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Ultrafast and Ultrasensitive Dielectric Liquids/Mixtures:  
Basic Measurements and Applications

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Basic properties of cryogenic and room temperature dielectric liquids/mixtures with high electron yields (under irradiation by ionizing particles) and high excess electron drift velocities are discussed. A number of ultrafast and ultrasensitive liquid media--appropriate for possible use in liquid-filled radiation detectors and other applications--are identified.

## I. INTRODUCTION

Contrary to low-pressure gases where electrons are "free," in liquids electrons are quasifree or localized (e.g., see Refs. 1-5). Excess electrons are quasifree in liquids for which the electron ground-state energy,  $V_0$ , is negative ( $< 0$  eV). Such liquids can be cryogenic or "warm" (room temperature). Examples are given in Table I. It is in such liquids (and their mixtures with appropriate additives) that the search for ultrafast and ultrasensitive liquid media is being focused.

II. ELECTRON DRIFT VELOCITIES, ELECTRON ENERGIES, AND ELECTRON ATTACHMENT TO MOLECULES IN DIELECTRIC LIQUIDS WITH  $V_0 < 0$  eV

In liquids/mixtures with  $V_0 < 0$  eV (such as those in Table I), quasifree electrons drift fast, have energies in excess of thermal at high applied electric fields  $E$ , and attach to molecules as in gases [but with notable

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TABLE I: Examples of Liquids with Negative  $V_0$ 

Liquid	$V_0$ (eV) <sup>a</sup>
- <u>Cryogenic</u>	
Ar(87 K)	-0.20
Xe(165 K)	-0.61
- <u>Room Temperature</u>	
Neopentane [C(CH <sub>3</sub> ) <sub>4</sub> ]	-0.43
Tetramethylsilane [Si(CH <sub>3</sub> ) <sub>4</sub> ]	-0.57
Tetramethylgermanium [Ge(CH <sub>3</sub> ) <sub>4</sub> ]	-0.64
Tetramethyltin [Sn(CH <sub>3</sub> ) <sub>4</sub> ]	-0.75
2,2,4,4-Tetramethylpentane [(CH <sub>3</sub> ) <sub>3</sub> OCH <sub>2</sub> C(CH <sub>3</sub> ) <sub>3</sub> ]	-0.36

<sup>a</sup>See Refs. 1-6 for original sources of  $V_0$  data.

changes in the energy position, cross section, and lifetime of the negative ion state(s) involved] (e.g., see Refs. 1-8). Figures 1 through 6 exemplify these properties for cryogenic liquids.

In Fig. 1 the electron drift velocity  $w$  as a function of the density-reduced electric field  $E/N$  is shown for gaseous Ar<sup>9,10</sup> and Xe<sup>9,11</sup> and for liquid Ar and Xe.<sup>12</sup> ( $w_L$  and  $w_G$  refer to the  $w$  in the liquid and the gas, respectively). At any value of  $E/N$ , the  $w_L$  in the liquid far exceeds the  $w_G$  in the low-pressure gas, especially for Xe at low  $E/N$ , reflecting the profound changes in the momentum transfer cross section  $\sigma_m(\epsilon)$  between the gas,  $(\sigma_m)_G(\epsilon)$ , and liquid,  $(\sigma_m)_L(\epsilon)$ .<sup>2,8</sup>

In Fig. 2 the characteristic energy  $\left[ \frac{3}{2} e \frac{D_T}{\mu} \right]_L$  versus  $E/N$  is shown for liquid Ar<sup>13</sup> ( $T = 87$  K) and liquid Xe<sup>14</sup> ( $T = 165$  K) ( $D_T$  is the transverse

electron diffusion coefficient and  $\mu$  is the electron mobility). For comparison, the calculated<sup>8,11</sup>  $\left[ \frac{3}{2} e \frac{D_T}{\mu} \right]_G$  versus  $E/N$  for gaseous Ar and gaseous Xe at room temperature ( $T = 300$  K) and at  $T = 165$  K for Xe and at  $T = 87$  K for Ar are also shown in the figure. While the  $\left[ \frac{3}{2} e \frac{D_T}{\mu} \right]_L (E/N)$  for liquid Ar are lower than the corresponding gaseous values, the opposite behavior is observed for Xe. In the  $E/N$  range over which  $D_T/\mu$  measurements were made in the liquid phase (Fig. 2), the characteristic energies are larger in liquid Xe than in liquid Ar.

In Fig. 3 are shown<sup>8</sup> the various estimates of the mean electron energy  $\langle \epsilon \rangle_L (E/N)$  in liquid Ar. For comparison, the gaseous  $\langle \epsilon \rangle_G (E/N)$  is shown in the figure for  $T = 300$  K and 87 K. Over the entire  $E/N$  range investigated, all estimates give--for a fixed  $E/N$ -- $\langle \epsilon \rangle_L < \langle \epsilon \rangle_G$ . Similarly, in Fig. 4 are shown the  $\langle \epsilon \rangle_L (E/N)$  estimates<sup>8</sup> for liquid Xe. Contrary to the case of Ar,  $\langle \epsilon \rangle_L > \langle \epsilon \rangle_G$  for Xe at all  $E/N$  values (see Fig. 4). The fact that for Xe  $\langle \epsilon \rangle_L > \langle \epsilon \rangle_G$  at all values of  $E/N$  in Fig. 4 is consistent with the result  $w_L > w_G$  (Fig. 1) and indicates that  $(\sigma_m)_L \ll (\sigma_m)_G$  for  $\epsilon \lesssim 1$  eV.

In Fig. 5 is plotted the rate constant,  $(k_a)_L$ , for electron attachment to  $SF_6$ ,  $N_2O$ , and  $O_2$  in liquid Ar (Ref. 18) as a function of  $\langle \epsilon \rangle_L$  (Ref. 8; see Fig. 3). While the  $\langle \epsilon \rangle_L$  dependence of  $(k_a)_L$  for the three solutes is similar to the respective  $(k_a)_G (\langle \epsilon \rangle)$  in gases,<sup>8,9,19</sup> the  $(k_a)_L (\langle \epsilon \rangle)$  functions are normally shifted to lower energies and are larger in magnitude than those  $(k_a)_G (\langle \epsilon \rangle)$  in gases (e.g., see Fig. 6 and Refs. 2 and 7).

For room-temperature dielectric liquids,  $w(E)$  has been measured by many authors especially at low  $E$  (e.g., Refs. 1-6, 8, 20, 21). In Fig. 7 are shown our<sup>21</sup> recent measurements of  $w(E)$  in tetramethylsilane (TMS) and 2,2,4,4-tetramethylpentane (TMP). These measurements extend to  $E \gtrsim 1.2 \times 10^5$

$V\text{ cm}^{-1}$  and were made using a new technique (see below). For both TMS and TMP, the mobility  $\mu$  ( $= w/E$ ) decreases with  $E$  (Fig. 8) indicating that the  $\langle \epsilon \rangle_{\perp}$  exceeds  $1.5\text{ kT}$  (see also Ref. 22).

The technique employed for the  $w(E)$  measurements in Fig. 7 is especially suitable for accurate measurements of  $w(E)$  in fast dielectric liquids: it is being developed (through the use of a subnanosecond laser pulse) to also measure longitudinal electron diffusion coefficients in dielectric liquids. The principle of the technique is shown in Fig. 9. After extensive purification,<sup>23</sup> the liquid under study was contained in a cell which consisted of a six-way stainless steel cube with two windows for the entry and exit of the laser beam and two electrical feedthroughs (one for the high voltage and the other for the signal) to which the electrodes (two stainless steel parallel-plate circular disks of 1" in diameter and at a distance of a few mm apart) were attached. The beam of an excimer laser ( $\lambda = 308\text{ nm}$ , pulse duration  $\sim 17\text{ ns}$ ) was focused at the center of the negative high voltage electrode in a circular area of  $\sim 5\text{ mm}$  in diameter. Voltages in excess of  $40\text{ kV}$  could be applied to the high voltage electrode.

The signal due to the drifting pulse of electrons--generated by the laser pulse at the cathode--was measured and recorded in two different ways:

(i) In the voltage mode (Fig. 10a) the signal was fed directly to a fast (response time  $\sim 3\text{ ns}$ ) charge-sensitive preamplifier and was captured, averaged and stored, by a transient digitizer as a voltage waveform.

(ii) In the current mode (Fig. 10b) the input of the preamplifier was grounded through a  $50\ \Omega$  resistor. This, in effect, corresponds to electronic differentiation of the voltage-mode signal and gives the transient current waveform.

By numerically differentiating the current-mode signal (Fig. 10c) a waveform corresponding to the rate of charge injection from the cathode and collection at the anode is obtained. The drift time was measured by determining points A and B on any of the three types of waveforms (voltage, current or charge).

### III. ULTRAFAST AND ULTRASENSITIVE DIELECTRIC LIQUIDS/MIXTURES

#### A. Ultrafast Dielectric Liquids/Mixtures

The fast electron motion in such (cryogenic or room temperature) media finds application in a number of areas such as radiation detectors (e.g., see Refs. 24-26) and pulsed power switches.<sup>27</sup> In connection with radiation detectors, liquid Ar and liquid Xe are excellent detector media. It can be seen from Fig. 1, for example, that the  $w$  in liquid Ar--and especially liquid Xe--is larger than in the corresponding gas over a large range of  $E/N$ . This is highly desirable since the magnitude of  $w$  determines the time response of radiation detectors and since a large  $w$  reduces electron-ion recombination and thus increases the gain of the detector. The saturation of the  $w$  versus  $E/N$  curve for liquid Xe at comparatively low  $E/N$  values (see Fig. 1) and the much higher density of liquid Xe (allowing improved detector spatial resolution) are additional advantages for using Xe as a detector fluid.

