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HEAVY ELECTRONS: ELECTRON DROPLETS GENERATED BY PHOTOGALVANIC AND PYROELECTRIC EFFECTS*

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Electron clusters, X-rays and nanosecond radio-frequency pulses are produced by 100 mW continuous-wave laser illuminating ferroelectric crystal of $LiNbO_3$. A long-living stable electron droplet with the size of about 100 μm has freely moved with the velocity $\sim$0.5 cm/s in the air near the surface of the crystal experiencing the Earth gravitational field. The microscopic model of cluster stability, which is based on submicroscopic mechanics developed in the real physical space, is suggested. The role of a restraining force plays the inerton field, a substructure of the particles' matter waves, which a solitary one can elastically withstand the Coulomb repulsion of electrons. It is shown that electrons in the droplet are heavy electrons whose mass at least 1 million of times exceeds the rest mass of free electron. Application for X-ray imaging and lithography is discussed.

Keywords: electron droplet, laser beam, submicroscopic mechanics, inerton, heavy electron

1. Introduction

Wigner crystallization[1] of electrons predicted in the 1930s received a remarkable support in the 1970s when electron crystals/clusters were experimentally observed on the surface of liquid helium bubbles (see e.g. review paper[2]). This allowed further theoretical studies, for instance, such as electron crystallization in a polarizable medium[3], clusterization of electrons[4] and computer models of two-dimensional electron crystals[5].

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In such crystals the behavior of electrons is governed by a competition between the Coulomb repulsion and a kind of a confinement field. Wigner associated this confinement field with the wave nature of electrons that obey the Schrödinger equation[1]. In the case of a crystal, such field is associated with phonons[6].

In the 1990s electron clusters were generated at room temperature. It has been found by Shoulders[7,8] and others[9−12] that electron clusters, which embraced around 10^{10} electrons and had the size from several to tens of micrometers, could easily move at a low speed in a vacuum or/and the air passing macroscopic distances. Based on a number of data Shoulders noted that had been obvious one got more energy out of electron clusters of certain experiments than one put in (their cold droplets burned through crystals). In other words, an additional energy content is available in charged clusters. We should also point out recent results by Santilli[13] who jointly with co-workers has been studying strongly interacting electrons, atoms and molecules, which at special conditions are transformed to coupled dimers and clusters; all these species have been studied in the framework of hadronic mechanics, a new discipline that deals with strongly interacted and coupled entities. Such entities were called "magnecules" by Santilli and, in particular, he proposed a remarkable industrial application of his invention, namely, the magnegas technology (the combustion of magnegas, which is produced from liquid waste, liberates heat of about 0.8 times of the natural gas at extremely clean exhaust)[13].

Thus the phenomenon of strongly coupled entities and, in particular, charged clusters is of interest to both academic and applied studies.

In this paper we present experimental results on the self-organized spatio-temporal pattern formation during scattering of laser light in the photorefractive ferroelectric crystals of $LiNbO_3$. Some of these patterns may be explained by assuming formation of charged clusters (or electron droplets). Laser-induced nonlinear (holographic) scattering in electro-optic crystal allows self-visualization of the space-charge waves, which are formed in the crystal volume by recording of set of holographic gratings. These holographic gratings are recorded by interference patterns formed between pump beam and scattered waves, producing moving space-charge waves (SCW) inside the crystal. Due to electro-optic effect these SCW modulate refractive index (forming holographic gratings) and pump beam diffract on these holographic gratings and thus visualizing SCW[14,15]. These results are relatively well understood for the volume SCW.

We have found unusual behavior of the specular reflection (reflection of the laser beam from the front crystal surface), that resemble visualization of the volume SCW. We hypothesised that observed moving scattering spots may be due to the formation of charged plasma clusters (electron droplets) formed near the crystal surface. This assumption is supported also by the fact that strong radio-frequency signals (with maximum in MHz region) are picked-up by the needle-shaped and plain electrodes with capacitive coupling.

