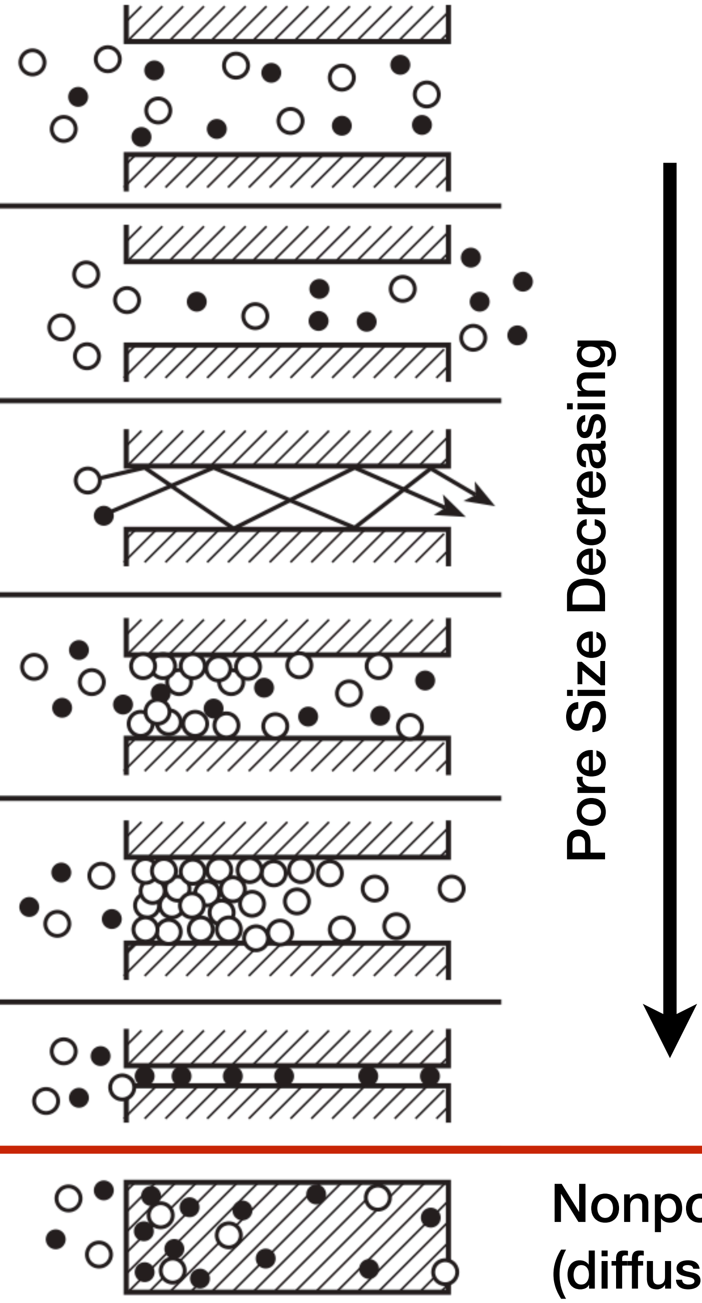
ChE-402: Diffusion and Mass Transfer

Lecture 6

Intended Learning Outcome

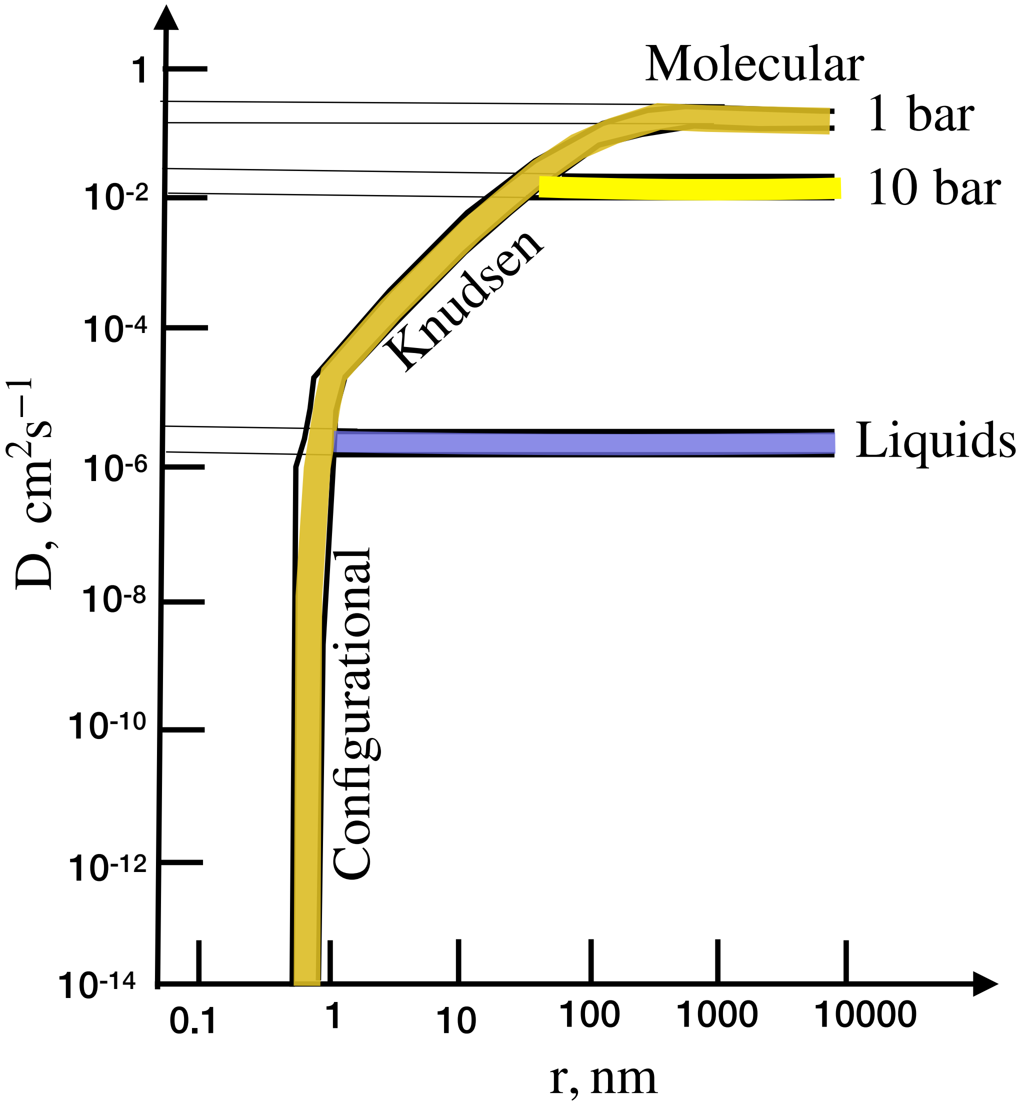
- To analyze diffusion of gas molecules in porous (nanoporous) materials.
- To analyze diffusion of ions under applied electric field.
- To analyze the effect of ion charge on diffusion.