The magnitude of  $w$  can be considerably increased over a wide  $E/N$  range--as in gases<sup>28</sup>--by the addition of suitable molecular additives to liquid Ar and Xe. Such additives must be nonelectron attaching, have appropriate cross sections at low energies, and adequate vapor pressure so that additive concentrations of a few percent are possible. Besides enhancing  $w$ , such additives would reduce the size and affect the  $E/N$  dependence of the electron diffusion coefficient and mean electron energy which crucially affect

the particle detector's position characteristics and gain, and the influence of electronegative impurities. By analogy to gases, small amounts (< few per cent) of molecular additives (e.g.,  $\text{CH}_4$ ,  $\text{C}_2\text{H}_6$ ) were added to liquid Ar and Xe and remarkable increases in  $w$  were observed (e.g., see Fig. 11 and Refs. 29 and 30).

Similarly, the large  $w$  values for a number of room temperature liquids (Fig. 7; Table II; Refs. 1-5, 26) make such media good candidates for liquid-filled radiation detectors. It is seen from Fig. 7 that the  $w$  approaches  $10^7 \text{ cm s}^{-1}$  at  $E$  values of  $\sim 10^6 \text{ V cm}^{-1}$ . While the  $w(E)$  of such room temperature liquids may be further increased by appropriate additives, such  $w(E)$  enhancements are not expected to be significant.

TABLE II:  $V_o$ ,  $I_L$ , and  $w$  for Four Fast Room Temperature Liquids

Liquid	$V_o$ (eV)	$I_L$ (eV) <sup>a</sup>	$w$ (cm s <sup>-1</sup> ) <sup>b</sup>
2,2,4,4-Tetramethylpentane	-0.36	8.2	$2.4 \times 10^6$
Neopentane	-0.40	8.85	$\sim 2.5 \times 10^6$
Tetramethylsilane	-0.57	8.1	$6.5 \times 10^6$
Tetramethyltin	-0.75	6.9	-

<sup>a</sup>Refs. 3, 31, and 32.

<sup>b</sup>For  $E = 10^6 \text{ V cm}^{-1}$ .

## B. Ultrasensitive Dielectric Liquids/Mixtures

In attempting to identify the key physical quantities which determine free electron production (by ionizing particles) and allow the selection and

development of "ultrasensitive" liquids, let us refer to the following three simple expressions:

$$G_{fe}^0 = p_{esc} G_{te} \quad (1)$$

$$G_{fe}^E = G_{fe}^0 + AE \quad (2)$$

$$I_L = I_G + V_o + P^* \quad (3)$$

In Eq. (1),  $G_{fe}^0$  is the yield of free electrons generated in the liquid by the deposition of 100 eV energy by a particular type (e.g.,  $\alpha$ ,  $\beta$ ,  $\gamma$ ) of ionizing radiation in the absence of an applied electric field (i.e.,  $E = 0$ );  $G_{te}$  is the total electron yield [ $G_{te} = 100 \text{ eV}/W$ , where  $W$  is the average energy (in eV) required to produce an electron-ion pair]; and  $p_{esc}$  is the escape probability (i.e., the probability that the initial electron-ion pair will separate and not recombine). While  $p_{esc} \approx 1$  for low-pressure gases (i.e., geminate recombination is unimportant), in liquids normally  $p_{esc} \ll 1$  (i.e., most geminate electron-ion pairs recombine with a resultant strong reduction in  $G_{fe}^0$ ). In Eq. (2),<sup>4,33</sup>  $G_{fe}^E$  is the free electron yield when an electric field  $E$  is applied across the volume in which the electrons are generated;  $G_{fe}^E$  exceeds  $G_{fe}^0$  by an amount  $AE$  where  $A$  is a constant that depends on the liquid.<sup>4,33</sup> In Eq. (3) (e.g., see Refs. 1-5, 34, and 35)  $I_L$  and  $I_G$  are the ionization threshold energies for a species embedded in the liquid and in the low pressure gas, respectively, and  $P^*$  is the polarization energy of the positive ion in the liquid.

The simple expressions (1) to (3) suggest a number of ways of selecting and developing ultrasensitive (large  $G_{fe}^E$ ) dielectric liquids/mixtures. Clearly, the larger the  $G_{te}$  and  $p_{esc}$  are, the higher the  $G_{fe}^E$ .

#### Pure Liquids ( $V_o < 0$ eV)

The total electron yield  $G_{te}$  for pure liquids can be increased if  $W$  can be lowered. In view of (3)--and since  $P^*$  and  $V_o$  are negative quantities-- $I_L <$

$I_G$  (e.g., see Refs. 1-5, 31, 32, 34, 35; Tables II and III) and thus,  $W_L < W_G$  (see Ref. 1) and  $(G_{te})_L > (G_{te})_G$ . This is certainly the case for liquid Ar and Xe (Column 4, Table III).

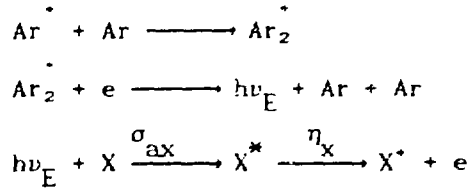
While the total electron yield  $G_{te}$  can be larger in the liquid than in the corresponding gas, the free electron yield  $G_{fe}^E$  is smaller in the liquid--by an amount which depends on the applied electric field--even for the very fast liquids (Column 5, Table III). This is especially the case for densely ionizing particles (e.g.,  $\alpha$ -particles; Column 6, Table III) due to the very low values of  $p_{esc}$ . It should be noted that  $p_{esc}$  increases with increasing electron drift velocity  $w$ ; the  $w$ --as the electron thermalization length--increases with decreasing electron scattering cross section of the liquid.

For pure liquids ( $V_0 < 0$  eV), then, a low  $I_L$  and a large  $w$  and  $E$  are desirable for a large  $G_{fe}^E$ .

#### Dielectric Liquids ( $V_0 < 0$ eV) with Molecular Additives

Clearly the free electron yield can be considerably increased by increasing  $G_{te}$  and  $p_{esc}$  in liquid rare gas-molecule mixtures. Traces of nonelectron attaching additives with low  $I_L$  in rare gas liquids lower the  $W_L$  of the mixture via Penning ionization and other photoionization processes and thus, increase  $G_{te}$ . A profound increase in  $G_{fe}^E$  can be realized [Figs. 12A, B; Refs. 39, 40] by the use of an additive X to liquid Ar (or Xe) which can absorb efficiently the recombination luminescence which is abundantly produced in rare gas liquids (e.g., Ref. 25) and be efficiently ionized. For a liquid Ar, X system these processes can be written as





where  $h\nu_E$  is the liquid argon excimer (E) recombination luminescence which peaks at  $\sim 9.55$  eV and  $\sigma_{ax}$  and  $\eta_x$  are, respectively, the absorption cross section and ionization efficiency of  $X^*$ . To optimize these processes one needs to select an  $X$  with an optimum  $\sigma_{ax}\eta_x$  product. Such additives (e.g., amines, tetramethylgermanium)<sup>39,40</sup> can be added in parts per million levels to binary liquid argon-molecule mixtures already optimized for a maximum electron drift velocity. A large  $w$  and a high applied field  $E$  will further increase  $G_{fe}^E$  by increasing  $p_{esc}$  (Fig. 12).

TABLE III:  $I_L$ ,  $I_G$ , and Free Electron Yields for Some Efficient Liquids

Liquid	$I_L$ (eV)	$I_G$ (eV)	Electron Yield (Electrons/100 eV)		
			$G_{te}^o$ (e. $\gamma$ ) <sup>a</sup>	$G_{fe}^o$ (e. $\gamma$ ) <sup>a</sup>	$G_{fe}^E$ ( $\alpha$ ) <sup>b</sup>
Ar	$\sim 14.1^c$	$15.755^d$	$4.4^e$ $(3.8)_G^h$	$2.3^f$ $(4.3)^{f,g}$	$0.45^{f,g}$
Xe	$\sim 8.9^c$	$12.127^d$	$6.5^e$ $(4.6)_G^h$	$4.4^i$	-
$C(CH_3)_4$	$8.85^j$	$10.23^k$	$4.30^l$	$1.1^f$ $(1.8)^{f,g}$	$0.036^{f,g}$
$Si(CH_3)_4$	$8.1^j$	$9.65^k$	-	$0.74^f$ $(1.19)^{f,g}$	$0.029^{f,g}$

<sup>a</sup>For low-ionization density particles (electrons,  $\gamma$ -rays).

<sup>b</sup>For high-ionization density particles ( $\alpha$ -particles).

<sup>c</sup>Ref. 1, p. 307.

<sup>d</sup>Ref. 9.

<sup>e</sup>Ref. 1, p. 304.

<sup>f</sup>Ref. 26 (T = 296 K).

<sup>g</sup>For  $E = 10^4 \text{ V cm}^{-1}$  (Ref. 26).

<sup>h</sup>Gaseous value determined from the W-values in Ref. 9.

<sup>i</sup>Ref. 36.

<sup>j</sup>From Table II.

<sup>k</sup>Ref. 37.

<sup>l</sup>Ref. 23.