In the present paper we present experimental results on the generation of electron droplets (plasma clusters) at the illumination of the $LiNbO_3$ crystal by a focused

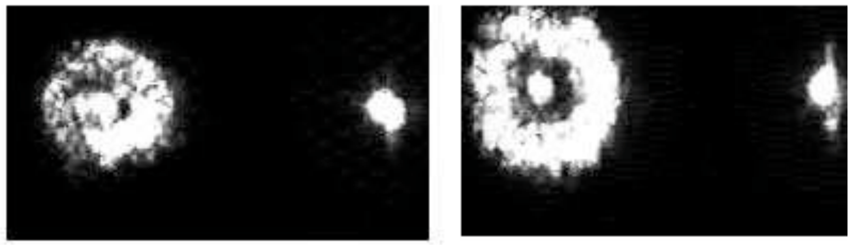

Fig. 1. Nonlinear enhanced back-reflected scattering from the ferroelectric crystal surface as seen on the screen with the hole (left side of each picture). On the right side is the specular reflected beam with a 'droplet' for two frames (separated by 1 sec) from the video.

laser beam (CW green laser, $\lambda = 532$ nm, $P = 100$ mW). These droplets are stable and slowly move along the charged crystal surface passing at last a few centimeteres before annihilation. Moreover, we carry out a detailed theoretical study of the confinement field as such, which holds electrons in a cluster. Namely, based on the theory of real physical space by Bounias and Krasnoholovets[16−19] and sub-microscopic mechanics[20−25] developed by one of the authors, we disclose the inner reasons confining electrons together.

2. Experimental

Illumination of the $LiNbO_3$ crystal by a focused laser beam (CW green laser, $\lambda_{\rm laser} = 532$ nm, $P = 100$ mW), produced in the specular reflection spots periodically generated bright droplets that moves along the crystal surface (Fig.1). The typical signal of the laser-initiated discharge from the crystal surface in the air is shown on Fig. 2. In this experiment the laser beam was focused on the Z-face of the crystal. The signal was picked up by the needle electrode that touched the crystal surface near the illuminated spot. The needle-type electrode enhances the electric field near the crystal surface and facilitates plasma formation and provokes discharges. At the same time the needle electrode served as antenna, delivering a radio-signal burst to the oscilloscope. Creation and annihilation of plasma clusters (droplets) generate nanosecond RF pulses and (when placed in modest vacuum) bursts of X-rays. It was already demonstrated that the intensity of X-ray generation from ferroelectric crystals is strong enough to produce a shadow image on the commercial dental X-ray films[26]. We suggest the explanation, based on analogy with electron clusters (called "EV" by Shoulders[7,8] and "ectons" by Mesyats in Ref. 11,12) in plasma discharges, created by nonlinear photogalvanic and pyroelectric effects, that charges ferroelectric crystals to high-voltage and initiates gas discharges. The important difference between our results and results[7,8,11,12] is that in our case there was no externally applied electric field; the electric field was generated inside the crystal due to photogalvanic and pyroelectric effects induced by the laser illu-

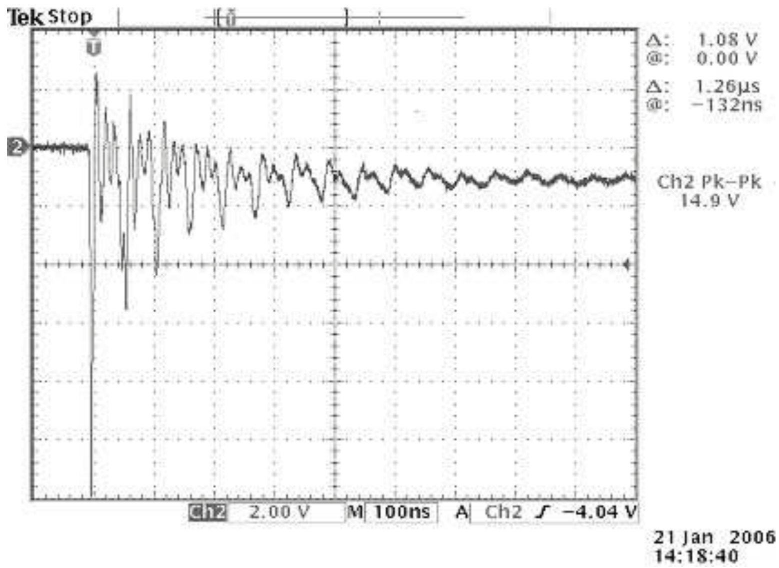

Fig. 2. Electrical signal, picked up by the needle electrode from the laser-illuminated spot of the $LiNbO_3$ crystal. Front edge of the electrical signal is in the nanosecond scale, damping oscillations are due to the reflections in the transmission line.

mination. So it would be better to call our charged clusters “photogalvanic ectons” (or “pectons”).

