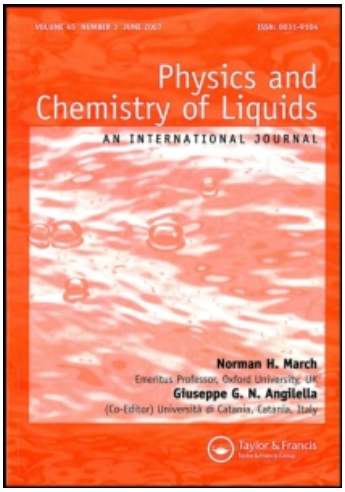

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ASYMPTOTIC FIELD DEPENDENCE OF APPROACH TO SATURATION OF DRIFT VELOCITY OF ELECTRONS IN LIQUID XENON

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The high electric field saturation drift velocity v_d^{sat} of electrons in liquid xenon near the triple point is 3 x 10^3 m/s. This value is recovered if $(v_d^{sat})^2\ \kappa^{sat}\tau^{sat} = D$. Here D is the self-diffusion coefficient of liquid xenon, τ^{sat} is the lower limit of phonon oscillation periods, and κ^{sat} is an electron energy-loss probability characteristic of scattering of field-driven electrons by the atoms of the liquid medium.

Given the form of the saturation drift velocity, the asymptotic field (E) dependence of the approach to the drift velocity saturation is then explored by expanding $\kappa(E)\tau(E)$ in the form $\kappa(E)\tau(E) = \kappa^{sat}\ \tau^{sat} + A_1/E^{\gamma}$ + higher-order terms. From experimental results of Huang and Freeman, γ is found to be 4/3. This form cannot, of course, be extended into regimes of much lower electric field where a further physical mechanism contributes to the electron mobility.

Keywords: Electron saturation drift velocity; liquid xenon; self-diffusion coefficient; phonons

1. INTRODUCTION

Almost twenty years ago, Huang and Freeman [1] made an extensive experimental investigation of electron mobilities in xenon over a sufficiently wide density range embracing gaseous, critical and liquid regimes.

While their study is the motivation for the present work, the specific interest here concerns their results for the electron drift velocity $v_d(E)$

as a function of electric field strength E. More explicitly, the results at the highest density in Figure 7 of ref.1 will be analyzed: these are presented over a range of electric field from 2kV/m to 4MV/m.
Two points are of especial interest to us:

(i) How can the magnitude of the high-field saturation drift velocity v_d^{sat} be recovered from a physical argument? This velocity is 3×10^3 m/s.
(ii) What is the asymptotic field dependence of the approach to the high-field saturation limit?

Before embarking on a detailed discussion of (i) and (ii) above, we record here that a major review on transport of electrons in nonpolar fluids, including an account of work on drift velocities of injected electrons as a function of electric field strength, has been given by Holroyd and Schmidt [2], with some 150 references. Here, it is relevant in the present context to cite the theoretical work of Atrazhev and Dimitriev [3] who adopt the framework of the Lekner-Cohen theory [4, 5].

As noted by Holroyd and Schmidt [2], electron mobility studies in liquids of the heavy rare gases have been carried out by Leycuras and Larour [6, 7] using the method of molecular dynamics. The electron is thought of as being temporarily localized at one rare gas atom, and it is seperated from neighbouring sites by steep potential barriers. Collisions with nearest neighbours result in the lowering of such barriers, and the electron hops to a neighbouring site. One-dimensional computed simulations on chains of 130 to 150 atoms reproduced some of the features of the electric field dependence of the electron drift velocity in liquid argon, krypton and xenon.

After this brief survey of some related studies, we return to the points (i) and (ii) of especial interest for the present work.

2. HIGH-FIELD SATURATION DRIFT VELOCITY v_d^{sat}

As to point (i) above, we first note on dimensional grounds that $(v_d^{sat})^2 \times \text{time} = L^2T^{-1}$, which has the dimensions of a diffusion coefficient. The questions then arise as to the physical significance of such diffusion, and the meaning of the 'characteristic' time. There can be little

doubt that the time must be connected with the scatteting of 'field-driven' electrons off the atoms of the dense liquid medium, to which case we restrict attention throughout. If we consider the energy distribution (the so-called frequency spectrum [9]) $g(\omega)$ of motions in a classical liquid like xenon, this is customarily defined from the self- function $S_s(k,\omega)$ accessible through incoherent neutron scattering as [8,9]

$$g(\omega) = \omega^2 \lim_{k\to 0} \frac{S_s(k,\omega)}{k^2} , \tag{1}$$

where $g(\omega = 0) = \mathrm{D}/\pi$, with D the self-diffusion coefficient of the liquid. If we write

$$(v_d^{\mathrm{sat}})^2 \times \tau^{\mathrm{sat}} = D , \tag{2}$$

then for the highest density (1.41×10^{28} molecules/m^3, 163K) results in Figure 7 of ref.1, with $D = 1.8 \times 10^{-9}$ m^2/s [4], one extracts $\tau^{\mathrm{sat}} = 2 \times 10^{-16}$s. This is about 10^{-3} times the period of the high frequency 'edge' of phonons in liquid xenon.