Diffusion in nanoporous materials



Viscous Diffusion	Flow in large pores (>100 nm) or at high pressure
Molecular Diffusion	Diffusion of A in B or B in A
Knudsen Diffusion	Flow in nanopores (2-100 nm)
Surface Diffusion	Flow along surface
Capillary Condensation	$\gamma_{sv} > \gamma_{sl}$
Configurational Diffusion	Flow in Å-scale pores (0.25-2 nm)
Sorption Diffusion	Nonporous (diffusion in free-volume, or lattice gaps)

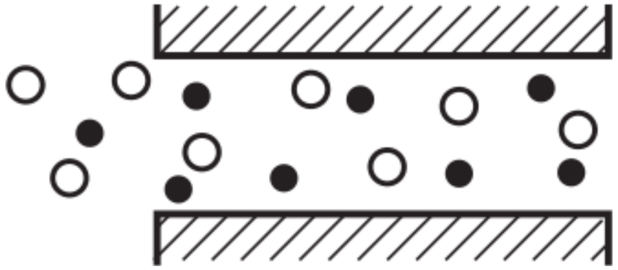
Gas diffusion in nanoporous materials



Adapted from
J. Karger, D. M. Ruthven, D. N. Theodorou, Diffusion in Nanoporous Materials

Viscous diffusion

Viscous flow in cylindrical tubes
(when there is a pressure difference between the two ends)



Hagen-Poiseuille equation:

$$v_1 = \frac{d^2 \Delta P_1}{32\eta_1 l} \qquad N_1 = c_1 v_1 = c_1 \frac{d^2 \Delta P_1}{32\eta_1 l} = \left(\frac{d^2 c_1 RT}{32\eta_1}\right)\frac{\Delta c_1}{l}$$

If we have no convection, and only diffusion

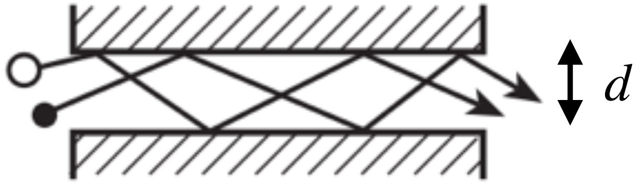
$$N_1 = J_1 = D_{vis}\frac{\Delta c_1}{l} \qquad \Rightarrow D_{vis} = \frac{d^2 c_1 RT}{32\eta_1} = \frac{d^2}{32\eta_1}P_1$$

Viscous diffusion increases at higher P

<u>Note: This is an approximate treatment; viscous flow is bulk flow (convection can be important)</u>

Knudsen diffusion

Occurs when mean free path, l, is larger than d (pore diameter)



$$\text{Knudsen number} = Kn = \frac{l}{d} > 1$$

- For liquids, mean free path is of the order of angstroms, therefore Knudsen transport is not important.
- For gases, mean free path ~ 10-200 nm

Diffusion coefficient derived from the kinetic theory of gases but by replacing l by d

$$D = \frac{1}{3}\bar{v}\,l \quad \Rightarrow \quad D_K = \frac{1}{3}\bar{v}\,d \qquad \bar{v} = \sqrt{\frac{8k_BT}{\pi m}} \qquad D_K = \sqrt{\frac{8k_BTd^2}{9\pi m}}$$