Since the velocity of a relatively stable droplet is about 0.5 cm/s, which is very small, it seems that the droplet cannot be composed of only electrons. At the same time the droplet must be charged, because it creates high electric field (several kV/cm) needed to modulate optical reflection from the crystal surface[26,27]. The electron droplet is created in a triple point, i.e. the contact of crystal and metal with the air bubbles near the crystal surface[11,12,26]. In our case metal contact is due to antireflection coating, and electron clouds are formed due to the photo ionization of the crystal surface and due to the E-field ionization of the air gas near the surface. Because of that, it is reasonable to assume that electron clouds may also include positive ions from the air, though their quantity seems rather inessential.

3. Theory

Since the velocity of droplets revealed in the experiment is extremely low, we must conjecture that electrons in a droplet are found under very peculiar conditions, because as a matter of fact free electrons have never been observed at a velocity lower than 10^6 m/s. However, these charged droplets in fact have been fixed in our experiments. They moved longitudinally to the crystal surface, which in the present case of Lithium Niobate is characterized by a strong longitudinal electric field (several kV/cm) perpendicular to the axis of crystal polarization.

Recent researches in sub atomic physics [17−25,6] allow us to look at the constitution of droplets from a deeper submicroscopic viewpoint, which is capable to shed light on the physical processes beyond the comprehension of conventional quantum mechanics.

3.1. *The behavior of particles*

Let us discuss now a simple model of an electron droplet considering it as a cloud of electrons tied by a confinement field. Having eluded the Coulomb repulsion, electrons must be attracted. To understand such conditions, we have to follow the principles of motion of canonical particles, as submicroscopic mechanics prescribes.

Submicroscopic mechanics of canonical particles[20−25], which has been developed in the real physical space[17−19], allows description of quantum systems studied on the sub atomic scale. The basis for this mechanics is a recent theory of the real space[16−19] which shows that our ordinary space represents a mathematical lattice of primary topological balls or superparticles, with the size of around the Planck one, $\sim 10^{-35}$ m. In this case the motion of a canonical particle is associated with strong interaction of the particle with space which results in the creation of a cloud of elementary excitations surrounding the particle. These excitations have been called *inertons* since they appear owing to a resistance, i.e. inertia, which a moving particle undergoes on the side of the space. As has been argued[20−25], the amplitude λ of spatial oscillations of the particle appears in conventional quantum mechanics as the de Broglie wavelength and inertons represent a substructure of the particle's matter waves.

Thus the sub-microscopic mechanics allows one to disclose the science far beyond the conventional quantum mechanical formalism. The amplitude Λ of the particle's cloud of inertons becomes implicitly apparent through the availability of the wave ψ-function. Therefore, the physical meaning of the ψ-function becomes completely clear: it describes the range of space around the particle perturbed by its inertonic effect.

As follows from sub-microscopic mechanics, the amplitude of the inerton cloud, i.e. a distance to which the front of the inerton cloud moves away from the core of the particle, is defined by expression

$$\Lambda = \lambda\, c/\upsilon \tag{1}$$

where λ is the de Broglie wave of the particle (the amplitude of the particle), υ is the particle velocity and c is the speed of light. In submicroscopic mechanics, a particle obeys the oscillatory motion at which the parameter λ characterizes a section of the particle path where the particle velocity changes from υ to zero and again rises to υ; the particle stops in the point $\lambda/2$ due to the transfer of its velocity and a part of its mass to the particle's inertons. In the next half section $\lambda/2$ the particle reabsorbs inertons, which restores the initial particle parameters, i.e. its velocity υ and mass m. Fig. 3 shows the scheme of such motion. Furthermore, the solutions

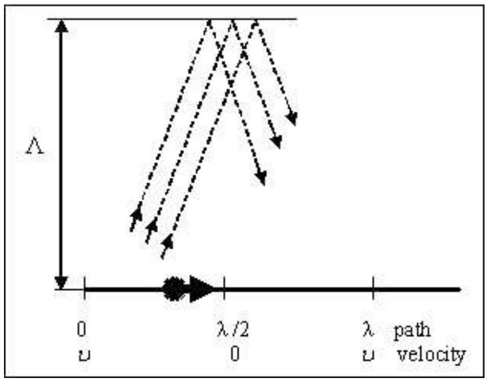

Fig. 3. Scheme of the motion of the particle surrounded by its cloud of inertons, as prescribed by submicroscopic mechanics.

