Microelectrostriction in an ionized medium

G. A. Askar'yan and V. A. Dolgoshein

P. N. Lebedev Physics Institute, USSR Academy of Sciences

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A new effect is considered, microelectrostriction produced in an ionized medium as a result of contraction of the medium in the electric field of the ions. It is shown that this effect can exceed in magnitude the thermal expansion connected with the ionization losses. Among the phenomena in which this effect can manifest itself or can be revealed are scattering or refraction of light, a non-thermoacoustic behavior of sound emission by charged particles, and others.

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1. We consider here a new effect, electrostriction contraction of matter as a result of ionization produced by any ionizing agent, such as charged particles, quanta, and others. We are interested in the microstriction that occurs in the field of the ions and is much longer lasting and stronger than the rapidly alternating striction in the field of a traveling particle and in the collective field of beams, since the large magnitude and duration of the microstriction produced by ions manifests itself noticably in macroscopic effects.

Let a flyby charged particle produce in a medium a total of N_{10} pairs of ions per unit track length ($N_{10} \sim Z^2/u^2$, where Z is the charge and u is the velocity of the particle). These ions recombine and their number $N_1(t)$ decreases rapidly with time because of the decreased density of their spatial distribution. The field of each ion attracts molecules of the medium and produces local condensations. The change of the volume of the medium in the field of each ion is $\Delta v = \kappa \int_{r_{\min}}^{\infty} p 4\pi r^2\, dr$, where $p = (\partial \epsilon / \partial \rho) \rho E^2 / 4\pi$ is the striction pressure, κ is the compressibility of the medium, $r_{\min}$ are the distances at which the compressibility is strongly decreased because of the repulsion of the approaching molecules ($r_{\min} \simeq 3 \times 10^{-8}$ cm), ϵ is the permittivity of the medium and is of the order of unity at short distances because of saturation of the orientation in strong fields (at $dE_{\text{eff}}(r_{\text{cr}}) \overset{\sim}{>} kT$, where d is the dipole moment of the molecule); $\Delta v \approx \kappa (\partial \epsilon / \partial \rho) \rho (e^2 / 2\epsilon^2)(1/r_{\min}) \approx 10^{-22}$ cm^3 for water. The fact that Δv depends on $r_{\min} \approx 3 \times 10^{-8}$ cm makes the macroscopic estimate insufficient. A microscopic estimate of the change of the volume of the medium following formation of a complex of ν molecules per ion yields $\Delta v \approx \nu v_0 - v_c$, where v_0 is the volume per molecule $v_0 \approx 1/n_a = M/\rho N_a \approx 3 \times 10^{-23}$ cm^3 for water. Here M is the molecular weight, N_a is Avogadro's number) and v_c is the volume per complex (it appears that attraction of the medium to the complex makes v_c close to the volume of the complex, $v_c \gtrsim \nu v_{\text{mol}} \approx 10^{-22}$ cm^3 at $\nu \approx 10$). Therefore $\Delta v \approx 10^{-22}$ cm^3. We shall assume $\Delta v \approx 10^{-22}$ cm^3 on the basis of the macroscopic and microscopic estimates. The change of volume per unit track length is $\Delta V_{1l}(t) \approx 2N_1(t) \Delta v$.

The change of the volume in the region of the radius a is produced within a time of the order of $t_s = a/c_s$, where c_s is the speed of sound.

We compare now the striction contraction with the thermal expansion produced when the medium is heated as a result of the ionization losses:

$$\Delta V_{1\mathrm{T}} \approx \frac{a}{C\rho}\left(\frac{dE}{dx}\right)_{\mathrm{ion}} \approx \frac{a}{C\rho} w_0 N_{10},$$

where w_0 is the energy loss per pair of produced ions, α is the coefficient of thermal expansion, and C is the heat capacity of the medium. The volume-changes ratio is

$$\frac{\Delta V_{1i}}{\Delta V_{1\mathrm{T}}} \approx \frac{2C\rho\Delta v}{aw}\,\frac{N_1(t)}{N_{10}} \approx \frac{10^{-4}}{a}\,\frac{N_1(t)}{N_{10}}.$$

Usually $\alpha = 10^{-5}$–10^{-4} deg^{-1}, so that the striction contraction can be noticeable also at $N_1(t) < N_{10}$.

We now determine the change of $N_1(t)$ with time. Assuming that $\dot{N}_1 \approx -\beta n_i^2 V_1 \approx -\beta N_1^2/\pi r_{tr}^2$, where $n_i(t)$ is the ion concentration on the track and r_{tr} is the "radius" of the track (the distance over which the electrons diffuse prior to the deceleration and sticking is $r_{tr} \approx 0.5\times10^{-6}$ cm (Ref. 1), and the running volume of the track is $V_1 \approx \pi r_{tr}^2$) and β is the ion–ion recombination coefficient. It is easy to estimate β from the time of approach of the two ions separated by a distance l:

$$t \approx \int \frac{dl}{v} \approx \int \frac{dl}{KE} \approx \int \frac{dl\, l^2 \epsilon}{Ke} \approx \frac{l^3 \epsilon}{3Ke},$$

but $l^3 \sim 1/n_i$ and from the definition $\beta \approx 1/n_i t$ we get $\beta \approx 3Ke/\epsilon \approx 2\times10^{-11}$ cgs esu, the experimental value of the mobility being $K \approx 1$ cgs esu.[2]

Therefore

$$N_1(t) = N_{10}\Big/\left(1 + \frac{\beta N_{10} t}{\pi r_{tr}^2}\right) = N_{10}\Big/\left(1 + \frac{t}{t_0}\right),$$

$$\text{where } t_0 = \frac{\pi r_{tr}^2}{\beta N_{10}}.$$

As the recombination proceeds, the effect of the striction contraction decreases and the thermal expansion on the particle tracks predominates.

