Properties of LAr

All values are on the liquid-vapor saturation line and at E=500 V/cm unless otherwise indicated.

Quantity	Symbol	Value	Units	Comments or [Ref]
Atomic number	Z	18		
Atomic weight	A	39.948(1)	g/mol	
Isotopic composition	A=36, 38, 40 stable; 39, 42 $t_{1/2}$>1y			[1, 2,3]
Thermodynamic properties				
Normal boiling point	T_{NBP}	87.303(2)	K	[4]
Density	ρ_{NBP}	1.396(1)	g/ml	[4]
Vapor/liquid volume ratio	V(g)/V(l)	241.7	none	At T_{NBP} [5]
Normal freezing point	T_{FUS}	83.8(3)	K	[4]
Temperature at triple point	T_{TRIPLE}	83.8058	K	ITS-90 def. [4]
Pressure at triple point	P_{TRIPLE}	0.68891(2)	bar	[4]
Density at triple point	ρ_{TRIPLE}	1.417	g/ cm^3	[5]
Temperature at critical point	T_C	150.687(15)	K	[4]
Pressure at critical point	P_C	48.63(3)	bar	[4]
Density at critical point	ρ_C	0.5356(10)	g/ cm^3	[4]
Heat of vaporization	ΔH_{VAP}	161.14	kJ/kg	[5]
Heat capacity	C_P	1.117	kJ/kg/K	[5]
Thermal conductivity	K	0.1256	W/m/K	[5]
Viscosity	η	270.7	μPa s	[5]
Speed of sound	v_S	838.3(1)	m/s	[5]
Response to electromagnetic radiation				
Dielectric constant	ε	1.505(3)		[6,7]
Index of refraction	n	1.38		At 128 nm [8,9,10]
Rayleigh scattering length	L_R	95	cm	At 128 nm [11,12,13]
Absorption length	L_A	>200	cm	For λ>128 nm
Response to ionizing radiation				
W-value for ionization	W_I	23.6(3)	eV/pair	mip [14, 15]
W-value for scintillation	W_S	19.5(10)	eV/photon	mip [16]
W-value for Cerenkov radiation	W_C	2700	eV/photon	β=1 [17]
Fano factor	F	0.107	none	[18]
Moliere radius	R_M	10.0	cm	[19]
Radiation length	X_0	14.0	cm	[19]
Nuclear interaction length	λ_I	85.7	cm	[19]
Critical energy	E_C	30.5	MeV	[19]
Minimum specific energy loss	dE_{MIP}/dx	2.12	MeV/cm	[19]
Scintillation emission peak	λ_{SCINT}	128(10)	nm	[20]
Decay time	τ_{SCINT}	6(2), 1590(100)	ns	[21]

Charged particle transport properties				
Electron drift velocity	$v_D(e-)$	1.60(2)	mm/μs	At T_{NBP} [22-25]
… variation wrt temperature	$\delta Log(v_D)/\delta T$	-1.9	%/K	
… variation wrt field	$\delta Log(v_D)/\delta E$	+0.094	%/(V/cm)	
Electron saturation drift velocity	$v_{SAT}(e-)$	6.6	mm/μs	[39]
Electron mobility at zero field	μ_0	518(2)	$cm^2/V\ s$	At T_{NBP}
Ion drift velocity	$v_D(Ion)$	$8.0(4)x10^{-6}$	mm/μs	At T_{NBP} [26]
… variation wrt temperature	$\delta Log(v_D)/\delta T$	+3.5	%/K	
… variation wrt field	$\delta Log(v_D)/\delta E$	+0.2	%/(V/cm)	
Electron transverse diffusion coef.	$D_T(e-)$	13(2)	cm^2/s	[27,28,29]
Electron longitudinal diffusion coef.	$D_L(e-)$	5(1)	cm^2/s	[29,30]
Electron diffusion at zero field	D_0	3.9	cm^2/s	At T_{NBP}
Ion diffusion coefficient	D_+	$3.2x10^{-3}$	cm^2/s	for TE
Recombination constant	R	0.66		For mip [31,32]
Electron attachment rate constant	k_S	$2.0x10^3$	$ppb^{-1}\ s^{-1}$	For O_2 [33-37]