Unlike in viscous flow, the Knudsen diffusion is independent of pressure

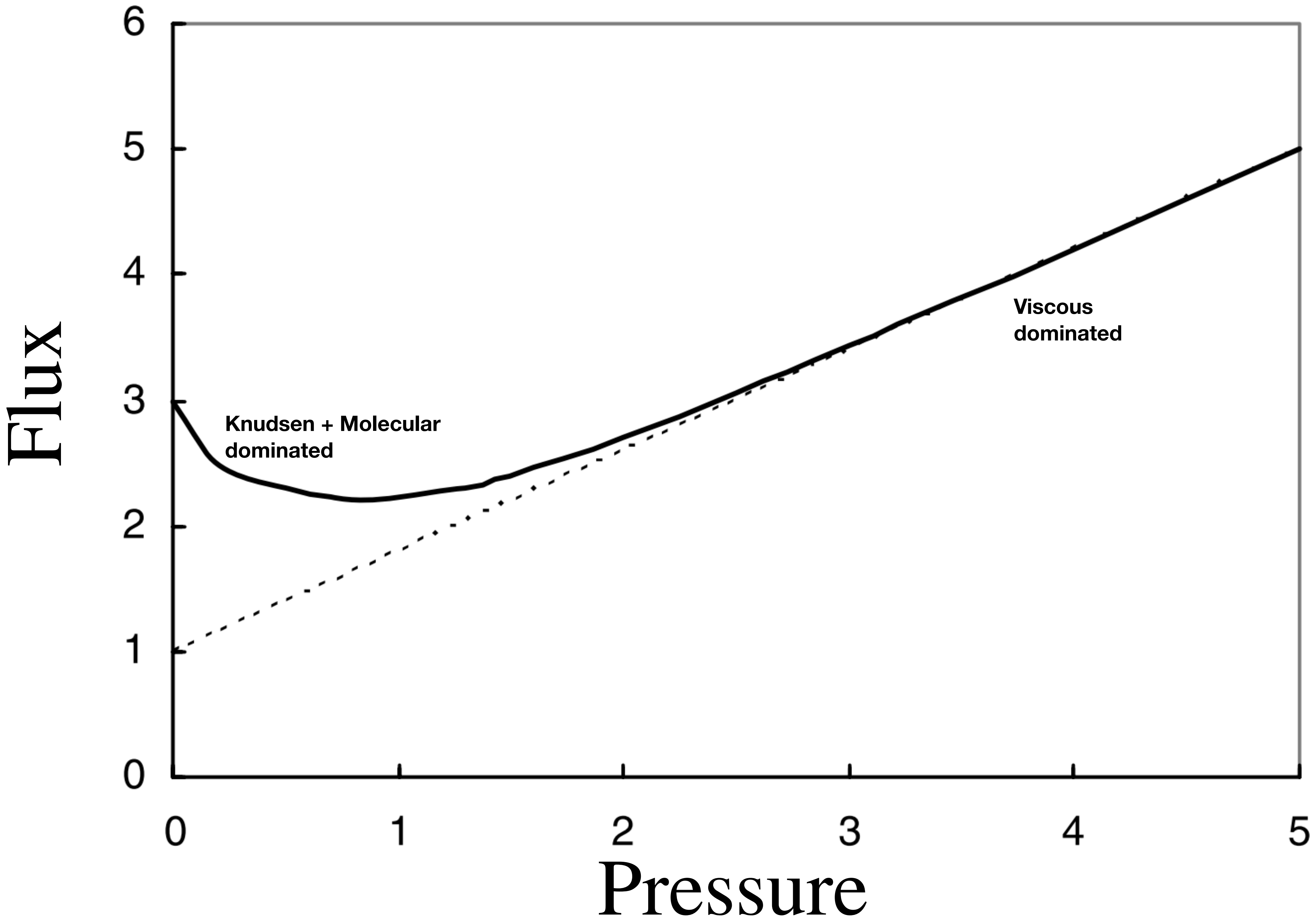
Molecular diffusion

Becomes important when more than 1 species is diffusing through the pore

When the pore is larger than mean free path, the effect of molecular-wall collision becomes negligible and molecular diffusion becomes important

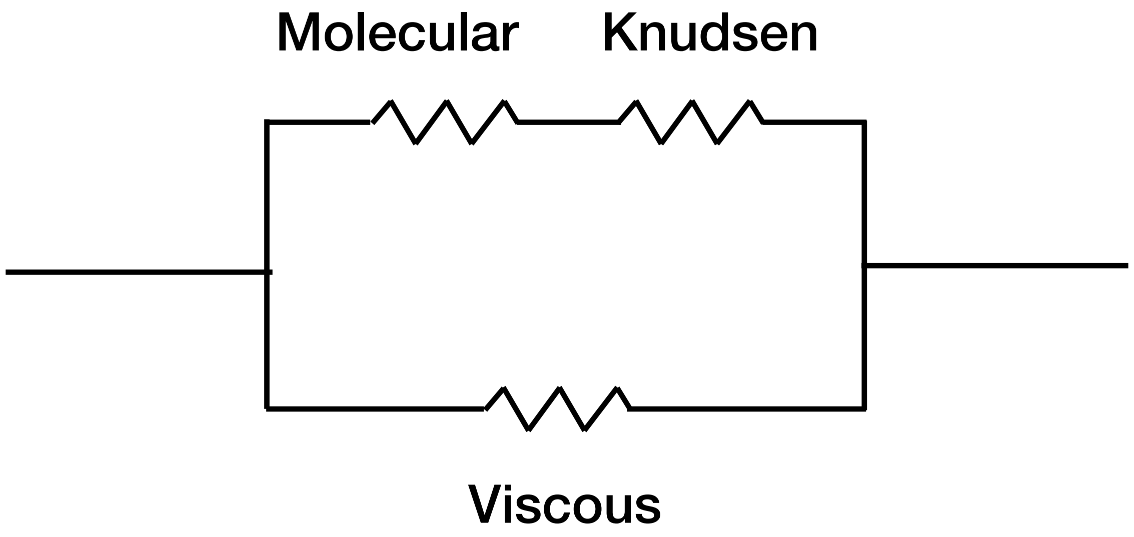
$$D_{AB} = \frac{1.86 * 10^{-3} * T^{1.5} * (1/M_1 + 1/M_2)^{0.5}}{P\sigma_{12}^2\Omega}$$

Combination of viscous, Knudsen and molecular diffusion



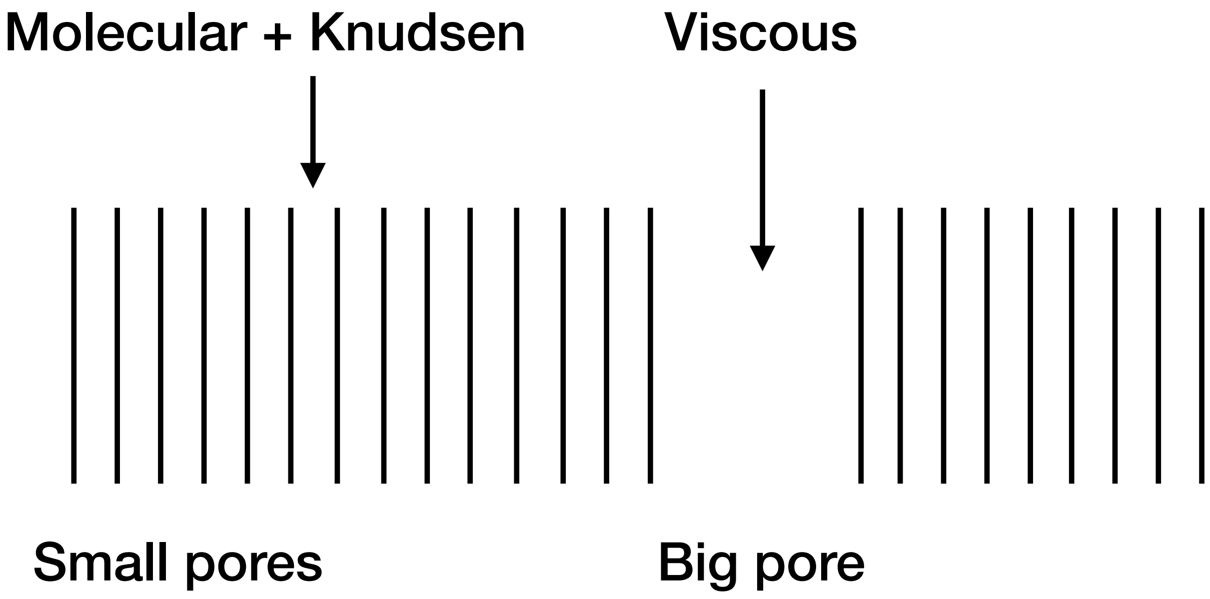
J. Karger, D. M. Ruthven, D. N. Theodorou, Diffusion in Nanoporous Materials