The time behavior of the microstriction contraction and of the microthermal expansion on the particle tracks and beams, as well as the recombination dynamics, can be investigated by using refraction or scattering of light from tracks of charged-particle beams (for example, it is possible to separate the purely striction effects, in water near $T = 4$ °C, where the thermal expansion ceases, it is possible to investigate small time intervals in liquids with long molecules when the microstriction is commensurate with or exceeds the thermal effects, etc.).

2. The microstriction compression can also play a substantial effect in emission of

sound or hypersound from charged particles in media,[3,4] especially at small values of the coefficient of thermal expansion or at high frequencies. In particular, it can explain the results of experiments[5] in which it was observed that a sound pulse from a beam of charged particles in water vanishes and reverses sign not at $T = 4$ °C, when the coefficient of thermal expansion $\alpha = 0$, but at $T = 5.7$ °C, when $\alpha \approx 10^{-5}$ deg^{-1}.

Let us estimate the Fourier components p_ω of the sound pulse: for thermal expansion[4] (which lasts a long time, since it is independent of the heat-localization volume)

$$P_{\omega T} \sim \ddot{V}_\omega \approx -i\omega \int \Delta \dot{V}_1(t) e^{i\omega t} dt \approx -i\omega \Delta V_{1T}$$

and for striction contraction, which has a short duration ($\omega t_0 \ll 1$)

$$p_{\omega i} \sim -\omega^2 \int \Delta V(t) e^{i\omega t} dt = -2\omega^2 \Delta v N_{10} \int \frac{e^{i\omega t} dt}{(1 + t/t_0)}$$

$$\approx -2\omega^2 \Delta v N_{10} \int_0^{t\sim \frac{1}{\omega}} \frac{dt}{1 + t/t_0} \approx -2\omega^2 \Delta v \frac{\pi r_{tr}^2}{\beta} \ln \frac{1}{\omega t_0} \cdot$$

The experimental conditions[5] were $N_{10} \approx 0.5 \times 10^6$ cm^{-1}, $\omega \approx 3 \times 10^5$ rad/sec, and $t_0 = 5 \times 10^{-7}$ sec, i.e., $\omega t_0 = 5 \times 10^{-2}$.

Therefore

$$\left| \frac{p_{\omega i}}{p_{\omega T}} \right| \approx \frac{2\omega \Delta v \dfrac{\pi r_{tr}^2}{\beta} \ln \dfrac{1}{\omega t_0}}{\dfrac{a}{C\rho} \, wN_{10}} \approx 10^{-5}/a \, ,$$

i.e., the contribution of striction contraction is noticeable already at $\alpha \approx 10^{-5}$ deg^{-1}.

If a prolonged particle beam with current J is turned on abruptly[5] we have

$$\Delta \dot{V}_{1T} \approx \frac{a}{C\rho} \frac{J}{e} wN_{10} \quad \text{and} \quad \Delta V_{1i} \approx \Delta v N_1(t) \frac{J}{e} t \cdot$$

Therefore, assuming a sound amplitude $p \sim \ddot{V}$ and being interested in times $t_s \sim a/c_s$, where a is the beam radius ($a \sim 0.5$ cm), we get

$$p_T \sim \frac{a}{C\rho} \frac{J}{e} wN_{10}/t_s \quad \text{and} \quad p_i \sim \frac{2\Delta v}{t_s^2} \frac{\pi r_{tr}^2}{\beta} \frac{J}{e} \, .$$

Therefore

$$\frac{p_i}{p_T} \approx \frac{2\Delta v \pi r_{tr}^2 C\rho}{t_s \, a wN_{10} \beta} \approx -\frac{10^{-5}}{a}$$

meaning that the pulse amplitudes become comparable at $\alpha \approx 10^{-5}$ deg^{-1}, i.e., the thermal expansion can be offset by the constriction under these conditions in accord with the experiments of Ref. 5.

We note that in the case of non-ionizing laser heating the thermoacoustic pulse vanishes exactly at $T = 4$ °C, as shown by experiments.[6]

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[1] E. Kobetich and R. Katz, Phys. Rev. **170**, 391, 401 (1968).

[2] G. Kaye and T. Laby, Tables of Phys. and Chem. Constants, Wiley, 1966.

[3] G.A. Askar'yan, At. Energ. **3**, 152 (1957).

[4] G.A. Askar'yan and B.A. Dolgoshein, Preprint No. 160, Phys. Inst. Acad Sci., 1976; Pis'ma Zh. Eksp. Teor. Fiz. **25**, 232 (1977) [JETP Lett. **25**, 213 (1977)].

[5] L. Sulak *et al.*, Proc. Dumand Workshop on Acoust. Neutrino Registration, San Diego, July 1977.

[6] P.N. Golubnichiĭ, G.S. Kalyuzhnyĭ, S.I. Nikol'skiĭ, and V.I. Yakovlev, Preprint No. 167, Phys. Inst. Acad. Sci., 1978.