energy of electron forced heating $\varepsilon=\varepsilon_t-\varepsilon_T$ due to the electric field force is such:

$$d\varepsilon/dt=d\varepsilon^+/dt–d\varepsilon^-/dt=eEV_d–\Delta\varepsilon/\tau=0 \quad (6)$$

In equation (6) $\Delta\varepsilon$ is the value of electron energy loss during time τ. As known, the electron energy loss in atomic gas at elastic scattering during each τ is $\Delta\varepsilon=2\varepsilon m/M$.

From these balance equations follows the so-called dispersion relation:

$$\varepsilon=MV_d^2/2Z \quad (7)$$

As clear, this ratio relates the average heating energy of drifting electron ε with the kinetic energy of transfer of some effective mass $m_d=M/Z$ with velocity V_d, what shows the existence of effective momentum $P_d=m_dV_d$. It means that to describe the drift of electrons in the gas, where they do not move freely, it is necessary use not only the mass of free electron m, but also the effective mass m_d. This fact is well known for solid state physics but never used before for the gas phase.

As known, from dispersion relation (7) the value of the m_d is commonly defined as the second derivative of the energy ε on the effective momentum $P_d=m_dV_d$, i.e., $m_d=(\partial^2\varepsilon/\partial P_d^2)^{-1}$. Then, from this dispersion relation really follows that $m_d=M/Z$.

Thus, at transfer (drift) of electron ensemble in atomic gas under electric field force there is formed not only the momentum $P_E=mV_d$, which corresponds to observed electronic current, but also a much larger effective momentum $P_d=m_dV_d=V_dM/Z$. This momentum corresponds to appearance of directed transfer of atoms due to transmission to them a part of momentum P_E of drifting electrons at their scattering on these atoms. The formation of this effective momentum P_D, whose relaxation time is $\tau_D=\tau M/m$, was not previously considered in gas phase (including plasma).

It is necessary to note that, since the average electron velocity v due to the energy of electron transfer heating ε is determined by the ratio $\varepsilon=mv^2/2$, then, taking into account that $\varepsilon=MV_d^2/2Z$, it gives an important relation v with V_d:

$$V_d=v(Zm/M)^{1/2} \quad (8)$$

Equation (8) establish for the first time correct relationship of the value of V_d with an electron velocity distribution function, from which the value of v follows as its integral convolution. This result is important for revealing significant anisotropy of this function for forced heated electrons in strong electric field [1, 3, 9, 11]. Significant anisotropy of electron velocity distribution function for forced heated electrons indicates the inconsistency of the concept of "running away" electrons with fundamental physical laws. As known, this concept has its theoretical substantiation only at very small anisotropy of this function even for strongly heated electrons, what don't corresponds to real physics of electron transfer in gas substance [12].

3.1. Correct Calculation of Z Value for Electron Drift in Atomic Gas Reveal the Reason of Electron "Abnormal" Fast Transfer

As shown above in equation (2), at stationary electron drift, when growth and dissipation rates of transfer momentum $P_E=mV_d$ are equal to each other, follows simple expression for the value of electron drift velocity:

$$V_d(E)=eE\tau_p/m$$

As clear, V_d value is proportional to τ_p value, which is relaxation time of transfer momentum $P_E=mV_d$. For correct calculation of V_d right τ_p value must be used, which, however, is not known a priori in each particular case of substance, since τ_p value is defined by scattering (dissipation) mechanism of drifting electrons. Because of this, it has been long ago accepted (more than a century ago) to substitute desired τ_p value by the value of electron free path time τ, which may be easily calculated from known cross-sections of electron scattering in the substance. Thus, it is generally wrong accepted to assume that $V_d(E)=eE\tau/m$, and, consequently, that electron mobility is $\mu=V_d/E=e\tau/m$.

However, this substitution for the case of elastically (and isotropically) scattered electrons leads to significant underestimation of V_d (and μ) values, since in this case the τ_p value is much larger (from 16 to 4 times) than τ value. As was shown [7], this result follows from correct application of momentum conservation law to the electron transfer momentum $P_E=mV_d$, in the case of drifting electrons in atomic gas, what is well confirmed by known experimental date for $V_d(E)$ dependences in dense rare gases [1,2,3,5,6].