Overall diffusion in pores



Diffusivity = 1/Resistance

$$\frac{1}{D} = \frac{1}{D_K} + \frac{1}{D_{AB}}$$



$$D_{total} = D_{vis} + D$$

J. Karger, D. M. Ruthven, D. N. Theodorou, Diffusion in Nanoporous Materials

Relative importance of viscous, Knudsen and molecular diffusion in gaseous diffusion

$$\frac{1}{D} = \frac{1}{D_{\mathrm{K}}} + \frac{1}{D_{\mathrm{AB}}}$$

$$D_{total} = D_{vis} + D$$

p (atm)	D_{AB} ($\mathrm{cm^2\,s^{-1}}$) Molecular	r (cm)	D_{K} ($\mathrm{cm^2\,s^{-1}}$)	D ($\mathrm{cm^2\,s^{-1}}$)[a)]	D_{vis} ($\mathrm{cm^2\,s^{-1}}$)	D_{total} ($\mathrm{cm^2\,s^{-1}}$)	$\frac{D_{\mathrm{vis}}}{D_{\mathrm{total}}}$
1.0	0.2	10^{-6}	0.03		0.0007		
		10^{-5}	0.3		0.07		
		10^{-4}	3.0		7.0		

$$D_{AB} = \frac{1.86 * 10^{-3} * T^{1.5} * (1/M_1 + 1/M_2)^{0.5}}{P\sigma_{12}^2\Omega}$$

$$D_K = \sqrt{\frac{8k_BTd^2}{9\pi m}}$$

$$D_{vis} = \frac{d^2}{32\eta_1}P_1$$

J. Karger, D. M. Ruthven, D. N. Theodorou, Diffusion in Nanoporous Materials

Diffusion for strong electrolytes in solution

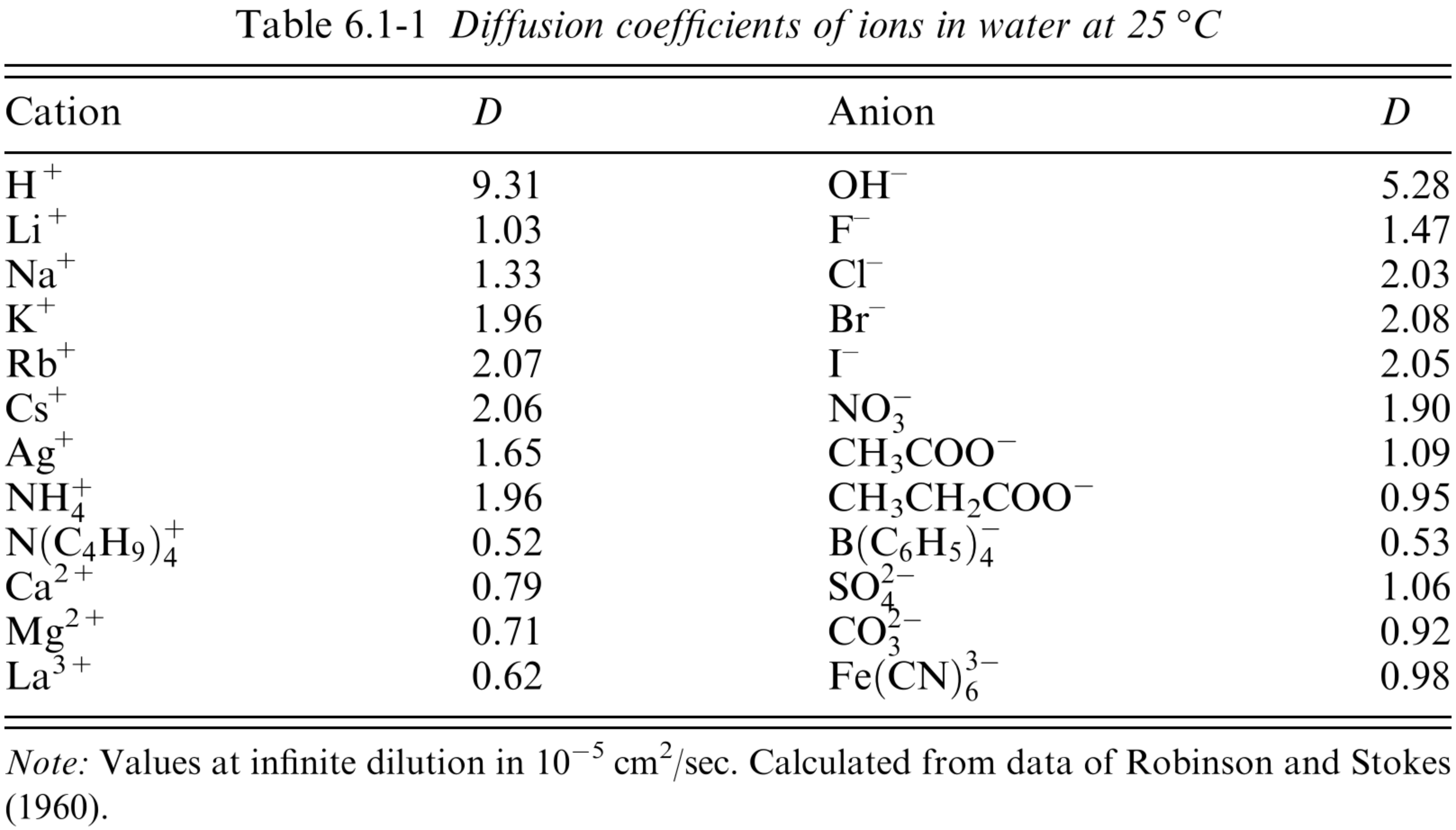
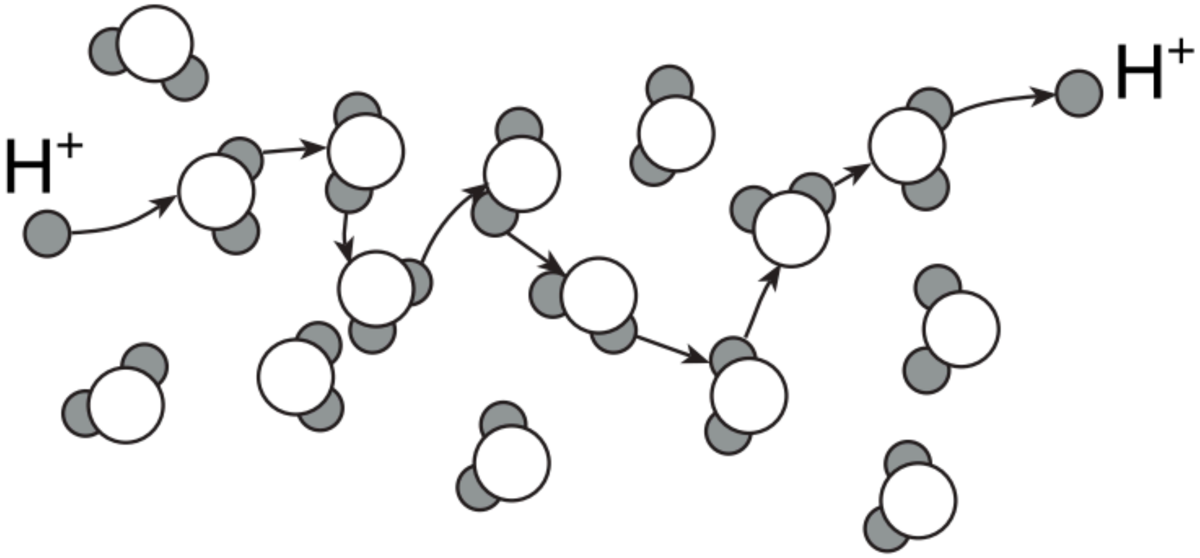