to the equations of motion show that the motion of the particle in the tessellation space is characterized by the two de Broglie's relationships for the particle[20,21,22]:

$$E = h\nu, \quad \lambda = h/(mv) \tag{2}$$

where $\nu = 1/(2T)$ and $1/T$ is the period of collisions between the particle and its inerton cloud. These two relationships result in the Schrödinger equation[28]. Consequently, submicroscopic mechanics, which is constructed in the real space, can easily be reduced into the formalism of conventional quantum mechanics developed in the phase space (the intercoupling between two mechanics is available in Refs. 20 to 25). It is interesting to note that when the inequality $v \ll c$ holds, trajectories of inertons are practically perpendicular to the particle path (see Fig. 3). In case of the rectilinear motion of a flow of canonical particles, or in the case of the vibrating motion of particles, particles' inerton clouds have to be scattered passing their energy and momentum to the corresponding particles. If particles are not high-speeded, the energy transfer will occur rather in directions transversal to their path (which in the first approximation one can associate with the X-axis). In that case the problem can be reduced to consideration of a flow of particles moving along the X-axis (or vibrating along and against the X-axis), which interact with each other by means of inerton clouds along the Y-axis. Such system of particles interacting through their clouds of inertons can be described by the Lagrangian

$$L = \sum_l \left(\tfrac{1}{2}\, m\dot{x}_l^2 + \tfrac{1}{2}\, \mu\, \dot{y}_l^2 - \omega_l \sqrt{m\mu}\; y_l\, \dot{x}_l + \tilde{\omega}_l \sqrt{m\mu}\; y_{l+1}\, \dot{x}_l \right) \tag{3}$$

where m and μ are masses of the lth particle and its inerton cloud, respectively; x_l and y_l are respective positions of the lth particle and its cloud of inertons; y_{l+1} is the position of the cloud of the $(l+1)$th particle (the particle is the frame of reference for its cloud of inertons); $\omega_l = \pi/T_l$ is the cyclic frequency of collisions between the lth particle and its inerton cloud; $\tilde{\omega}_l = \pi/\tilde{T}_l$ is the cyclic frequency of collisions between the l particle and the inerton cloud of the $(l+1)$th particle.

The Euler-Lagrange equations of motion for the Lagrangian (3) are as follows

$$\ddot{x}_l - \sqrt{\mu/m}\,\omega_l\,\dot{y}_l + \sqrt{\mu/m}\,\tilde{\omega}_l\,\dot{y}_{l+1} = 0; \tag{4}$$

$$\ddot{y}_l + \sqrt{m/\mu}\,\omega_l\,\dot{x}_l = 0; \tag{5}$$

$$\ddot{y}_{l+1} - \sqrt{m/\mu}\,\tilde{\omega}_l\,\dot{x}_l = 0. \tag{6}$$

Since in submicroscopic mechanics the relationship $\sqrt{m/\mu} = c/\upsilon$ holds[20,21], the solutions to Eqs. (4) to (6) become

$$x_l = \frac{\lambda_l}{\pi}\,(-1)^{[t/T_l]}\,\sin\left(\sqrt{\omega_l^2 + \tilde{\omega}_l^2}\,t\right) \tag{7}$$

$$\dot{x}_l = \upsilon\,\left|\cos\left(\sqrt{\omega_l^2 + \tilde{\omega}_l^2}\,t\right)\right| \tag{8}$$

$$(y_l - y_{l+1}) = \frac{\omega_l}{\sqrt{\omega_l^2 + \tilde{\omega}_l^2}}\,\frac{\Lambda_l}{\pi}\,\left[(-1)^{[t/T_l]}\cos\left(\sqrt{\omega_l^2 + \tilde{\omega}_l^2}\,t\right) - 1\right] \tag{9}$$

The notation $[t/T_l]$ means an integral part of the integer t/T_l. Since here the parameter t characterizes the proper time of the lth particle, the corresponding coordinate (7) is also treated as proper, i.e. it continuously increases in the positive direction in both cases of the motion of particles, rectilinear and vibratory.

In submicroscopic mechanics[20−25], in the case of a free particle relationships

$$\lambda = \upsilon\,T, \quad \Lambda = c\,T \tag{10}$$

are held. In the present case of a flow of interacting particles the relationships change to the following:

$$\lambda_l = \upsilon_l\,\pi/\sqrt{\omega_l^2 + \tilde{\omega}_l^2}, \quad \Lambda_l = c\,\pi/\sqrt{\omega_l^2 + \tilde{\omega}_l^2}. \tag{11}$$

Having obtained expressions (7) to (9), we use the following initial conditions: $x_l(0) = y_l(0) = \dot{y}_l(0) = 0$ and $\dot{x}_l(0) = \upsilon_l$.