The  $G_{fe}^E$  of fast room temperature dielectric liquids is limited compared to cryogenic liquid rare gases, especially for densely ionizing particles (Table III). For room temperature liquids the electron thermalization length--and hence  $p_{esc}$ --are much smaller than for the cryogenic liquids, internal conversion and dissociation processes rapidly deplete excited electronic states which might lead to Penning ionization in room temperature mixtures, and recombination luminescence is too weak or nonexistent to be useful as an additional electron production mechanism in mixtures. However, it might be possible to improve the efficiency of fast room temperature dielectric liquids by employing Penning mixtures where the ionization onset energy,  $I_L(X)$ , of the impurity X in these fast liquids is very low [e.g., the  $I_L$  of tetrakis(dimethylamino)ethylene (TMAE) in tetramethylsilane has been reported to be  $3.54 \text{ eV}^{41}$  and  $3.66 \text{ eV}^{42}$  and that of N,N,N',N' tetramethyl-p-phenylenediamine (TMPD) in the same liquid  $4.29 \text{ eV}^{43}$  and  $4.45 \text{ eV}^{44}$ ] and by applying very high electric fields.

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## FIGURE CAPTIONS

- Fig. 1.  $w$  versus  $E/N$  in gaseous Ar (■, □; Refs. 9 and 10) and Xe (•, ○; Refs. 9 and 11) and liquid Ar (□; Ref. 12) and Xe (▲, Ref. 12).  
Inset: Ratio  $w_G/w_L$  versus  $E/N$  for Ar and Xe.
- Fig. 2. Calculated<sup>8,11</sup>  $\left[\frac{3}{2} e \frac{D_T}{\mu}\right]_G$  versus  $E/N$  for gaseous Ar at  $T = 300$  K (○) and  $T = 87$  K (□) and gaseous Xe at  $T = 300$  K (Δ) and  $165$  K (▽).  
The experimental  $\left[\frac{3}{2} e \frac{D_T}{\mu}\right]_L$  versus  $E/N$  for liquid Ar (■; Ref. 13) and for liquid Xe (▼; Ref. 14) respectively at  $87$  and  $165$  K.  
Inset: Ratio  $\left[\frac{D_T}{\mu}\right]_G / \left[\frac{D_T}{\mu}\right]_L$  versus  $E/N$  for Ar (•) and Xe (Δ).
- Fig. 3. Calculated  $\langle \epsilon \rangle_L$  versus  $E/N$  for liquid Ar, ▼: Nakamura et al. (Ref. 15); ■: Christophorou (Ref. 7); ▲: Gushchin et al. (Ref. 16); ◆: Lekner (Ref. 17) in comparison with the calculated values of Christophorou et al. (Ref. 8) in liquid Ar at  $T = 87$  K (Δ) and gaseous Ar at  $T = 87$  K (○) and  $300$  K (□).
- Fig. 4. Calculated  $\langle \epsilon \rangle_L$  versus  $E/N$  for liquid Xe, ▲: Gushchin et al. (Ref. 16) in comparison with the calculated values of Christophorou et al. (Ref. 8) in liquid Xe at  $T = 165$  K (○) and gaseous Xe at  $T = 165$  K (■) and  $300$  K (□).
- Fig. 5. Rate constant,  $(k_a)_L$ , for electron attachment to  $SF_6$ ,  $N_2O$  and  $O_2$  measured in liquid Ar (Ref. 18) plotted versus  $\langle \epsilon \rangle_L$  (using the  $\langle \epsilon \rangle_L$  versus  $E/N$  estimates of Ref. 8).
- Fig. 6. Electron attachment rate constant for  $N_2O$  in gaseous,  $(k_a)_G$ , and liquid,  $(k_a)_L$ , argon plotted versus  $E/N$  and  $\langle \epsilon \rangle_G$  or  $\langle \epsilon \rangle_L$  (Ref. 7). The attachment is due to the reaction  $e + N_2O \longrightarrow N_2O^{*-} \longrightarrow O^- + N_2$ . Note the shift of the resonance to lower energies--and the increase in the rate constant--in the liquid.

- Fig. 7.  $w$  versus  $E$  for TMS ( $\blacktriangle$ ) and TMP ( $\bullet$ ) (Ref. 21). The  $w(E)$  values of Ref. 21 for TMS are  $\sim 20$  percent higher than those of Ref. 20. (See discussion in Ref. 21).
- Fig. 8. Mobility of excess electrons versus applied electric field in TMS ( $\blacktriangle$ ) and TMP ( $\bullet$ ) (Ref. 21).
- Fig. 9. Schematic of the experimental set up for the measurement of  $w(E)$  in fast liquids (Ref. 21).
- Fig. 10. Voltage (a), current (b), and charge (c) waveforms in TMP. Drift distance = 2.04 mm, applied voltage = 17,574 V, drift time = 97.8 ns (Ref. 21).
- Fig. 11.  $w$  versus  $E$  in liquid Ar (—) and liquid Ar/CH<sub>4</sub> mixtures:  $\nabla$  ( $N_{\text{CH}_4} = 2.6 \times 10^{20}$  molecules  $\text{cm}^{-3}$ ),  $\bullet$  ( $N_{\text{CH}_4} = 6.5 \times 10^{20}$  molecules  $\text{cm}^{-3}$ ).  $T(\text{Ar}) = 87$  K (Ref. 29; see this reference for data on other liquid Ar and liquid Xe mixtures).
- Fig. 12. Charge collected as a function of applied electric field for:
- Fig. 12(a):  $\beta$ -particles in pure argon ( $\bullet$ ) and liquid argon-triethylamine (TEA) mixture.
- Fig. 12(b):  $\alpha$ -particles in pure argon (A) and in liquid argon-triethylamine mixtures (Curve C:  $4.6 \times 10^{15}$  molecules  $\text{cm}^{-3}$ ; Curve D:  $1.1 \times 10^{15}$  molecules  $\text{cm}^{-3}$ ). [From Ref. 39; see this reference for details and data on other liquid argon mixtures.].