Table 6.1-1 *Diffusion coefficients of ions in water at 25 °C*

Cation	*D*	Anion	*D*
H^+	9.31	OH^-	5.28
Li^+	1.03	F^-	1.47
Na^+	1.33	Cl^-	2.03
K^+	1.96	Br^-	2.08
Rb^+	2.07	I^-	2.05
Cs^+	2.06	NO_3^-	1.90
Ag^+	1.65	CH_3COO^-	1.09
NH_4^+	1.96	$CH_3CH_2COO^-$	0.95
$N(C_4H_9)_4^+$	0.52	$B(C_6H_5)_4^-$	0.53
Ca^{2+}	0.79	SO_4^{2-}	1.06
Mg^{2+}	0.71	CO_3^{2-}	0.92
La^{3+}	0.62	$Fe(CN)_6^{3-}$	0.98

Note: Values at infinite dilution in 10^{-5} cm^2/sec. Calculated from data of Robinson and Stokes (1960).

Special case for diffusion of protons

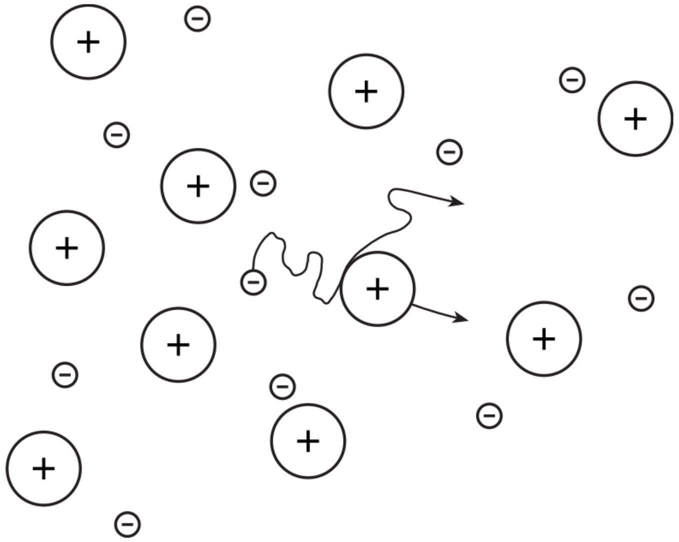


Grotthus mechanism

Coupled diffusion of ions in dilute solution

$$\begin{pmatrix}\text{ion}\\\text{velocity}\end{pmatrix} = \begin{pmatrix}\text{ion}\\\text{mobility}\end{pmatrix}\begin{pmatrix}\text{chemical}\\\text{forces} & + & \text{electrical}\\ & & \text{forces}\end{pmatrix}$$

$$v_i = -u_i(\nabla\mu_i + z_i F \nabla\psi)$$



u_i = representation of ion mobility $= \dfrac{1}{6\pi\eta r} = \dfrac{1}{f}$

z_i = charge on ion

F = Faraday constant $= eN_A$

$\nabla\psi$ = electrostatic potential gradient

Coupled diffusion of ions in dilute solution

$$v_i = -u_i(\nabla \mu_i + z_i F \nabla \psi)$$

$$\Rightarrow v_i = -u_i\left(\frac{RT}{c_i}\nabla c_i + z_i F \nabla \psi\right)$$

$$\Rightarrow c_i v_i = -u_i RT\left(\nabla c_i + z_i c_i \frac{F \nabla \psi}{RT}\right)$$

$$\Rightarrow J_i = -u_i RT\left(\nabla c_i + z_i c_i \frac{F \nabla \psi}{RT}\right)$$

$$\mu_i = \mu_{i,0} + RT \ln \frac{P_i}{P}$$

$$\mu_i = \mu_{i,0} + RT \ln \frac{c_i}{c}$$

$$\nabla \mu_i = RT \nabla \ln c_i = \frac{RT}{c_i}\nabla c_i$$

$$N_i = c_i v_i$$

In the absence of convective flux
(dilute solution)

$$J_i = N_i = c_i v_i$$

Coupled diffusion of ions in dilute solution

$$\Rightarrow \; J_i = -u_i RT\left(\nabla c_i + z_i c_i \frac{F\nabla\psi}{RT}\right)$$

$$\mathrm{u_i} = \text{ion mobility} = \frac{1}{6\pi\eta \mathrm{r}} = \frac{1}{\mathrm{f}}$$

$$\mathrm{u_i RT} = \frac{\mathrm{RT}}{6\pi\eta \mathrm{r}} = \frac{\mathrm{RT}}{\mathrm{f}} = \mathrm{D_i}$$

$$\Rightarrow \; J_i = -D_i\left(\nabla c_i + z_i c_i \frac{F\nabla\psi}{RT}\right)$$

Nernst-Plank Equation

Quiz

Can the flux of an ion decrease if one increases the electric field ?

- A. No, flux will always increase.
- B. Flux is not a function of electric field.
- C. Can decrease in some cases.
- D. Flux will always decrease when electric field is increased.

Quiz

NaCl (ionized form Na+, Cl-) is diffusing in a liquid under applied chemical potential gradient (concentration difference) and electric field. You decided to remove electric field (voltage). Will the measured current become zero ?

A. Yes, current will be zero as there is no electric field.
B. Current may not be zero
C. Current does not depend on electric field.
D. None of the above.