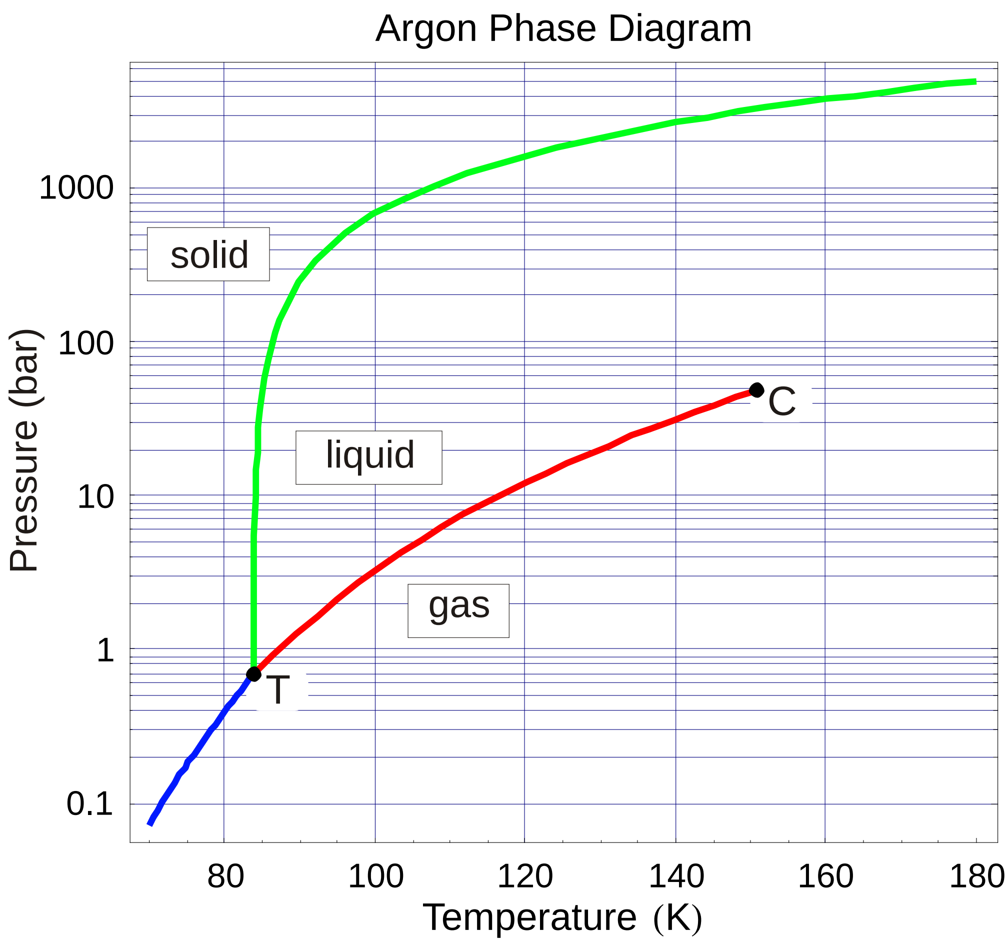
Isotopic composition and radiological purity

Isotope	Relative Mass	Abundance[3]	Decay Mode[3]	Half Life[3]	Q-value (MeV)[3]
36	35.967 546 28(27)	0.337(3)	stable	-	-
37		nil	EC, β^+	35.04 d	0.8135(3)
38	37.962 732 2(5)	0.063(1)	stable	-	-
39		1.01(8) Bq/kg [1]	β^-	269 y	0.565(5)
40	39.962 383 123(3)	99.600(3)	stable	-	-
41		nil	β^-	109.34 m	2.4916(7)
42		6×10^{-5} Bq/kg [2]	β^-	32.9 y	0.599(40)

Also ^{85}Kr (β^-, E_β =0.687 MeV, $t_{1/2}$=10.756 y) is a common radioactive contaminant of LAr at the level of 0.1 to 0.3 Bq/kg

Thermodynamic Properties

Phase Diagram [4]



Enthalpy

Fit to enthalpy data from [5]

Pade approximant:

$$\Delta H = \frac{A + BT}{1 + CT}$$

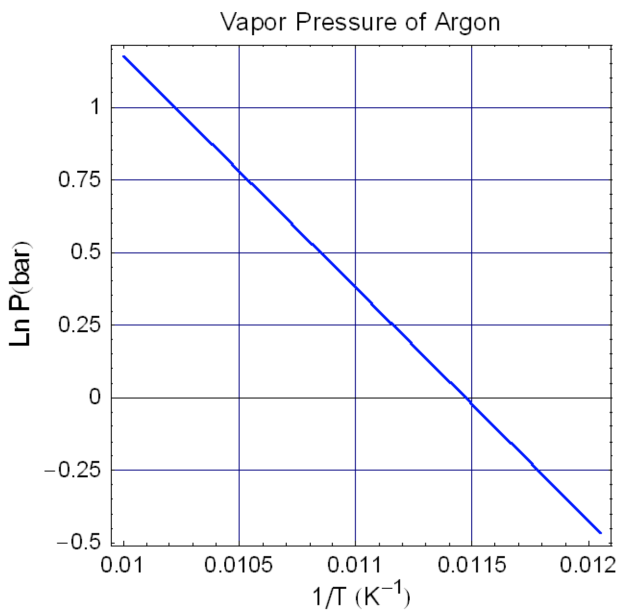
ΔH = enthalpy of vaporization in kJ/mol

T = temperature in K

for $83.8 \leq T \leq 100, \quad A = 7.98304, \quad B = -0.0481275, \quad C = \text{-}0.0047259$

RMS deviation = 0.167 J/mol

Vapor Pressure [5]