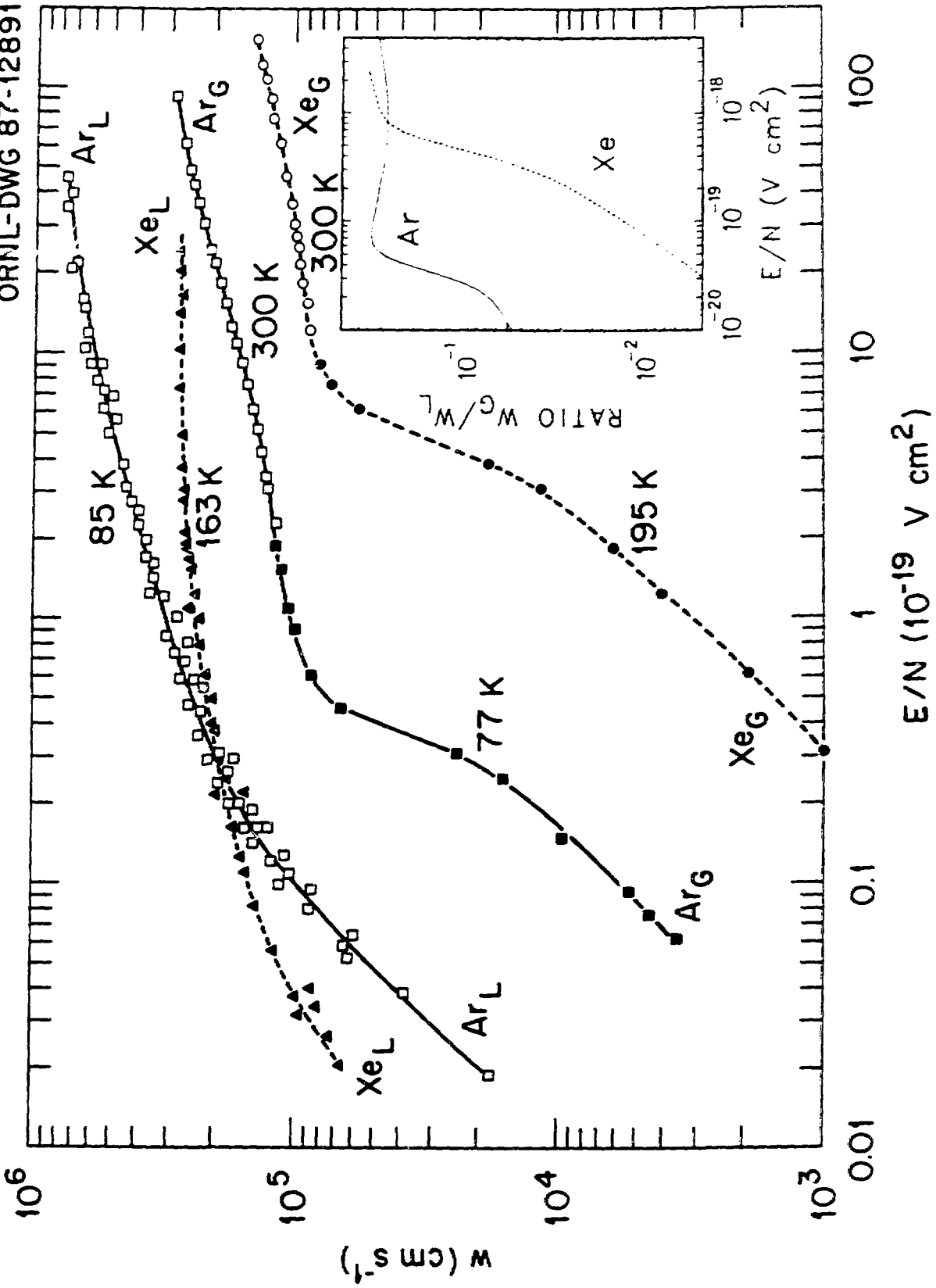


Figure 1



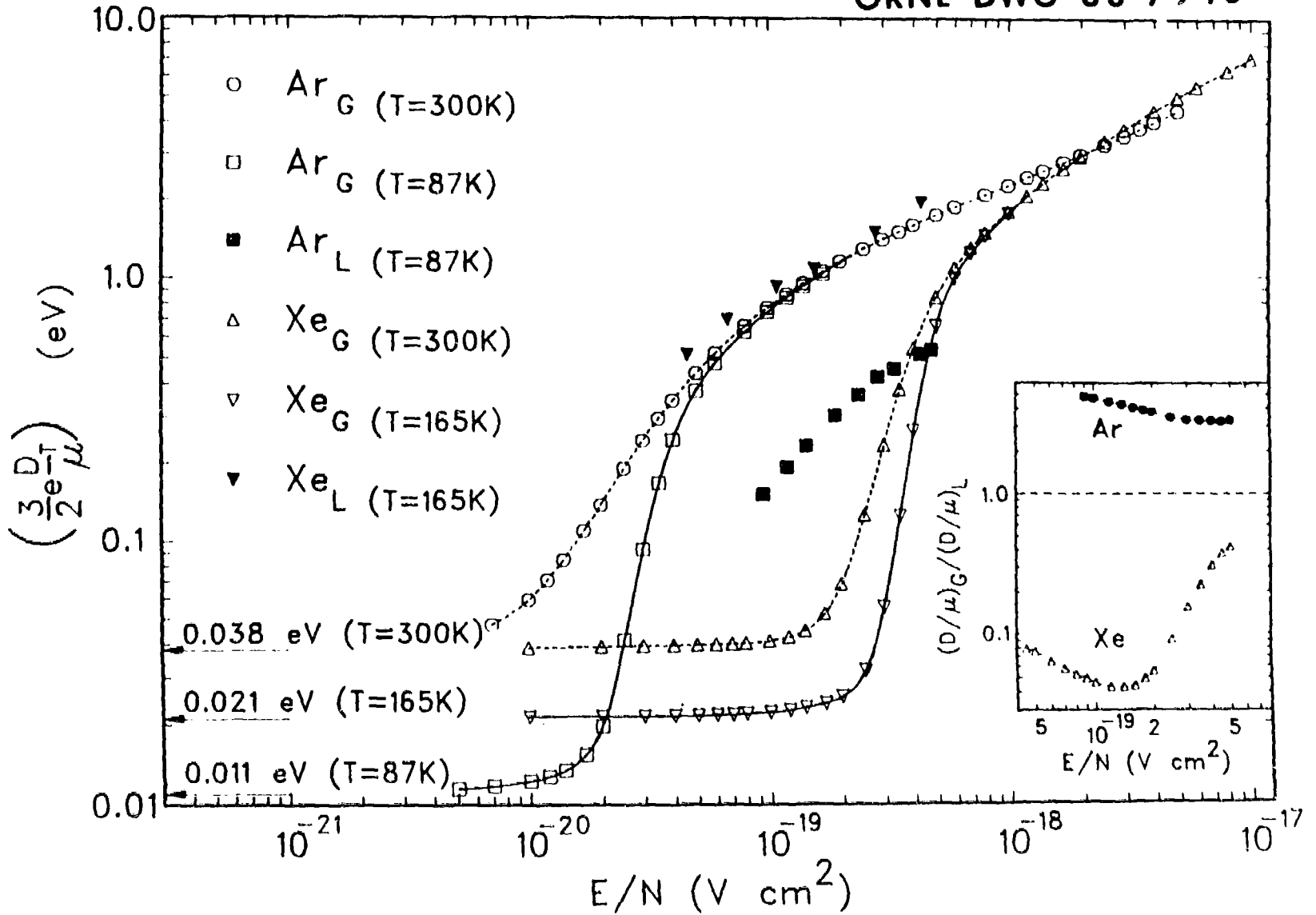


Figure 2

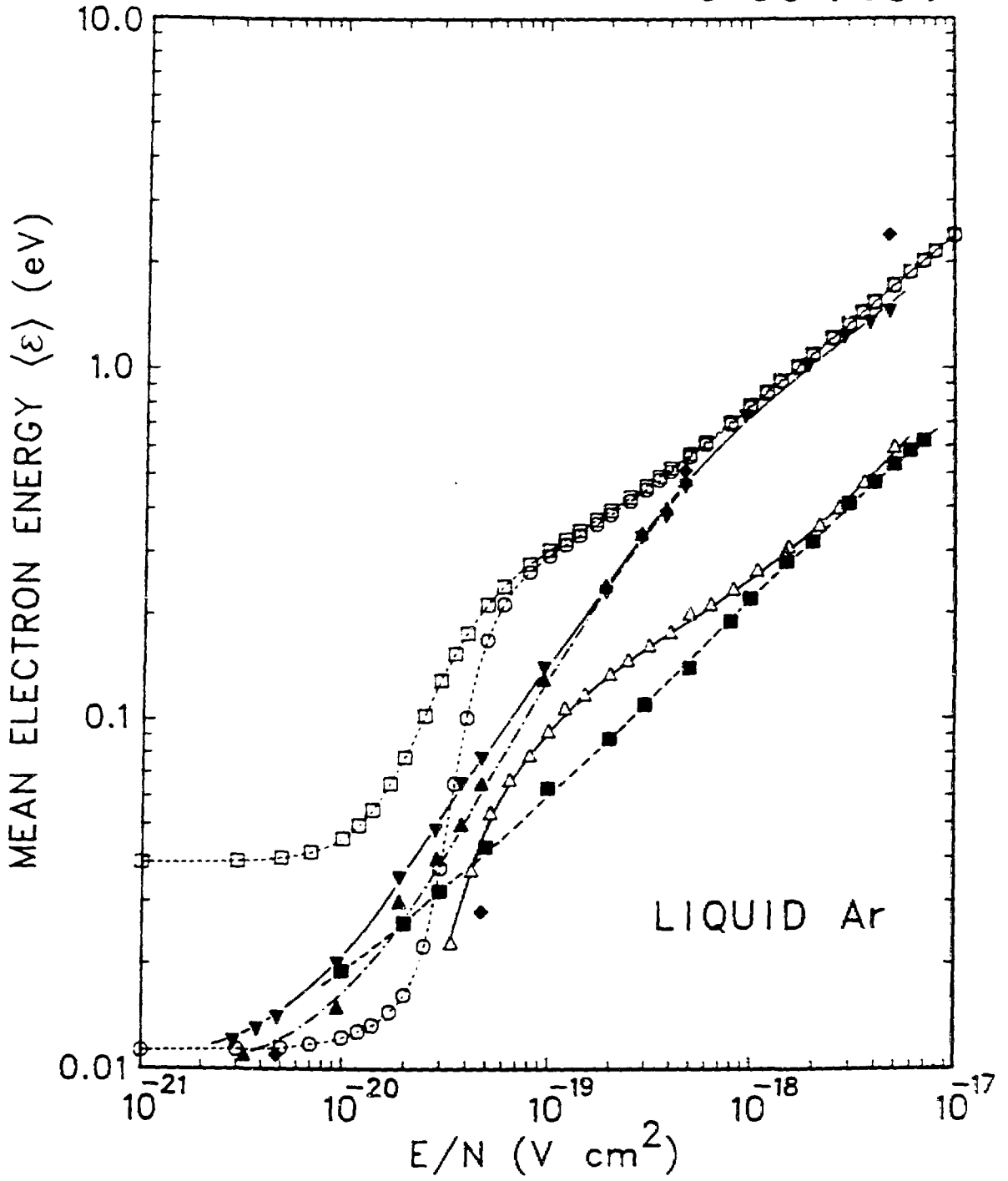