The average energy of electrons at saturation drift velocity in xenon is ~ 0.2 aJ (1eV) [1], and we suggest that an energy–loss probability factor $\kappa^{\mathrm{sat}} \approx 10^{-3}$ be included in eqn. (2), such that τ^{sat} retains a relationship to high frequency phonons:

$$(v_d^{\mathrm{sat}})^2 \kappa^{\mathrm{sat}} \tau^{\mathrm{sat}} = D \tag{3}$$

with $\kappa^{\mathrm{sat}}\tau^{\mathrm{sat}} = 2 \times 10^{-16}$s. Eqn. (3) separates $(v_d^{\mathrm{sat}})^2$ into the ratio of D, a characteristic of pure liquid xenon in the thermodynamic state under consideration, to the product of the period of high frequency phonons, which are the energy sink of the field-driven electrons in the liquid, and the electron scattering probability per phonon period.

3. ASYMPTOLIC FIELD DEPENDENCE; APPROACH TO SATURATION

Having addressed point (i) raised above, let us turn to point (ii)-the asymptotic field dependence of approach to the 'saturation' formula (3).

We shall make, in exploring this second question, the simplest possible assumption in generalizing eqn. (3). Since D is characteristic of the pure liquid medium, we shall write

$$[v_d(E)]^2 \kappa(E)\tau(E) = D \tag{4}$$

Here $v_d(E)$ denotes the drift velocity as a function of field strength as measured by Huang and Freeman,[1] while $\kappa(E)\tau(E)$ is evidently now a field-dependent time characteristic of energy transfer from the electron to the liquid. Dividing eqn. (3) by eqn. (4), rearranging and then subtracting $\kappa^{sat}\tau^{sat} \equiv \kappa^s\tau^s$ from both sides, yields

$$\left[\frac{v_d^{sat}}{v_d(E)}\right]^2 - 1 = \frac{\kappa(E)\,\tau(E) - \kappa^s\,\tau^s}{\kappa^s\,\tau^s}. \tag{5}$$

Motivated by the form (5), we have used the data for the highest density in ref. 1 to plot the LHS of eqn. (5) against field strength E. A log-log plot yields a straight line with slope $-1.29 \approx -4/3$ (Fig. 1). It therefore follows from eqn. (5) that we can write for the asymptotic approach to the saturation value of the excitation parameter $\kappa^s\tau^s$:

$$\kappa(E)\,\tau(E) = \kappa^s\,\tau^s + \frac{A_1}{E^{4/3}} + \text{higher-order terms in field strength.} \tag{6}$$

Having established the exponent in eqn. (6) as 4/3 from the data, Figure 1 can also be utilized to estimate $A_1 = 3 \times 10^{-10}$ $(\text{V/m})^{4/3}\text{s}$.

The value of $\kappa(E)\tau(E)$ increases with decreasing E, which indicates that as E is decreased the field-driven electrons excite progressively lower energy (higher τ) phonons.

4. SUMMARY

In summary, it is proposed that an interpretation of the field-dependent drift velocity data of Huang and Freeman[1] is afforded by asserting, as in eqn. (4), that the square of the drift velocity of the electrons can be represented as the self-diffusion constant D of the pure liquid divided by a field-dependent excitation parameter $\kappa(E)\tau(E)$. Given this

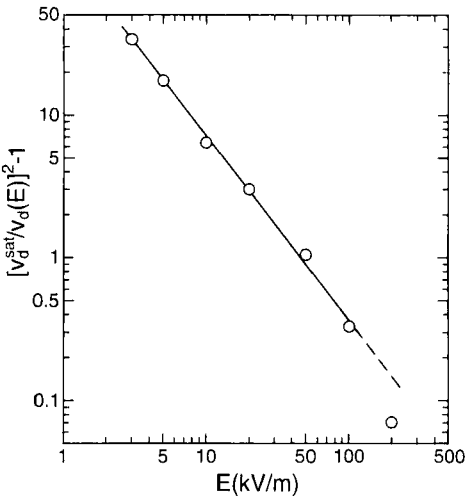

FIGURE 1 Plot of the left-hand-side of eqn. (5) against the applied electric field strength E, for electrons in liquid Xe at 163K and density 1.41×10^{28} molecules/m^3. Data from Ref. 1, Figure 7.

assumption, the asymptotic eqn. (5) then follows to the saturation limit. Of course, it is well known that, when the field strength is lowered sufficiently, another physical mechanism comes in, as evidenced by considerable structure in the lower density plots of v_d against E in Figure 7 of ref. 1. Naturally, it must not be assumed that, when a further mechanism is operative, eqn. (4) will continue to afford a physically useful decomposition of $[v_d(E)]^2$.

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[8] See, for example,March, N. H. (1990), *Chemical physics of liquids* (Gordon and Breach: New York) p.147.
[9] $\hbar\omega$ is the energy transfer between a neutron and a simple liquid, where ω is the change in the phase angular speed of the neutron in the scattering process; the corresponding change in frequency is $v = \omega/2\pi$. Similarly $\hbar k$ is the momentum transfer, where k is related to the change of neutron wavelength from λ_0 to λ by $k = 2\pi(\lambda_0^{-1} - \lambda^{-1})$.
[10] Calculated from data in Erlich, R. S. and Carr, H. Y. (1970) *Phys. Rev. Lett.*, **25**, 341.