Case of strong 1:1 electrolyte (for example NaCl)

Although the concentrations of ions may vary through the solutions, the concentrations and the concentration gradients of anions and cations are equal everywhere because of electroneutrality.

Species 1: cation

Species 2: anion

$$c_1 = c_2$$

$$\nabla c_1 = \nabla c_2$$

$$J_1 \neq J_2$$

$$J_i = -D_i\left(\nabla c_i + z_i c_i \frac{F\nabla\psi}{RT}\right)$$

z =1 for Na$^+$, and -1 for Cl$^-$

When a current density *i* is maintained, $J_1 - J_2 = \frac{i}{|z|}$

i is positive when it flows
from positive to negative electrode

Applying Nernst-Plank equation for cations and anions

$$J_1 = -D_1\left(\nabla c_1 + |z| c_1 \frac{F\nabla\psi}{RT}\right)$$

$$J_2 = -D_2\left(\nabla c_2 - |z| c_2 \frac{F\nabla\psi}{RT}\right)$$

Case of strong 1:1 electrolyte (for example NaCl)

$$J_1 - J_2 = \frac{i}{|z|} \qquad J_1 = -D_1\left(\nabla c_1 + |z|c_1\frac{F\nabla\psi}{RT}\right) \qquad J_2 = -D_2\left(\nabla c_2 - |z|c_2\frac{F\nabla\psi}{RT}\right)$$

$$\Rightarrow \frac{i}{|z|} = (D_2\nabla c_2 - D_1\nabla c_1) - (D_1c_1 + D_2c_2)|z|\frac{F\nabla\psi}{RT}$$

Current is not zero when the electrostatic potential is zero

We can now try to remove the electrostatic potential in the flux equation

$$|z|\frac{F\nabla\psi}{RT} = -\frac{\frac{i}{|z|} - (D_2\nabla c_2 - D_1\nabla c_1)}{(D_1c_1 + D_2c_2)}$$

Electrostatic potential is not zero when i=0

$$\Rightarrow J_1 = -D_1\left(\nabla c_1 - c_1\frac{\frac{i}{|z|} - (D_2\nabla c_2 - D_1\nabla c_1)}{(D_1c_1 + D_2c_2)}\right)$$

Case of strong 1:1 electrolyte (for example NaCl)

$$J_1 = -D_1\left(\nabla c_1 - c_1\frac{\frac{i}{|z|} - (D_2\nabla c_2 - D_1\nabla c_1)}{(D_1c_1 + D_2c_2)}\right)$$

$$\Rightarrow J_1 = -D_1\left(\frac{\nabla c_1(\cancel{D_1}c_1 + D_2c_2) - c_1\frac{i}{|z|} + c_1(D_2\nabla c_2 - \cancel{D_1\nabla}c_1)}{(D_1c_1 + D_2c_2)}\right)$$

$$c_1 = c_2$$

$$\nabla c_1 = \nabla c_2$$

$$\Rightarrow J_1 = -D_1\left(\frac{D_2\nabla c_1 - \frac{i}{|z|} + D_2\nabla c_1}{D_1 + D_2}\right)$$

$$\Rightarrow J_1 = -\left[\frac{2D_1D_2}{D_1 + D_2}\right]\nabla c_1 + \left[\frac{D_1}{D_1 + D_2}\right]\frac{i}{|z|}$$

Case of strong 1:1 electrolyte (for example NaCl)

$$J_1 = -\left[\frac{2D_1D_2}{D_1+D_2}\right]\nabla c_1 + \left[\frac{D_1}{D_1+D_2}\right]\frac{i}{|z|} \qquad J_2 = -\left[\frac{2D_1D_2}{D_1+D_2}\right]\nabla c_2 + \left[\frac{D_2}{D_1+D_2}\right]\frac{-i}{|z|}$$

Limit 1: i = 0

$$J_1 = -\left[\frac{2D_1D_2}{D_1+D_2}\right]\nabla c_1$$

$$J_1 = -\left[\frac{2}{1/D_1+1/D_2}\right]\nabla c_1$$

$$J_1 = -D_{eff}\nabla c_1$$

Slow moving species will dominate transport

Also, $J_1 = J_2$

Limit 2: solution is well mixed

$$J_1 = \left[\frac{D_1}{D_1+D_2}\right]\frac{i}{|z|} = t_1\frac{i}{|z|}$$

$$J_2 = \left[\frac{D_2}{D_1+D_2}\right]\frac{-i}{|z|} = t_2\frac{-i}{|z|}$$

t_i is called transference number

Fast moving ion will mainly carry current

$J_1 \neq J_2$

Case of strong non 1:1 electrolyte (for example $CaCl_2$)

$$z_1 c_1 = -z_2 c_2 \qquad z_1 \nabla c_1 = -z_2 \nabla c_2$$

c_T = 1M, $CaCl_2$

c_1 = 1M Ca^{+2} $\quad$ c_2 = 2M Cl^{-1}

$z_1 = 2$ $\quad$ $z_2 = -1$

We can apply the Nernst-Planck equation, and equate flux to current to find new equation

$$J_i = -D_i\left(\nabla c_i + z_i c_i \frac{F\nabla\psi}{RT}\right) \qquad z_1 J_1 + z_2 J_2 = i$$

$$\Rightarrow J_1 = -\left[\frac{D_1 D_2(z_1^2 c_1 + z_2^2 c_2)}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2)}\right]\nabla c_1 + \left[\frac{D_1 z_1 c_1}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2)}\right] i$$

Reduces to our previous result when $|z_1| = |z_2|$

$$J_1 = -\left[\frac{2D_1 D_2}{D_1 + D_2}\right]\nabla c_1 + \left[\frac{D_1}{D_1 + D_2}\right]\frac{i}{|z|}$$

Proof:

$$z_1 J_1 + z_2 J_2 = i$$

$$J_1 = -D_1\left(\nabla c_1 + z_1 c_1 \frac{F\nabla\psi}{RT}\right) \qquad J_2 = -D_2\left(\nabla c_2 + z_2 c_2 \frac{F\nabla\psi}{RT}\right)$$

$$\Rightarrow i = -(z_2 D_2 \nabla c_2 + z_1 D_1 \nabla c_1) - (z_1^2 D_1 c_1 + z_2^2 D_2 c_2)\frac{F\nabla\psi}{RT}$$