Figure 3

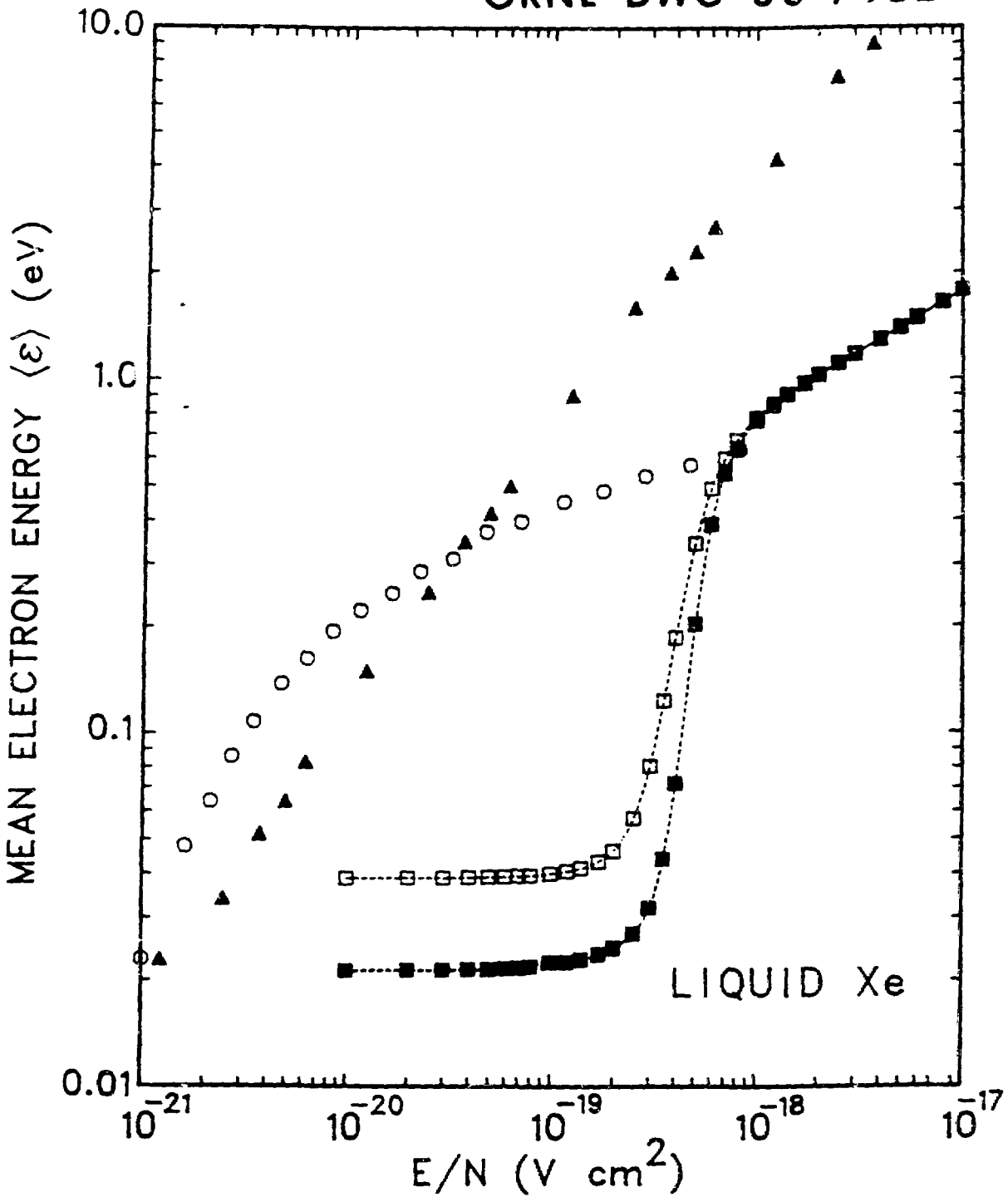


Figure 4

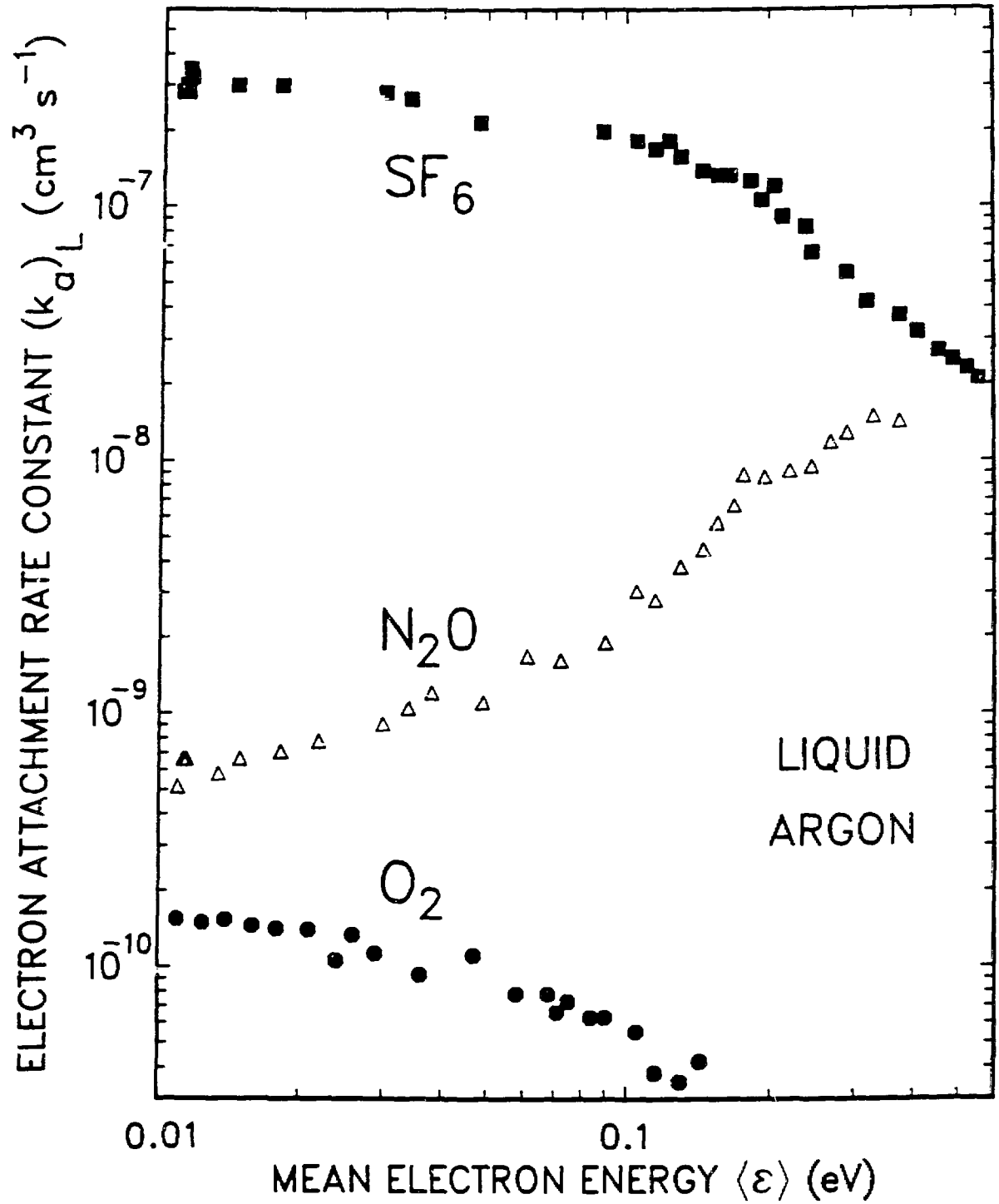


Figure 5

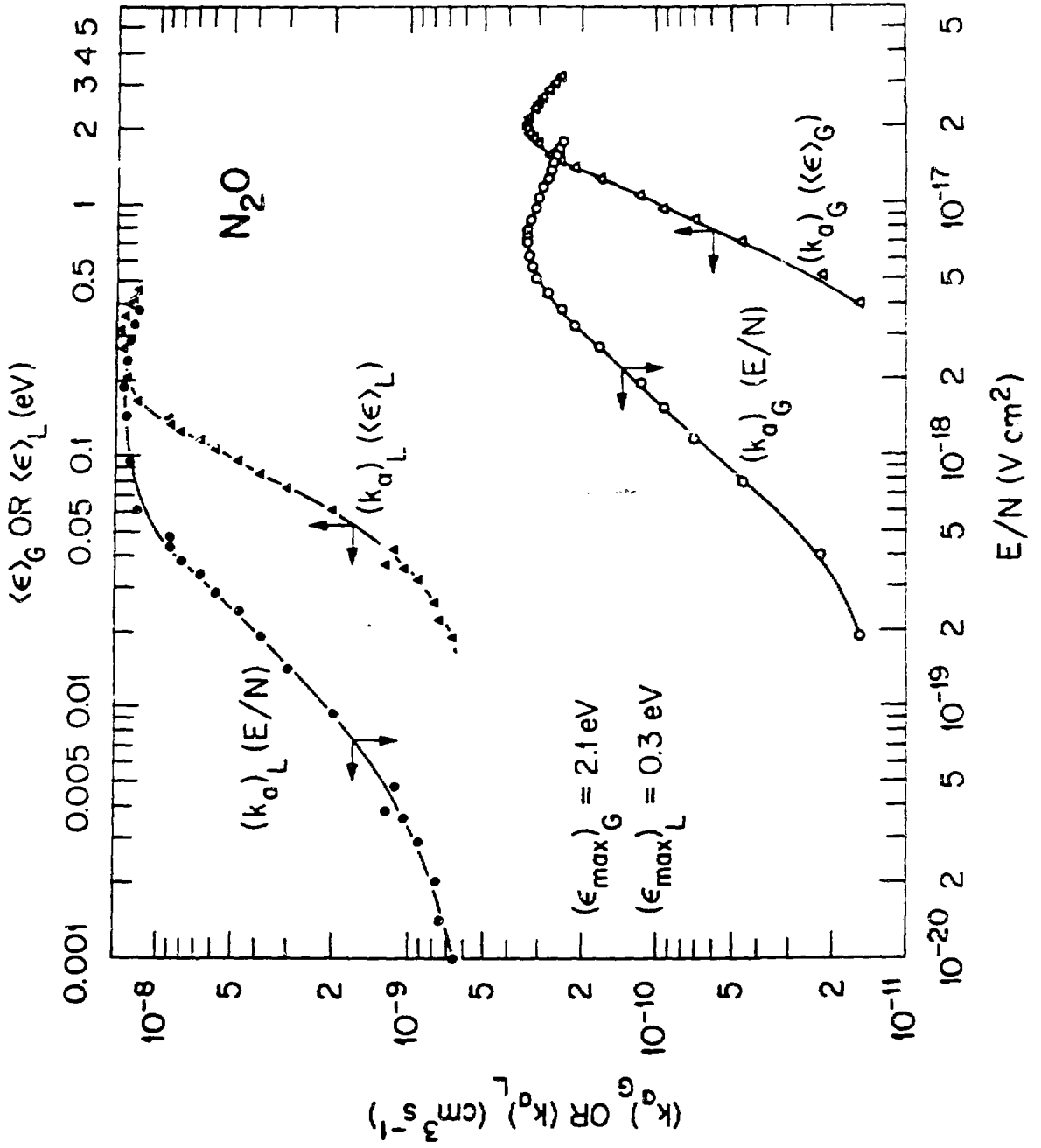