As reasonable, the value of τ_p should be equal to several values of τ, since dissipation (relaxation) of transfer impulse P_E may occurs only at electron scattering, whose statistically mean frequency is determined by τ. Thus, there should be quantitative relation between τ_p and τ values, i.e. it should be $\tau_p=Z\tau$, where Z is a number larger than 1. Then, correct expression for calculation of the value of $V_d(E)$ must be such:

$$V_d(E)=eE\tau_p/m=eEZ\tau/m$$

This gives that the stationary drift momentum of electrons should be equal to:

$$P_E=eEZ\tau$$

In order to correctly calculate V_d value it is necessary establish Z value since the value of τ may be calculated. To obtain the value of Z, it is important to take into account real physics of stationary drift of elastically scattered electrons, i.e. to understand why constant value of V_d is achieved at applied constant E. For that it is convenient to consider transfer of electron assembly during one electron free path time τ, during which all drifting electrons are scattered. As clear, this scattering of all electrons of large assembly is isotropic (randomly in arbitrary directions), since these many drifting electrons will be scattered on the atoms statistically uniformly.

It should be taken into account, that during time τ a statistically mean increase of transfer momentum $P_E=mV_d=eEZ\tau$ (in direction of E action) is equal to eEτ. For the case of stationary electron drift, it must be so that a backscattered (against direction of E action) part of $P_E=mV_d=eEZ\tau$ during this time τ must also be equal to eEτ. As clear from the value of $P_E=mV_d=eEZ\tau$, this backscattered part must be equal to Z^{-1} part of stationary electron drift momentum $P_E=eEZ\tau$. Thus, in order to obtain desired Z value, it is necessary to determine the part of momentum $P_E=eEZ\tau$, which is backscattered for the time τ, during which transfer momentum $P_E=eEZ\tau$ is scattered isotropically. This part, which may be revealed by spatial analysis of P_E scattering [7], must be equal to Z^{-1}, what gives desired value of Z.

At spatial analysis of backscattered part of P_E it is necessary take into account the presence for drifting electrons of their thermal (isotropic) momentum, which introduce no contribution to P_E, but strongly affect its backscattered part, changing significantly Z value. Such spatial analysis of backscattered part of P_E was done for two limiting cases of E values [7]. For small E and small P_E, when drifting electrons are nearly thermal, it was obtained that Z=16. This value corresponds well to known D. Bohm's coefficient 16, introduced by him to explain observed "abnormal" fast diffusion of thermal electrons in the gas of argon under crossed magnetic and electric fields. As was noted above, to explain "abnormal" fast electron diffusion, D. Bohm used an idea of chaotic motion of electrons due to electron magnetodynamic behavior. However, magnetodynamic influence is not necessary since the motion of drifting electrons in the gas substance is chaotic in principle due to isotropic scattering of drifting electrons (each time τ in arbitrary directions) because of electron very small mass.

For large E values, when drifting electrons are strongly heated above their thermal energy, and so their thermal momentum may be neglected, it was obtained that Z=4 [7]. This result for large E values, when only directed transfer momentum P_E is scattered, may be simply substantiated. As known, at isotropic scattering of some flow an exactly ¼ part of this flow is scattered in any direction, therefore in this case namely ¼ part of P_E will be backscattered, and consequently it means that in this case Z=4. As was shown [5,6], these theoretically obtained limiting values for Z and decreasing of Z value from 16 to 4 at increasing E are entirely confirmed by known experimental data for electron drift velocity field dependence in dense rare gases.

4. Conclusions

Developed statistically correct theory [1,2,3], which is based on fundamental conservation laws of momentum and energy for drifting electrons in gas substance and takes into account real physical properties of these processes, reveals several neglects in commonly used physical kinetics for electron forced transfer in gas substance under electric field force.

The use of the theory for transfer momentum of drifting electrons $P_E=mV_d=eEZ\tau$, shows that the reason of electron "abnormal" fast transfer in the gas phase (tokamak plasma and at known D. Bohm's diffusion) is caused by significant (from 16 to 4 times) underestimation of electron drift velocity (and mobility) at accepted calculation, when is used Z=1. Really in the case of atomic gas the value of Z amount from 16 to 4, decreasing in this range at electron forced heating in strong electric fields [7].

Really drift velocity (and mobility) of electrons in gas phase must be so "abnormal" fast, what is simply a consequence of the fact that light electrons are isotropically scattered on heavy particles of gas substance. To suppress the damage of tokamak chamber by "abnormal" fast transfer of hot electrons, what disturbs conditions of controlled fusion realization, it is reasonable to increase inner diameter of tokamak chamber what is now proposed for the future DEMO project.

Developed theory [1,2,3] reveals the need of the use of effective electron mass for entire description of electron transfer (drift) in gas substance. Also it first establish correct relationship of electron drift velocity with electron velocity distribution function and reveals significant anisotropy of this function for forced heated electrons in strong electric fields.

The use of obtained relationship $\tau_p=Z\tau$ let correctly calculate the concentration of conduction electrons (from the value of electron conductivity) without significant (in Z=16 times) overestimation of electron concentration because of accepted use of wrong relationship $\tau_p=\tau$.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Author Contributions

I.A.B. wrote the manuscript, initiated the work, and supervised the process. Author has read and agreed to the published version of the manuscript.

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