We can now try to remove the electrostatic potential in the flux equation

$$\frac{F\nabla\psi}{RT} = -\frac{i + (z_2 D_2 \nabla c_2 + z_1 D_1 \nabla c_1)}{(z_1^2 D_1 c_1 + z_2^2 D_2 c_2)}$$

$$\Rightarrow J_1 = -D_1\left(\nabla c_1 - z_1 c_1 \frac{i + (z_2 D_2 \nabla c_2 + z_1 D_1 \nabla c_1)}{(z_1^2 D_1 c_1 + z_2^2 D_2 c_2)}\right)$$

Proof:

$$J_1 = -D_1\left(\nabla c_1 - z_1 c_1 \frac{i + (z_2 D_2 \nabla c_2 + z_1 D_1 \nabla c_1)}{(z_1^2 D_1 c_1 + z_2^2 D_2 c_2)}\right)$$

$$\Rightarrow J_1 = -D_1\left(\frac{(z_1^2 \cancel{D_1} c_1 + z_2^2 D_2 c_2)\nabla c_1 - z_1 c_1\, i - z_1 c_1 (z_2 D_2 \nabla c_2 + z_1 D_1 \cancel{\nabla} c_1)}{(z_1^2 D_1 c_1 + z_2^2 D_2 c_2)}\right)$$

$$\Rightarrow J_1 = -D_1\left(\frac{z_2^2 D_2 c_2 \nabla c_1 - z_1 c_1\, i - z_1 z_2 D_2 c_1 \nabla c_2}{(z_1^2 D_1 c_1 + z_2^2 D_2 c_2)}\right)$$

$$z_1 c_1 = -z_2 c_2$$

$$z_1 \nabla c_1 = -z_2 \nabla c_2$$

$$\Rightarrow J_1 = -D_1\left(\frac{z_2^2 D_2 c_2 \nabla c_1 - z_1 c_1\, i + z_1^2 D_2 c_1 \nabla c_1}{(z_1^2 D_1 c_1 + z_2^2 D_2 c_2)}\right)$$

$$\Rightarrow J_1 = -\left[\frac{D_1 D_2 (z_1^2 c_1 + z_2^2 c_2)}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2)}\right]\nabla c_1 + \left[\frac{D_1 z_1 c_1}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2))}\right] i$$

Case of strong non 1:1 electrolyte (for example $CaCl_2$)

$$J_1 = -\left[\frac{D_1 D_2 (z_1^2 c_1 + z_2^2 c_2)}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2)}\right] \nabla c_1 + \left[\frac{D_1 z_1 c_1}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2)}\right] i$$

When $i = 0$

$$J_1 = -\left[\frac{D_1 D_2 (z_1^2 c_1 + z_2^2 c_2)}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2)}\right] \nabla c_1 \qquad \Rightarrow J_1 = -\left[\frac{(z_1^2 c_1 + z_2^2 c_2)}{\left(\frac{z_1^2 c_1}{D_2} + \frac{z_2^2 c_2}{D_1}\right)}\right] \nabla c_1$$

Total electrolyte flux = $J_T = J_1/|z_2| = J_2/|z_1|$

Total electrolyte concentration = $c_T = c_1/|z_2| = c_2/|z_1|$

c_T = 1M, $CaCl_2$

c_1 = 1M Ca^{+2} $\quad$ c_2 = 2M Cl^{-1}

$|z_1| = 2$ $\quad$ $|z_2| = 1$

$$\Rightarrow J_T = -\left[\frac{(|z_1| + |z_2|)}{\left(\frac{|z_1|}{D_2} + \frac{|z_2|}{D_1}\right)}\right] \nabla c_T$$

- Slow moving species is likely to dominate transport
- If fast species has lower charge, it can reduce the domination of slow species.

Case of strong non 1:1 electrolyte (for example $CaCl_2$)

$$J_1 = -\left[\frac{D_1 D_2 (z_1^2 c_1 + z_2^2 c_2)}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2)}\right] \nabla c_1 + \left[\frac{D_1 z_1 c_1}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2)}\right] i$$

Well-mixed case

$$J_1 = \left[\frac{D_1 z_1 c_1}{(D_1 z_1^2 c_1 + D_2 z_2^2 c_2)}\right] i$$

- Fast moving species is likely to carry current

Exercise problem 1

Helium/Argon mixture is diffusing through a 100 nm pore at 1 bar and 25 ºC. Report $D_{molecular}$, D_K and D_{vis} for helium at 1 bar and 10 bar. Calculate D_{total} at 1 and 10 bar pressures.

$$\mathrm{D_{He,Ar} = 0.7\ cm^2 s^{-1}\ at\ 1\ bar}$$

$$D_K = \sqrt{\frac{8k_B T d^2}{9\pi m}}$$

$$D_{vis} = \frac{d^2}{32\eta_1} P_1$$

$$\eta_{\mathrm{He}} = 2 * 10^{-5}\ \mathrm{Pa\ s}$$

At 1 bar,

$$D_{molecular} = 0.7\ cm^2/s$$

$$D_K = \sqrt{\frac{8 * 1.38 * 10^{-23} * 298 * (100 * 10^{-9})^2}{9 * 3.14 * 0.004/(6.022 * 10^{23})}} = 0.419\ cm^2/s$$

$$D_{vis} = \frac{(100 * 10^{-9})^2}{32 * 2 * 10^{-5}} * 10^5 = 0.016\ cm^2/s$$

$$1/D = 1/D_K + 1/D_{molecular} \Rightarrow D = 0.262\ cm^2/s$$

$$D_{Total} = D + D_{vis} = 0.278\ cm^2/s$$

At 10 bar,

$$D_{molecular} = 0.7/10 = 0.07\ cm^2/s$$

$$D_K = 0.419\ cm^2/s$$

$$D_{vis} = 0.016 * 10 = 0.16\ cm^2/s$$

$$1/D = 1/D_K + 1/D_{molecular} \Rightarrow D = 0.06\ cm^2/s$$

$$D_{Total} = D + D_{vis} = 0.22\ cm^2/s$$

Exercise Problem 2

Calculate the effective diffusion coefficient for HCl in water at 25 °C, neglecting i