Solutions (7) to (9) show that the considered overlapping of inerton clouds does not introduce any dispersion in the flow of particles, i.e. they continue to move along the X-axis with the same initial velocity υ, which obeys the behavior prescribed by rule (9), i.e. a moving canonical particle is characterized by the spatial amplitude λ that signifies a section in which the particle velocity periodically decays: $\upsilon \to 0 \to \upsilon \to 0 \to \upsilon$.

Thus, submicroscopic mechanics developed in the real space makes it possible to determine the particle's position and velocity/momentum at the same moment of time. Submicroscopic mechanics deals with the field of inertia of moving canonical particles. Carriers of this field, inertons, fill out a range of space covered by the particle's ψ-function of conventional quantum mechanics (the volume of this range is $\approx \lambda\,\Lambda^2$). In this way, inertons representing a substructure of matter may be interpreted as carriers of quantum mechanical interactions. These quasi-particles of the tessellattice (the real space) transfer momentum and energy from the quantum system under consideration to the nearest quantum object. And also inertons, as local deformations of the real space, transfer mass properties from the particle to its surrounding[29].

3.2. *Inerton field in the crystal lattice*

On the surface of the crystal studied, a bunch of falling photons from a laser beam (the same in the case of a bunch of photons induced by means of the discharge[7−12]) results in an elastic response pulse on the side of the surface. In other words, the mechanical impact of the falling photon bunch induces a back action of the crystal lattice. Besides, the bunch's photons induce electron emission in the impact area of the crystal boundary. Thus the illumination expels electrons from the crystal and also creates an echo pulse that leaves the crystal together with knocked electrons.

As it is known in conducting and semiconducting crystals, electrons interact with vibrating quanta of the crystal lattice. The vibratory energy of the lattice can be written as follows,

$$L = \frac{1}{2} \sum_{\vec{l}\alpha} M \dot{\xi}^{\,2}_{\vec{l}\alpha} - \frac{1}{2} \sum_{\vec{l}\alpha,\, \vec{n}\beta}{}^{'} V_{\alpha\beta} \left(\vec{l} - \vec{n} \right) \xi_{\vec{l}\alpha} \xi_{\vec{n}\beta}. \tag{12}$$

Here M is the mass of an atom located in the $\vec{l}$th site of the crystal lattice; $\xi_{\vec{l}\alpha}$ $(\alpha = 1,\ 2,\ 3)$ are three components of the $\vec{l}$th atom displaced from the equilibrium position; $\dot{\xi}_{\vec{l}\alpha}$ are three components of the velocity of this atom; $V_{\alpha\beta}\left(\vec{l} - \vec{n}\right)$ are the components of the elasticity tensor of the crystal lattice.

It is generally recognized that such elastic interaction in the lattice is caused by electrostatic and electromagnetic interactions between atoms. Nevertheless, it was shown in paper[30] that the inerton component should also be present in the total interaction of atoms in the lattice. In the $\vec{k}$-presentation the force matrix of the crystal becomes[30]

$$W_{\alpha\beta}\left(\vec{k}\right) = \tilde{V}_{\alpha\beta}\left(\vec{k}\right) \; + \; \tilde{\tau}^{-1}_{\alpha\beta} \sum_{\alpha'} \tilde{\tau}^{-1}_{\alpha'\beta}\left(\vec{k}\right) \, \frac{e_{\alpha'}}{e_{\beta}} \tag{13}$$

where the second term describes the interaction of atoms, which is stipulated from the overlapping of their inerton clouds. The force matrix determines basic branches of collective vibrations of the crystal $\Omega_s\left(\vec{k}\right)$ $(s = 1,\ 2,\ 3)$, which are found from the secular equation

$$\| \, \Omega^2_s\left(\vec{k}\right) - W_{\alpha\beta}\left(\vec{k}\right) \| \; = 0. \tag{14}$$

Recall, inerton clouds of atoms appear simply due to the motion of atoms, *because it is the motion of an object through the real space (the interaction of the moving object with space), which generates the inerton field surrounding the object.*

Coming back to the problem of generation of the echo pulse, we can now state that it transfers not only a pulse of a classical acoustic wave, but also includes a flow of inertons. If acoustic waves can propagate only in a medium, a flow of inertons can spread coming through both a medium and a vacuum (which is the real physical space). In other words, inertons of the echo pulse can be re-absorbed by both atoms and free electrons. The absorption of the inerton field by emitted electrons brings about significant changes in the behavior of these electrons. Namely, the inerton field is able to tie the electrons together. Since inertons transfer mass (or in other words, local deformations of space[17]), the absorption of inertons by electrons will mean the increase of electrons' mass.