Figure 6

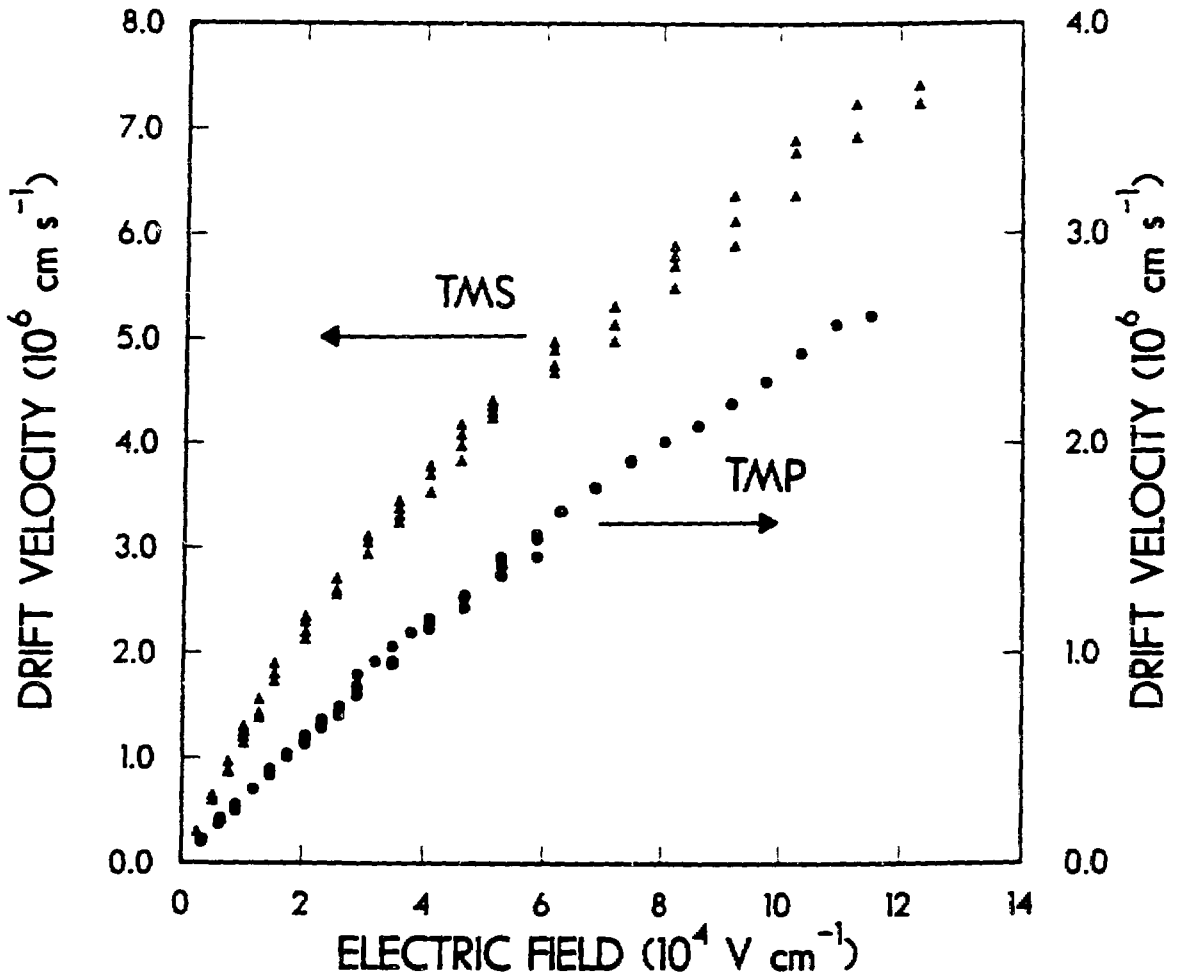


Figure 7

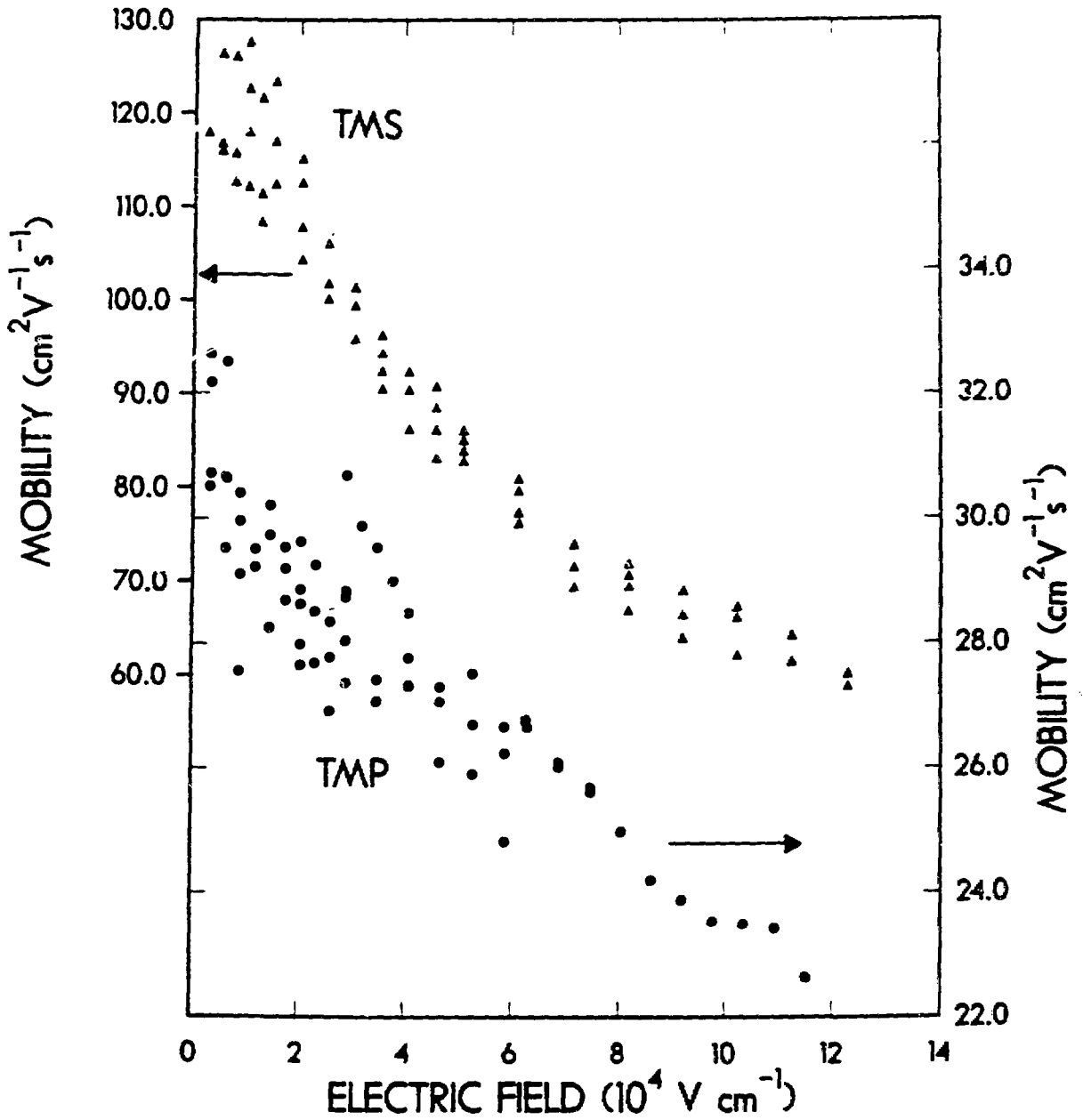


Figure 8

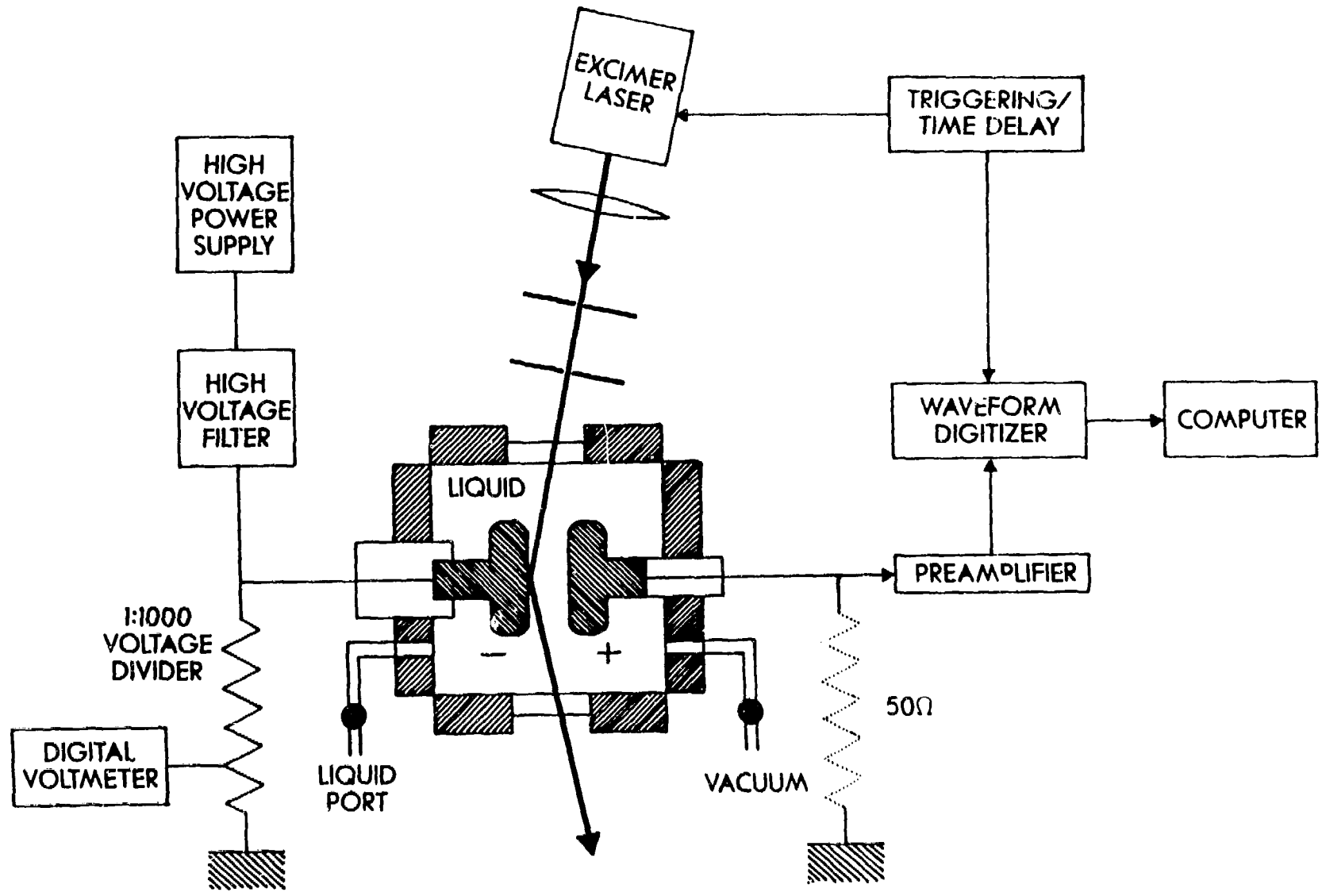