Modified Clausius-Clapeyron Equation:

$$\ln\frac{P}{P_C}=\frac{T_C}{T}(At+Bt^{1.5}+Ct^{2}+Dt^{4.5})$$

$t=(1-T/T_C)$

P = vapor pressure in bar

T = temperature in K

$T_C,\ P_C$ = $150.687K, 48.63\ bar$

$for\ T_T \le T \le T_C,\quad A=-5.940\,978\,5,\quad B=1.355\,388\,8,\quad C=-0.464\,976\,07\quad D=-1.539\,904\,3$

Density [5]

Polynomial approximant:

$$\ln\frac{\rho_{LIQUID}}{\rho_C}=At^{0.334}+Bt^{2/3}+Ct^{7/3}+Dt^{4}$$

$t=(1-T/T_C)$

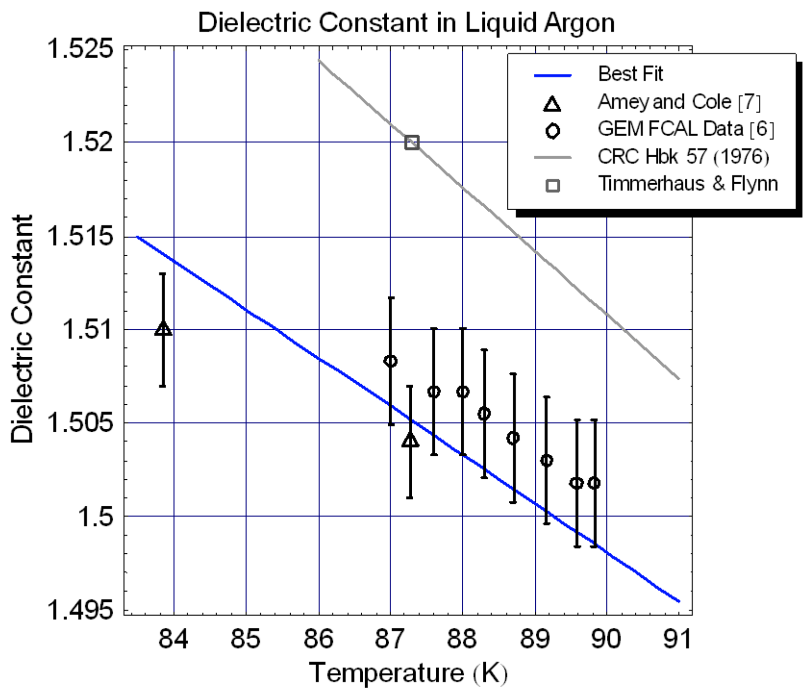
ρ_{LIQUID} = density in g/cm^3

T = temperature in K

$T_C,\ \rho_C=150.687K,\ 0.5356$ g/cm^3

$for\ T_T \le T \le T_C,\quad A=1.500\,426\,2,\quad B=-0.313\,812\,90,\quad C=0.086\,461\,622\quad D=-0.041\,477\,525$

Dielectric constant [6, 7]



Data are points from:
[Circles] W. Don Carlos, et al., *Experimental data on GEM LAC FCAL tube design*, GEM TN-92-179 (1992) (unpublished).

[Triangles] R.L. Amey and R.H. Cole, *Dielectric constants of liquefied noble gases and methane*, J. Chem. Phys. **40** (1964) 146.

[Gray line] The Handbook of Chemistry and Physics, 57th edition, CRC Press (1976). Page E-55 gives the value of $1.53_8$for the value of the dielectric constant at 82.15K, with a linear temperature slope of -0.34×10^{-4} K^{-1}.

[Gray square] K.D. Timmerhaus and T.M. Flynn, Cryogenic Process Engineering, Plenum Press NY (1989), p20 gives κ=1.52 at the normal boiling point.

Clausius-Mossotti relation:

$$\kappa = \frac{1 + 2\alpha_{CM}\rho_L}{1 - \alpha_{CM}\rho_L}$$

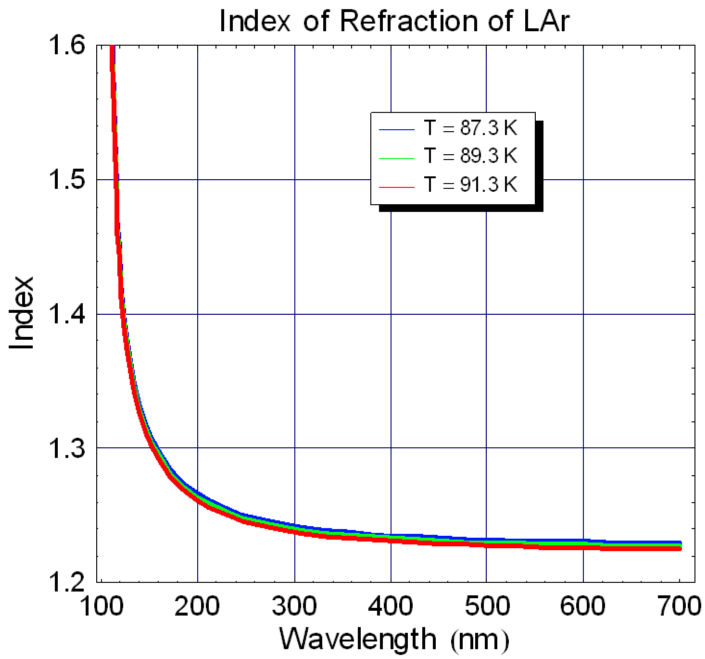
κ = dielectric constant of the liquid

ρ_L = liquid density (see density section above)

with $\alpha_{CM} = 0.1033\ \mathrm{cm^3/gm}$

for $T_T < T < T_C$

Index of refraction [8, 9, 10]