In any case electrons are characterized by two kinds of interactions: the Coulomb interaction and an elastic interaction caused by the overlapping of electrons' inerton clouds (or wave $\psi-$functions in terms of the conventional quantum mechanical formalism). The absorption of inertons hardens the elastic interaction between electrons and hence suppresses their Coulomb repulsion. In papers[4,6] the statistical behavior of interacting particles was studied for different paired potentials and, in particular, the possibility of clusterization of electrons was also analyzed. Let us apply those results to the problem of electron droplet.

3.3. *The droplet stability*

The two kinds of interactions allow us to write the Hamiltonian of interacting electrons in a droplet in the form typical for the model of ordered particles, which is characterized by a certain nonzero order parameter,

$$H(n) = \sum_{s} E_s\, n_s - \tfrac{1}{2} \sum_{s,\, s'} V_{s\,s'}\, n_s n_{s'} + \tfrac{1}{2} \sum_{s,\, s'} U_{s\,s'}\, n_s n_{s'}. \tag{15}$$

Here E_s is the additive part of the electron energy (the kinetic energy) in the sth state. The main point of our approach is the initial separation of the total potential of electron-electron interaction into two terms: the repulsion and attraction components. So, in the Hamiltonian (15) the potential $V_{s\,s'}$ represents the paired energy of attraction and the potential $U_{s\,s'}$ is the paired energy of repulsion. The potentials take into account the effective paired interaction between electrons located in states s and s'. The filling numbers n_s can have only two meanings: 1 (the sth knot is occupied in the model lattice studied) or 0 (the sth knot is not occupied in the model lattice studied). The signs before positive functions $V_{s\,s'}$ and $U_{s\,s'}$ in the Hamiltonian (15) directly specify proper signs of attraction (minus) and repulsion (plus).

The statistical sum of the system under consideration

$$Z = \sum_{\{n\}} \exp\left(-H(n)/k_{\rm B}T\right) \tag{16}$$

can be presented in the field form[4,6]

$$Z = {\rm Re} \frac{1}{2\pi i} \int D\phi \int D\psi \oint dz\, \exp\left[S\left(\phi,\, \psi,\, z\right)\right] \tag{17}$$

where the action

$$S = \sum_s \Big\{ -\tfrac{1}{2} \sum_{s'} \Big(\tilde{U}^{-1}_{ss'} \phi_s \phi_{s'} + \tilde{V}^{-1}_{ss'} \psi_s \psi_{s'} \Big) + \ln \Big| 1 + \tfrac{1}{z} \exp \Big(-\tilde{E}_s + \psi_s \Big) \cos \phi_s \Big| \Big\} + (N-1) \ln z \tag{18}$$

and $D\phi$ and $D\psi$ imply the functional integration with respect to abstract fields ϕ_s and ψ_s, respectively, and $z = \xi + i\zeta$. Then the action (18) allows the modification[4,6]

$$S = \tfrac{1}{2} K \times \Big\{ (a-b)\ \aleph^2 - \big(\langle n \rangle^{-1} - 1 \big)\ \big(\aleph^{-1} + 1 \big)^2 \exp (2 b\, \aleph) - \ln (\aleph + 1) \Big\} + (\aleph - 1) \ln \xi \tag{19}$$

where the following functions are introduced

$$a = \frac{3}{k_{\rm B} T} \int_1^{\aleph^{1/3}} U\,(\bar{r} x)\, x^2\, d\,x, \tag{20}$$

$$b = \frac{3}{k_{\rm B} T} \int_1^{\aleph^{1/3}} V\,(\bar{r} x)\, x^2\, d\,x. \tag{21}$$

In expressions (19) to (21) $\langle n \rangle$ is the average filling number of a lattice knot, $\aleph$ is the combined variable that includes a mixture of fields ϕ_s and ψ_s, and the fugacity $\xi = \exp(-\mu / k_{\rm B} T)$ where μ is the chemical potential. The value of $\aleph$ exactly corresponds to the value of particles in a cluster, such that $K \aleph = N$, where $\aleph$ is the total quantity of particles in the system under considerations and K is the number of clusters. In other words, in our problem N is the quantity of all electrons emitted from the area of crystal irradiated by the laser beam and $\aleph$ is the number of electrons that forms the cluster. Besides, expressions (20) and (21) are written in dimensional form where x is the dimensionless distance and $\bar{r}$ is the normalizing factor (for instance, it may be an average distance between electrons in a cluster).