Figure 9



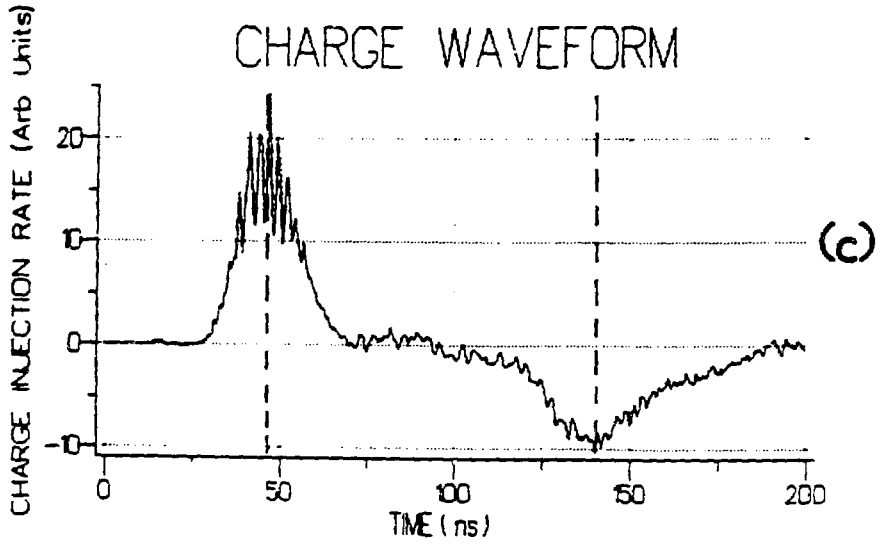
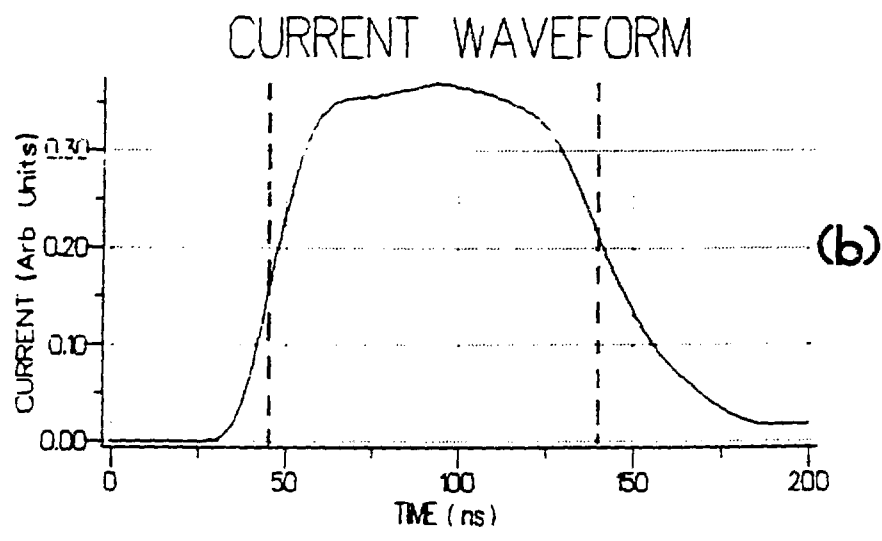
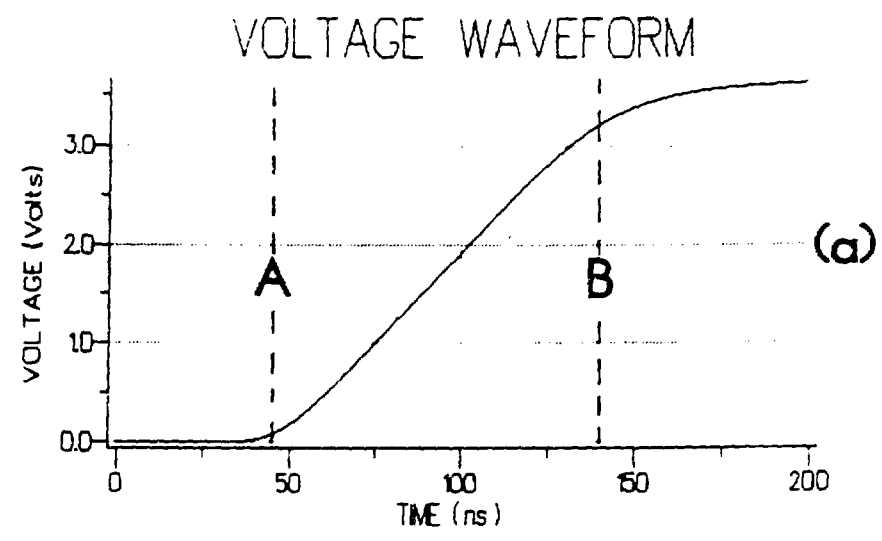