Lorentz-Lorentz relation:

$$n_L = \sqrt{\frac{\frac{\rho_G}{\rho_L}(n_G^2+2)+2(n_G^2-1)}{\frac{\rho_G}{\rho_L}(n_G^2+2)-(n_G^2-1)}}$$

$$n_G = 1 + c\left(\frac{a1}{b1-\lambda^{-2}} + \frac{a2}{b2-\lambda^{-2}} + \frac{a3}{b3-\lambda^{-2}}\right)$$

n_L = index of refraction of the liquid λ (in μm)

ρ_G = gas density = 0.001790 gm/cm^3

ρ_L = liquid density (see density section above)

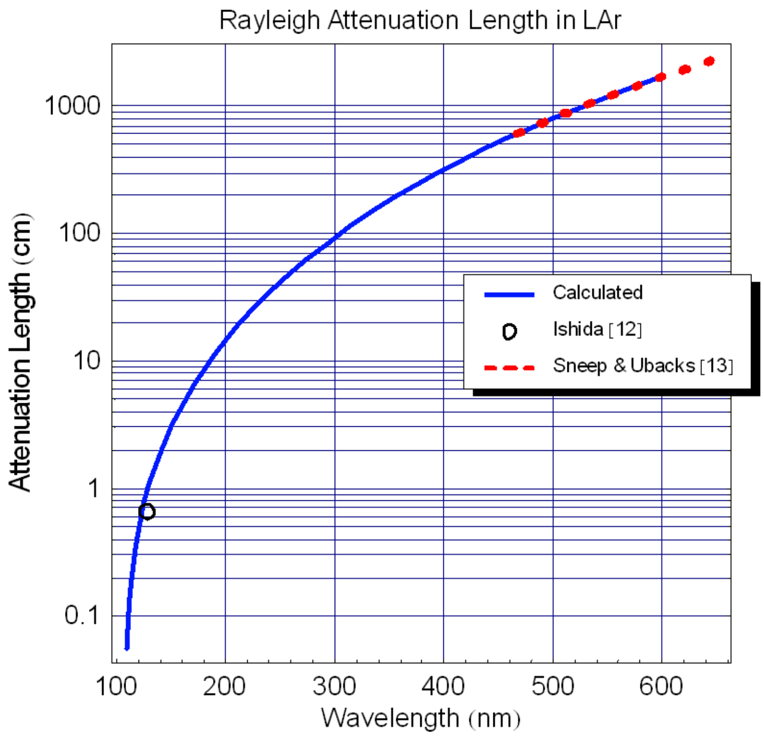
with $c = 1.2055\times10^{-2}$

$a1 = 0.2075$ $\quad a2 = 0.0415$ $\quad a3 = 4.333$

$b1 = 91.012\,\mu\text{m}^{-2}$ $\quad b2 = 87.892\,\mu\text{m}^{-2}$ $\quad b3 = 214.02\,\mu\text{m}^{-2}$

for $T_T < T < T_C$

Rayleigh scattering attenuation length [11, 12, 13]



$$L_R^{-1} = \frac{k_B T \rho(T)^2 \kappa_T}{96\pi^5 \lambda^4} \left(\frac{(\epsilon(\lambda)-1)(\epsilon(\lambda)+2)}{3\rho(T)} \right)^2$$

L_R = Rayleigh scattering attenuation length

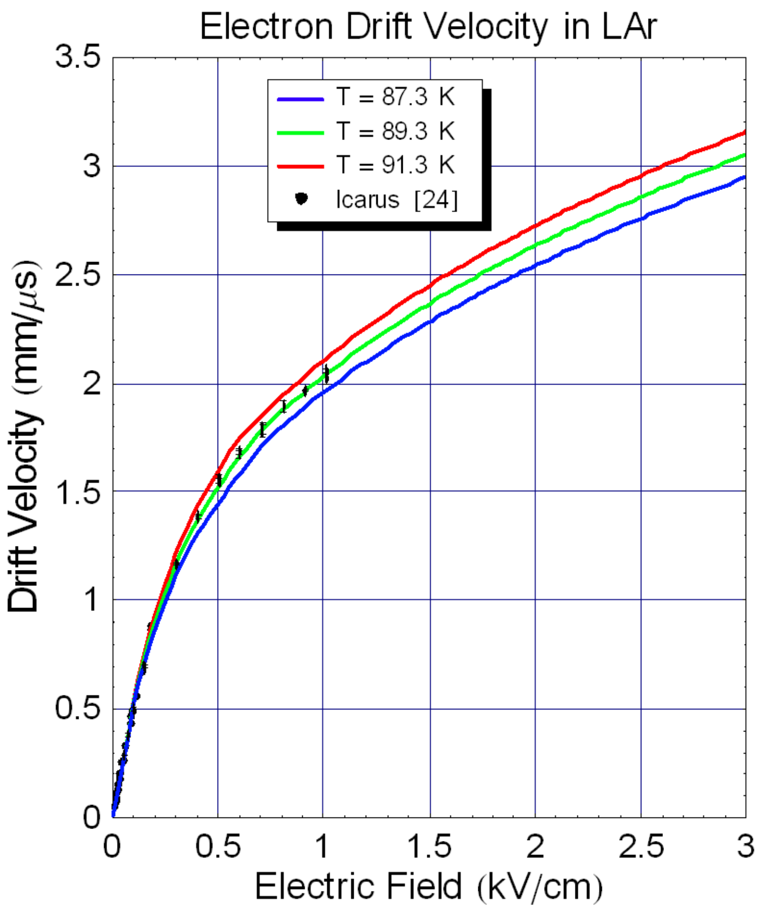
$\epsilon(\lambda)$ = dielectric constant at wavelength $\lambda = n(\lambda)^2$