It is obvious that the repulsive paired potential for electrons is

$$U = \frac{1}{4\, \pi\, \varepsilon_0}\ \frac{e^2}{\bar{r} x}. \tag{22}$$

An elastic interaction of electrons through the inerton field may be presented in the form of a typical harmonic potential

$$V = \tfrac{1}{2}\, m\, \omega^2 \cdot (\delta \bar{r}\ x)^2 \tag{23}$$

where m is the mass of an electron in the droplet, ω is the cyclic frequency of its oscillations and $\delta \bar{r}$ is the amplitude of the electron displacement from its equilibrium state (note that this amplitude is directly connected with the de Broglie wavelength of the electron, $2\delta \bar{r} = \lambda$, see Ref. 6) .

Then preserving main terms in the action (19) we obtain

$$S \approx \tfrac{1}{2} K \times \left(\frac{3\, e^2}{8\, \pi\, \varepsilon_0\, \bar{r}\, k_{\rm B} T}\ \aleph^{2/3}\ -\ \frac{3\ m\ \omega^2\ \delta \bar{r}^2\ \aleph^{5/3}}{k_{\rm B} T} \right) \aleph^2. \tag{24}$$

The minimum of action (24) is reached at the solution of the equation $\partial S/\partial \aleph = 0$ (if the inequality $\partial^2 S/\partial \aleph^2 > 0$ holds). With the approximation $\aleph \gg 1$ the corresponding solution is

$$\aleph \approx \frac{20}{11} \; \frac{e^2/\,(4\pi\varepsilon_0\,\bar{r})}{\frac{1}{2}m\omega^2\,\delta\bar{r}^{\,2}}; \tag{25}$$

in other words, the quantity of electrons involved in a droplet is determined by the ratio of repulsive and attractive paired potentials.

3.4. *Heavy electrons*

Let us numerically estimate the quantity of electrons $\aleph$ in a droplet. Expression (25) can be rewritten as follows

$$\aleph \approx \frac{20}{11} \; \frac{e^2/\,(4\pi\varepsilon_0\,\bar{r})}{\hbar\omega} \tag{26}$$

where $\hbar\omega$ is the vibration energy of an electron in the droplet. The radius of generated droplets has been estimated as $R = 5 \times 10^{-5}$ m. If we set the concentration of electrons $n_{\text{electr}} \approx 10^{18}$ m^{-3}, we can put the average distance between electrons $\bar{r} = 10^{-8}$ m. Then we derive from expression (26)

$$\aleph \approx 4 \; \times \; \frac{10^{16}\;\left[\sec^{-1}\right]}{\omega}. \tag{27}$$

Putting $\omega = 10^6$ sec^{-1} we obtain $\aleph \approx 4 \times 10^{10}$, which conforms with estimates of other researchers regarding the number of electrons in a droplet. The fitting value of ω enlists the support in our experimental results, as we have mentioned in Introduction that radio-frequency signals, which have been picked-up, fall exactly within the MHz region.

Such simple analysis shows that the kinetic energy of electrons in a droplet should be very small in comparison with the kinetic energy of free electrons and electrons in conductors and semiconductors where this energy is proportional to $\omega \geq 10^{15}$ s^{-1}). However, if we equate energy $\hbar\omega \cong 10^{-28}$ J (at $\omega = 10^6$ s^{-1}) and the vibration energy $\frac{1}{2}m\omega^2\delta\bar{r}^{\,2}$ of an electron, we will reveal that the amplitude of oscillations of the electron near its equilibrium position will be non-realistically large, $\delta\bar{r} \approx 10^{-5}$ m.

Thus the only resolution to fit the problem of small ω to the large value of $\aleph$ is to accept an increase in the mass of electrons. Then setting in equality

$$\hbar\omega = \tfrac{1}{2}\,m^{*}\omega^2\,\delta\bar{r}^{\,2} \tag{28}$$

the reasonable meaning $\delta\bar{r} \approx \; (10^{-10}$ to $10^{-9})$ m, we derive for the effective mass of an electron in the droplet $m^{*} \approx 2 \times \left(10^{-22}\right.$ to $\left.10^{-24}\right)$ kg, which exceeds the rest mass of electrons millions of times.