Figure 10

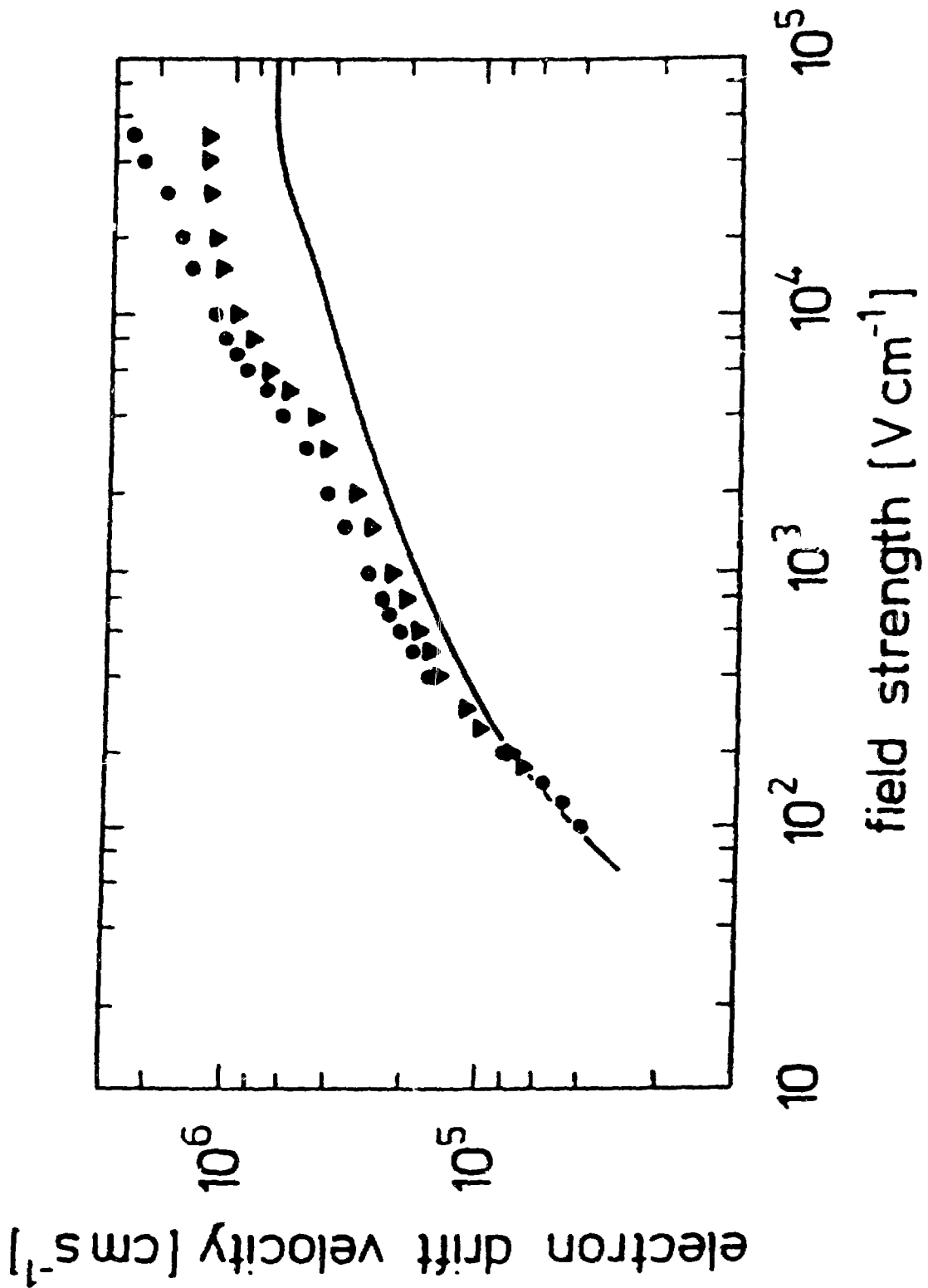


Figure 11

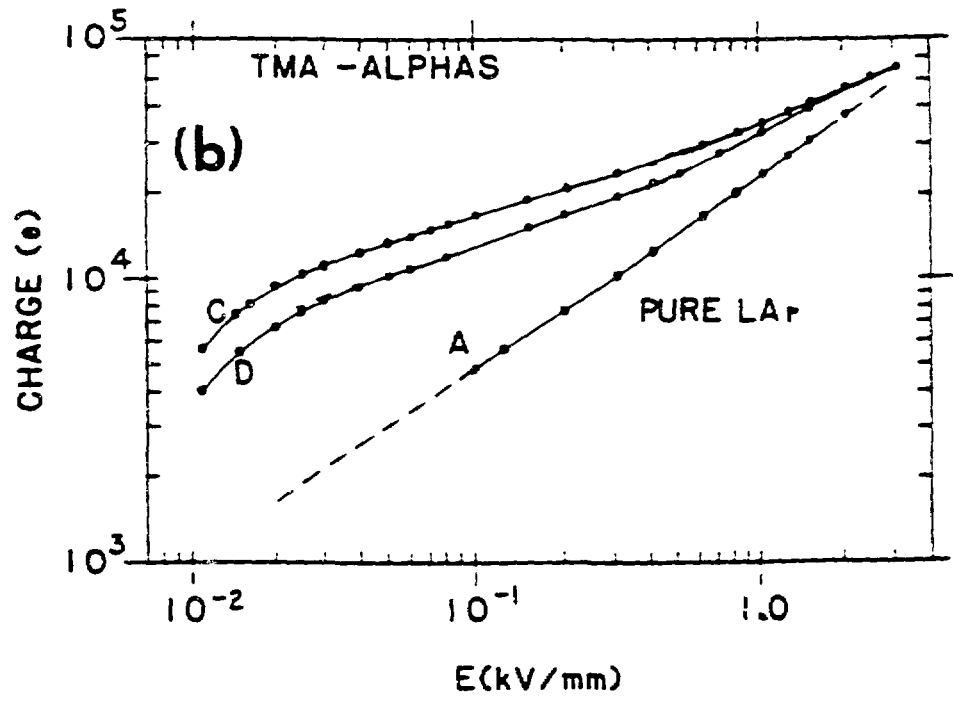
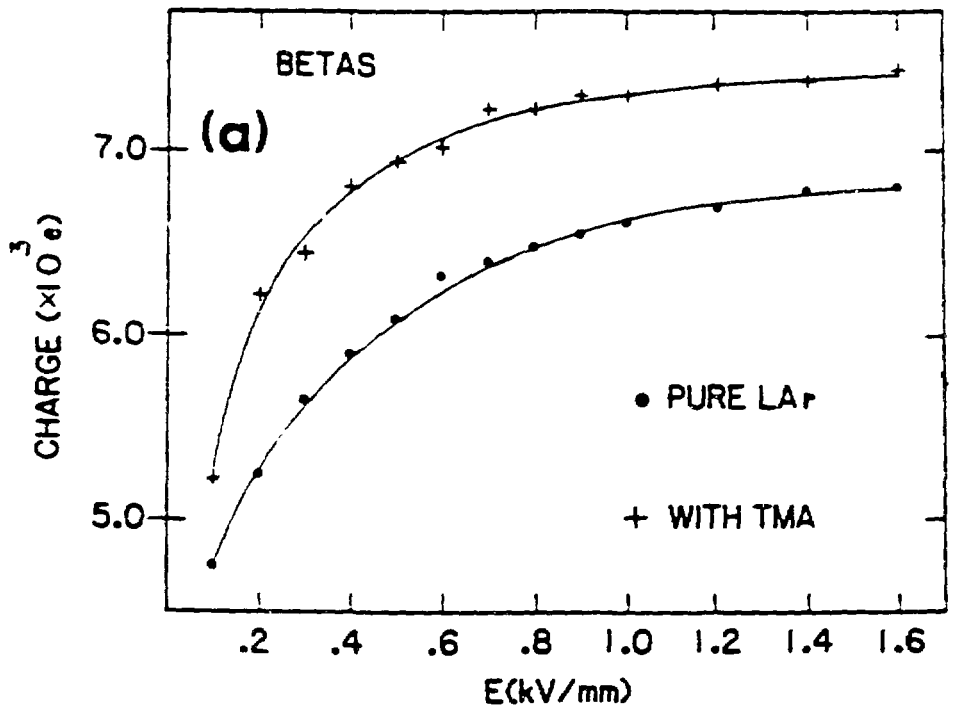
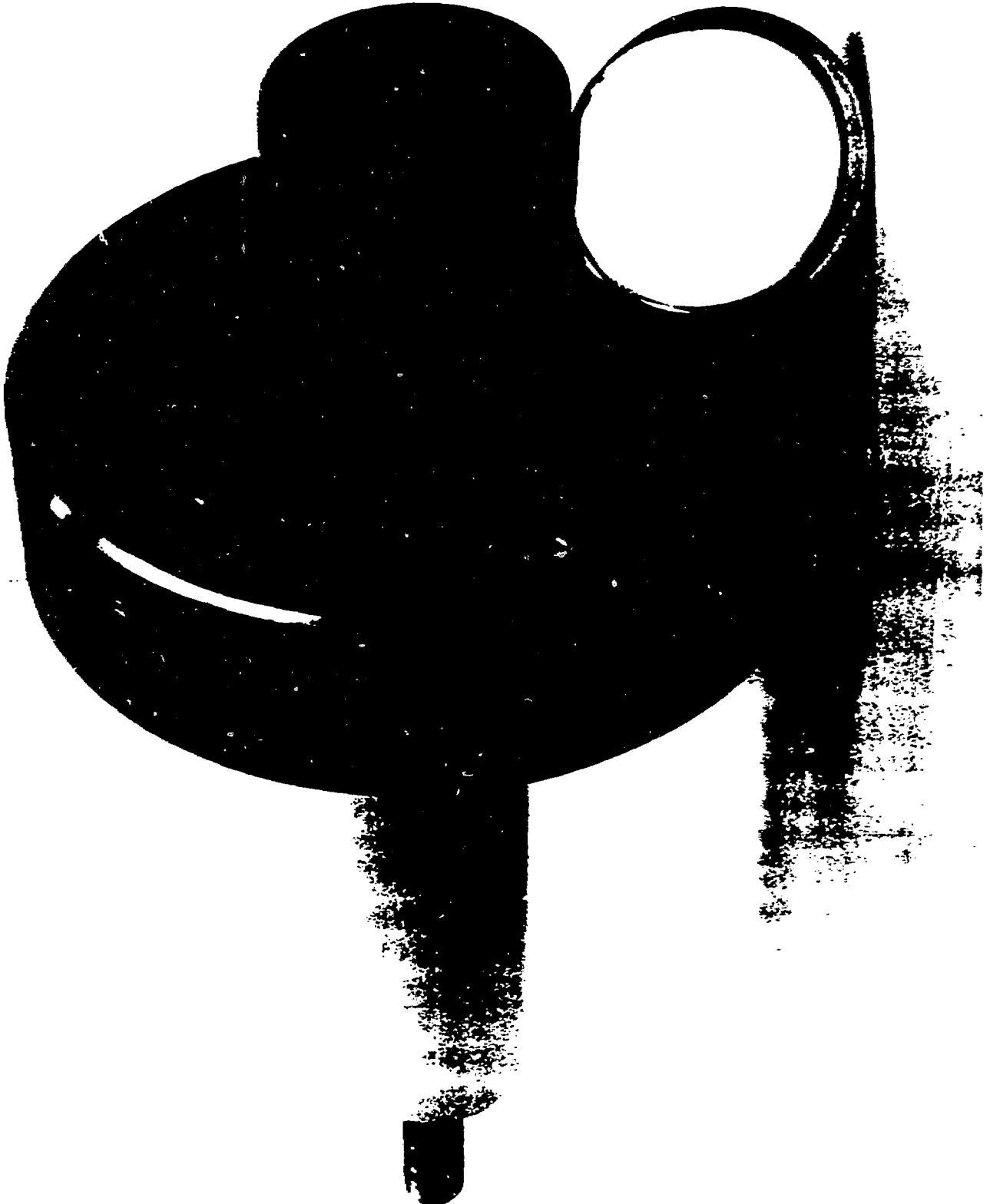


Figure 12

B

A



FHS