$\rho(T)$ = density at temperature T

κ_T = isothermal compressibility = 2.18×10^{-10} cm^2/dyne

If the difference in the attenuation lengths calculated for Rayleigh scattering (94 cm) and measured by Ishida (66±3)[12] can be attributed to atomic absorption in the measurement, then the partial attenuation length for atomic absorption in their experiment is ~ 2 m. Absorption by atomic Ar is very small at 128 nm; the nearest resonance transition is at 106.7 nm. The absorption length determined from the dispersion, for a reasonable line width, via the Kramers-Kroenig dispersion relation is >1000 m at 128 nm. Absorption by impurities (O_2, N_2, H_2O and carbon compounds) is probably the dominant absorptive mechanism in LAr at 128 nm. The cross section for absorption by O_2 at 128 nm is about 3x10^{-19} cm^2 [40], which implies an attenuation length of 2.1 m for 800 ppb O_2 in LAr. The cross section for N_2 is about 1.2x10^{-18} cm^2 [41] so an N_2 concentration of 170 ppb contributes 2.1 m to the total absorption length. H_2O may be the dominant contributor: the cross section at 128 nm is 7.4x10^{-18} cm^2 [42] for an attenuation length of 2.1 m for 30 ppb.

Electron drift velocity [22, 23, 24, 25]



Kalinin empirical function[22] fit to Icarus[24] and Aprile[25] data:

$$v_{e^-,DRIFT} = (1 + p1(T - t0)) \times (p3\,E\,Ln[1 + p4/E] + p5\,f^{\,p6}) + p2(T - t0)$$

$v_{e^-,DRIFT}$ = electron drift velocity in mm/μs

T = temperature in K

E = electric field in kV/cm

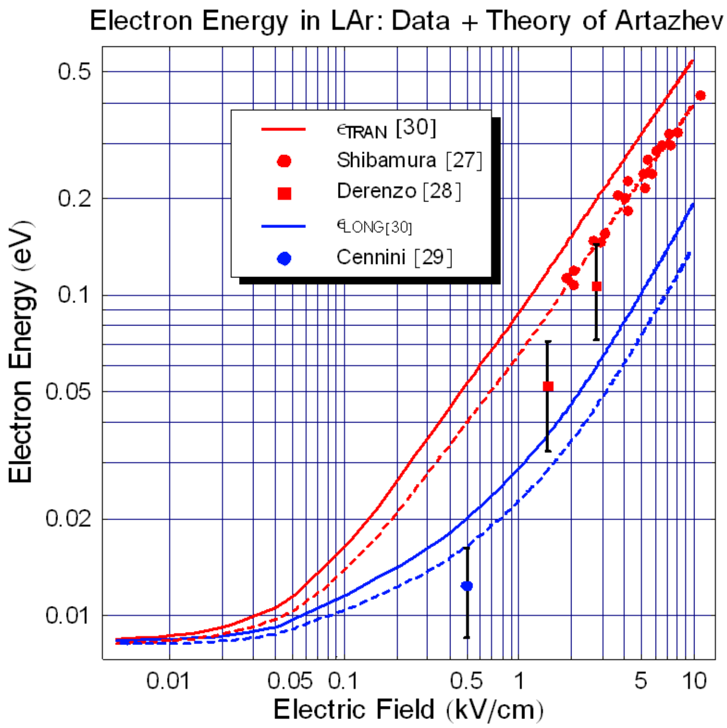
valid for $87 \le T \le 94$ *and* $0.3 \le E \le 0.8$

$p1 = -0.0462553 \quad p2 = 0.0148508 \quad p3 = 1.64156 \quad p4 = 1.273$

$p5 = 0.0086608 \quad p6 = 4.71489 \quad t0 = 104.326$

Curves in the figure are this parameterization below 0.7 kV/cm, merging smoothly (continuous derivative) with Walkowiak [23] parameterization above 0.8 kV/cm.