4. Discussion

What is the origin for such large mass? At the moment of irradiation of the crystal, the flow of energy of the laser beam squeezes a local area of the crystal where a local deformation emerges. The back-reflected pulse removes this deformation that then is distributed to emitted electrons. Peculiarities of the droplet formation are not yet deeply understood, however, major principles of the mechanism of increase in the electron mass have become clear: the space deformation caused in the crystal by a pulse/flow of photons passes into emitted electrons. This claim, as well as the direct accordance between notions of a local deformation of space and mass, are confirmed by our mathematical theory of the real physical space[16−19,29], which represents a detailed formalization of fundamental physics.

Since the droplet can be formed only in the course of non-adiabatic processes, the time of formation of a droplet should be much less than the relaxation time of electrons in a metal ($t \ll \tau_{\text{relax.}} \ll 10^{-12}$ s) and the inverse Debye frequency ($t \ll \nu_{\text{D}}^{-1} \approx 10^{-13}$ to 10^{-12} s). The bond energy of an electron in the droplet can be evaluated as composition

$$E_{\text{bond}} = \aleph \hbar \omega \approx 4 \times 10^{-18} \text{ J}. \tag{29}$$

This energy is injected in the crystal through a surface area comparable with the size of the droplet, by the laser beam with power $P = 100$ mW during a time of about $t \approx 10^{-16}$ s. This time satisfies the above inequalities.

An electron can be knocked out by a hard ultraviolet photon with the frequency $E_{\text{bond}}/h = \nu_{\text{ph}} = 6 \times 10^{15}$ s, or $\lambda_{\text{ph}} = 50$ nm. When knocking, the electron loses its heavy mass and the difference $\Delta m = m^* - m_0$ will transform to inertons that are emitted from the electron and the electron is returned to its rest mass m_0.

Note in passing that the idea of a variation in mass is important also in thermodynamic processes[31]. Namely, in paper[31] the mass-energy relation $\pm\Delta mc^2$ has been linked to the laws of thermodynamics, which is also supported by the submicroscopic consideration. Formalization of fundamental physics allows us easily to account for such variations in mass, because mass is treated as a local deformation of the tessellation space and this is a fractal volumetric deformation of a cell of space[16−19] (whereas a fractal deformation of the surface of a cell corresponds to the notion of the electric charge and electromagnetic polarization[17,18,32]).

Therefore, the notion of the defect of mass Δm is an inherent property not only for atomic nuclei, but for any physical system, from quantum (for instance, electron) to macroscopic.

Since electron droplets consist of the mass substance, they are able to behave as conventional matter droplets that are studied in the framework of fluid, or hydrodynamic mechanics. That is, moving electron droplets can change their shape with time, which one can see in Fig. 1, and such behavior indeed is prescribed for droplets by the hydrodynamic laws (see, e.g. Refs. 33 and 34).

5. Conclusion

The research carried out in the present work shows that electron droplets can be created at the irradiation of the polar (pyroelectric and ferroelectric) crystals boundary by a laser beam at special conditions. A detailed understanding of these conditions requires further experimental and theoretical studies.

From the experimental results of our examination we may conclude that a part of the photo-induced holographic scattering in the ferroelectric crystals may be interpreted as scattering on the charged plasma clusters (electron droplets). Needle-type electrodes greatly enhance near-surface plasma formation, resembling formation of the high-energy electron clusters described by Mesyats[11,12] as "ectons". But in contrast to previous works[11,12] in our case there are no externally applied high-voltage pulses: in our experiments high-voltage nanosecond electrical pulses were generated in the ferroelectric crystal by the low-power CW laser illumination due to photogalvanic and pyroelectric effects. For this reason our hypothetical charged plasma (electron) clusters may be called "photogalvanic electron clusters", or "pectons".

The mechanism of the droplet formation proposed in this work enables a natural description of the electron's confinement in terms of the submicroscopic concept in which an important role is played by excitations of the real space (inertons), which carry mass properties of physical entities. We have argued that this is the inerton interaction between electrons, which overcomes their Coulomb repulsion. The inerton interaction growth also means a huge increase in mass of an electron in the droplet, namely, up to millions of the rest mass m_0.

The submicroscopic concept allows many other applications in different branches of fundamental and condensed matter physics and, in particular, in applied studies dedicated to alternative sources of energy, because new species may possess an additional energy content associated with the defect of mass.

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