Electron diffusion [27, 28, 29, 30]



The data for transverse diffusion come from [27, 28]. The longitudinal diffusion is a single measurement from [29]. The transport theory calculation (solid lines) is from Atrazhev and Timoshkin [30], interpolated to the normal boiling point. We plot the electron energy, ε, rather than the diffusion coefficient, D, because the electron energy is the quantity directly measured by experiment (for longitudinal diffusion at least) and is the quantity directly entering in the calculation of the RMS spatial spread of an ensemble of electrons:

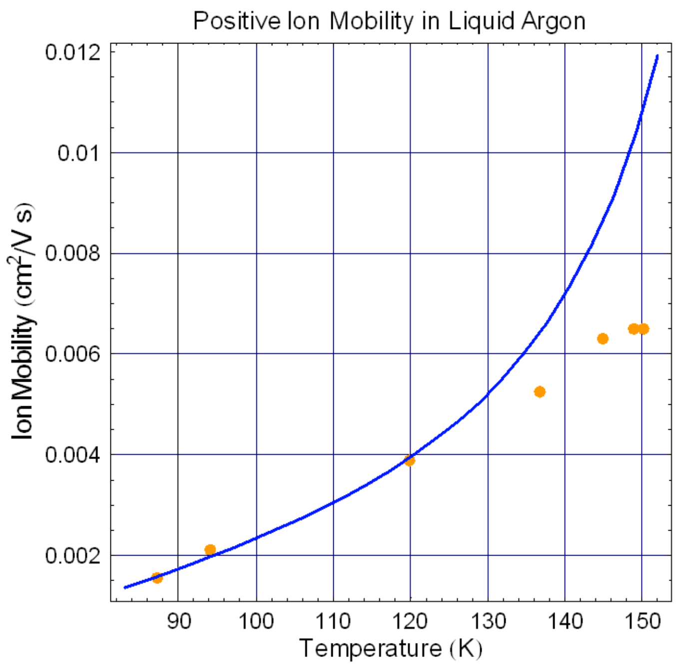
$$\sigma_{T(L)} = \sqrt{\frac{2\,\varepsilon_{T(L)}\,\Delta z}{E}}$$

with Δz the drift distance and E the field in volts per unit of drift distance. The Einstein-Smoulchowski relation defines the diffusion constant in terms of the electron energy:

$$D = \mu\,\varepsilon\,,$$

so that the diffusion constant requires the additional knowledge of the electron mobility μ. The dashed lines are the Atrazhev and Timoshkin theory scaled to the transverse data which give ε_{TRAN} = 40 meV (D_{TRAN} = 12.8 cm^2/s) and ε_{LONG} = 16.5 meV (D_{LONG} = 5.3 cm^2/s) at 500 V/cm.

Ion Drift Velocity [26]



Gee, *et al*. [26] provide measurements of the positive ion mobility in liquid argon from the normal boiling point up to the critical point, and demonstrates that the mobility is independent of electric field and that the product of mobility and liquid viscosity are constant (Stoke's law):

$$\mu_+\eta = (4.3 \pm 0.3)\times 10^{-6}\ Poise\, cm^2 / V s$$
$$\text{for } 87.2\text{K} \le \text{T} \le 135\text{K}$$

The curve in the figure above is the liquid viscosity from [5] scaled to the lowest three data points of [26].

Pade approximant:

$$\eta(T) = \frac{A + BT^{-1} + CT^{-2}}{1 + DT^{-1} + ET^{-2}}$$

$$v_{D,Ion}(E,T) = 4.32\times 10^{-6}\, E\,\eta(T)$$

$v_{D,Ion}$ = positive ion drift velocity in mm/μs

T = temperature in K

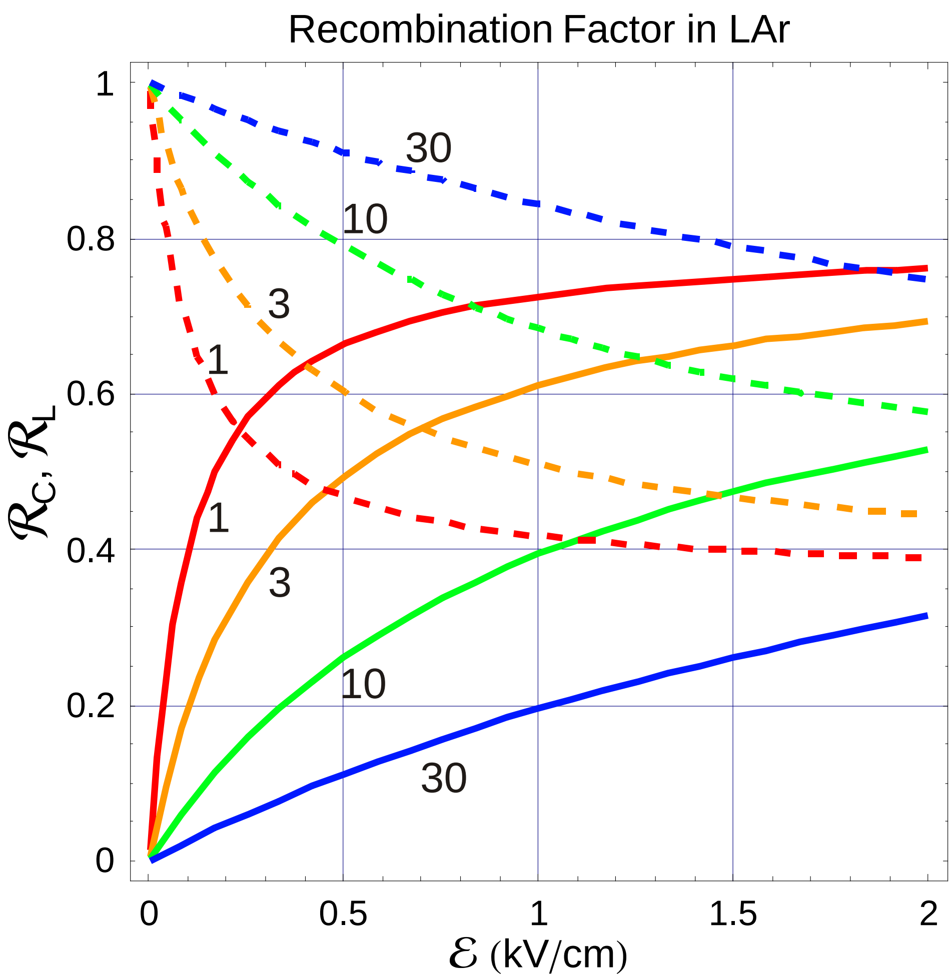
E = electric field in V/cm

for $83.8 \le T \le 100$, $A = \text{-}2.46184\times 10^{8}$, $B = 4.51273\times 10^{10}$, $C = -4.51527\times 10^{11}$,
$D = 2.15074\times 10^{8}$, $E = \text{-}1.28168\times 10^{10}$

Ions are in thermal equilibrium with the liquid, so the diffusion coefficient is

$$D_+ = \mu_+\eta \times k_B T_{NBP} = 3.2\times 10^{-3} cm^2 / s$$

Recombination [31, 32, 43]



Solid lines are the recombination factor for charge (charge collected at finite field divided by charge collected at infinite field) [31, 32]. Dashed lines are the light recombination factor (light collected at field divided by light collected at zero field) [43]. The numbers labeling the curves are the specific energy loss (dE/dx) in units of mip.

$$R_C = \frac{Q}{Q_\infty} = \frac{A}{1 + \frac{k}{\mathcal{E}} \times \frac{dE}{dx}}$$

$$R_L = \frac{L}{L_0} = 1 - \alpha R_C$$

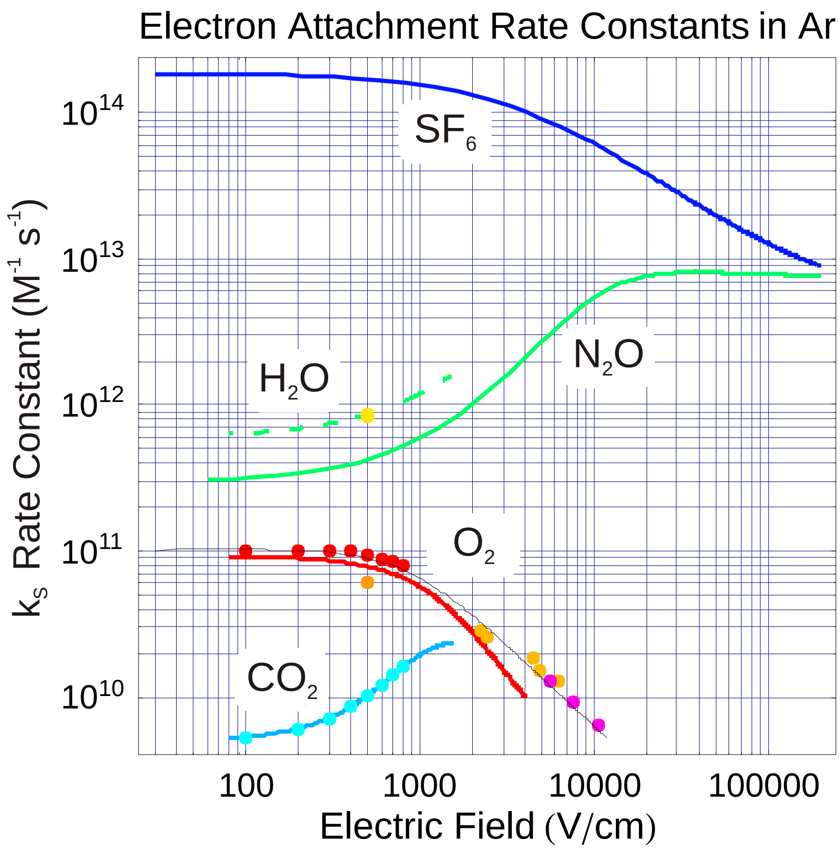
$\mathcal{E}$ *is electric field in kV / cm*

dE/dx is specific energy loss in MeV cm^2/g

with A=0.800, α=0.803, and k=0.0486 (kV/cm)/(MeV cm^2/g)

$$for\ \ 0.1 < \mathcal{E} < 1.0\ kV/cm\ \ and\ \ 1.5 < \mathrm{dE}/\mathrm{dx} < 30\ MeV\ \ cm^2/g$$

Electron attachment [33, 34, 35, 36]



The solid lines for O_2, N_2O, and SF_6 are from Bakale, Sowada, and Schmidt [33]; the red points for O_2 and all the points for CO_2 are from Bettini (ICARUS) [34]; for O_2 the orange points are from Aprile, Giboni, and Rubbia [35] (at 500 V/cm) and from Adams, *et al*. [36] (for the points above 2kV/cm), and the magenta points are from Hofmann, et al. [37]; and the yellow point for H_2O is from μBooNE docDB 429-v1 and the dashed curve is the curve for N_2O scaled to this point. The solid black line is a best fit, specified below, to the data for O_2.

$$Q(t) = Q_0\, Exp(-t/\tau_A)$$

$$with\ \tau_A = (k_S\, n_S)^{-1}$$

k_S is electron attachment rate constant in $\mathrm{M}^{-1}\, s^{-1}$

n_S is molar (M) solute concetration in LAr

$$1\ \mathrm{M} = 2.503\times10^{-8}\, \rho_{LIQUID}(T)\times \mathrm{ppb}$$

the attachment rate constant depends on electric field

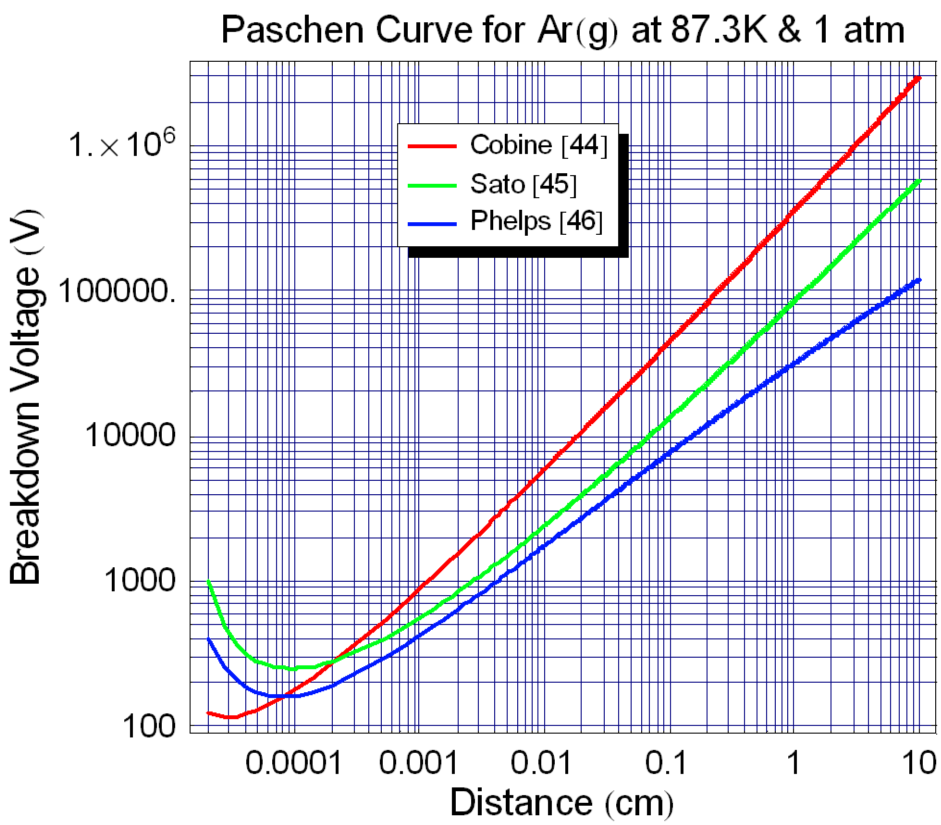
$$k_S = \frac{p_0 + p_1 E + p_2 E^2}{1 + q_1 E + q_2 E^2 + q_3 E^3}$$

$$with \quad p_0 = 348.066 \quad p_1 = 44068.9 \quad p_2 = 27.3268$$

$$q_1 = 4351.98 \quad q_2 = 1.88415 \quad q_3 = 0.00478478$$

E *is in* V/cm

Breakdown Voltage [44, 45, 46]



All of the curves in the figure are scaled from measurements made at and above room temperature. This requires an extrapolation to reach the largest distances in the figure. The "Phelps" curve represents actual measurements up to 1 cm on this scale; the others are larger extrapolations. The breakdown voltage is very sensitive to the presence of electronegative impurities at large distances, and to electrode preparation at small distances. Electronegative impurities and dirty electrodes increase the breakdown voltage. Since the cleanliness of LAr is extremely good, it is advisable to assume that actual breakdown will occur below the lowest reported values in gas at higher temperatures.

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