Calculate the transference number for proton and Cl^- ion

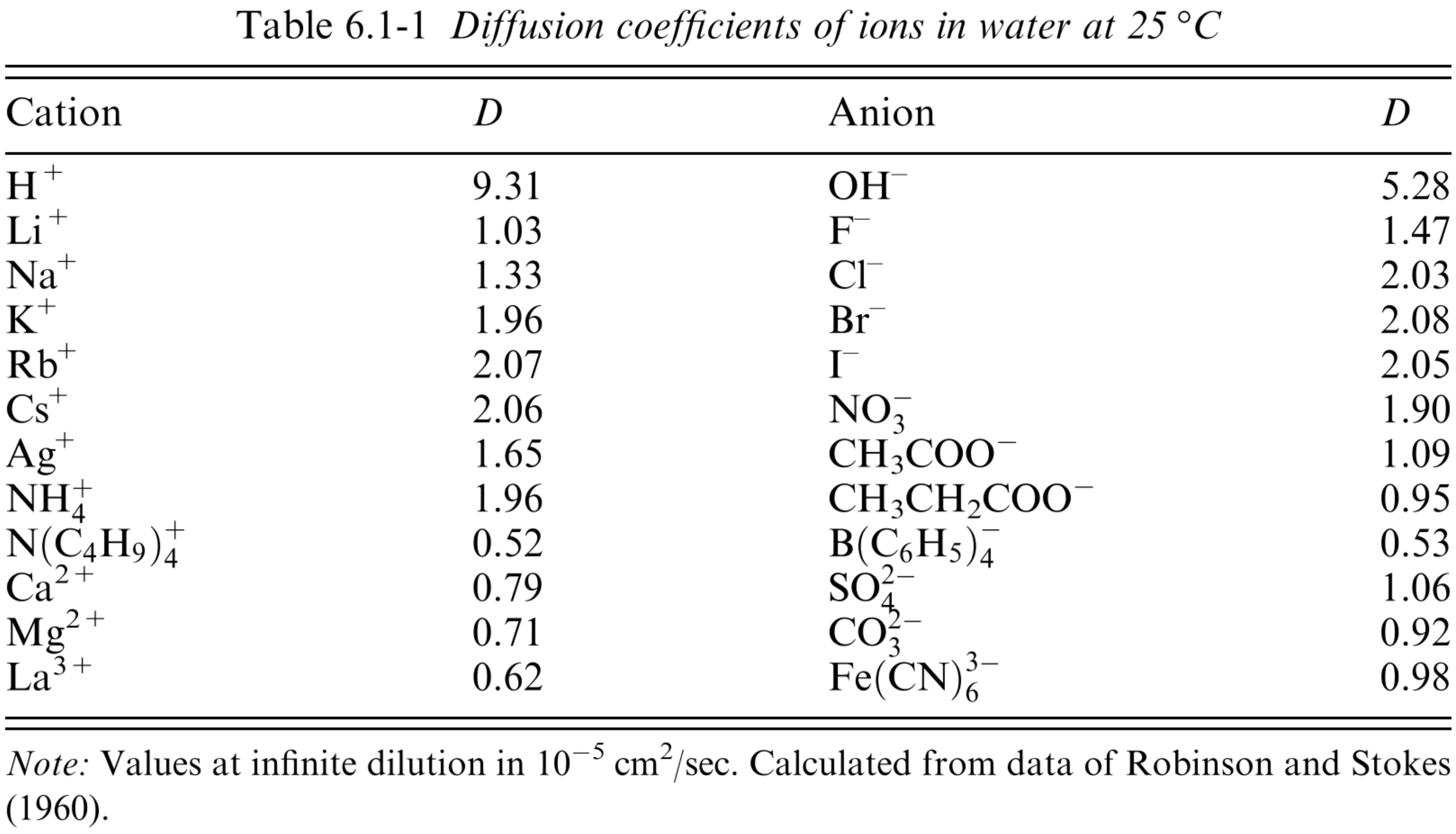


Table 6.1-1 *Diffusion coefficients of ions in water at 25 °C*

Cation	D	Anion	D
H^+	9.31	OH^-	5.28
Li^+	1.03	F^-	1.47
Na^+	1.33	Cl^-	2.03
K^+	1.96	Br^-	2.08
Rb^+	2.07	I^-	2.05
Cs^+	2.06	NO_3^-	1.90
Ag^+	1.65	CH_3COO^-	1.09
NH_4^+	1.96	$CH_3CH_2COO^-$	0.95
$N(C_4H_9)_4^+$	0.52	$B(C_6H_5)_4^-$	0.53
Ca^{2+}	0.79	SO_4^{2-}	1.06
Mg^{2+}	0.71	CO_3^{2-}	0.92
La^{3+}	0.62	$Fe(CN)_6^{3-}$	0.98

Note: Values at infinite dilution in 10^{-5} cm^2/sec. Calculated from data of Robinson and Stokes (1960).

Solution

Calculate the effective diffusion coefficient for HCl in water at 25 °C, neglecting i

$$D_{eff} = \left[\frac{2}{1/D_1 + 1/D_2}\right] = \left[\frac{2 * 10^{-5}}{1/9.31 + 1/2.03}\right] = 3.33 * 10^{-5} \ \ \mathrm{cm}^2/\mathrm{s}$$

In absence of current, diffusion is restricted by slower moving ion (Cl^-)

Calculate the transference number for proton and Cl^- ion

$$t_1 = \left[\frac{D_1}{D_1 + D_2}\right] = \left[\frac{9.31}{9.31 + 2.03}\right] = 0.82$$

$$t_2 = \left[\frac{D_2}{D_1 + D_2}\right] = \left[\frac{2.03}{9.31 + 2.03}\right] = 0.18$$

Table 6.1-1 *Diffusion coefficients of ions in water at 25 °C*

Cation	*D*	Anion	*D*
H^+	9.31	OH^-	5.28
Li^+	1.03	F^-	1.47
Na^+	1.33	Cl^-	2.03
K^+	1.96	Br^-	2.08
Rb^+	2.07	I^-	2.05
Cs^+	2.06	NO_3^-	1.90
Ag^+	1.65	CH_3COO^-	1.09
NH_4^+	1.96	$CH_3CH_2COO^-$	0.95
$N(C_4H_9)_4^+$	0.52	$B(C_6H_5)_4^-$	0.53
Ca^{2+}	0.79	SO_4^{2-}	1.06
Mg^{2+}	0.71	CO_3^{2-}	0.92
La^{3+}	0.62	$Fe(CN)_6^{3-}$	0.98

Note: Values at infinite dilution in 10^{-5} cm^2/sec. Calculated from data of Robinson and Stokes (1960).

The current is mainly carried by H^+ (82%)

Exercise problem 3

Calculate the diffusion coefficient for 0.001 M $LaCl_3$ in water at 25 °C in the absence of a current flow.

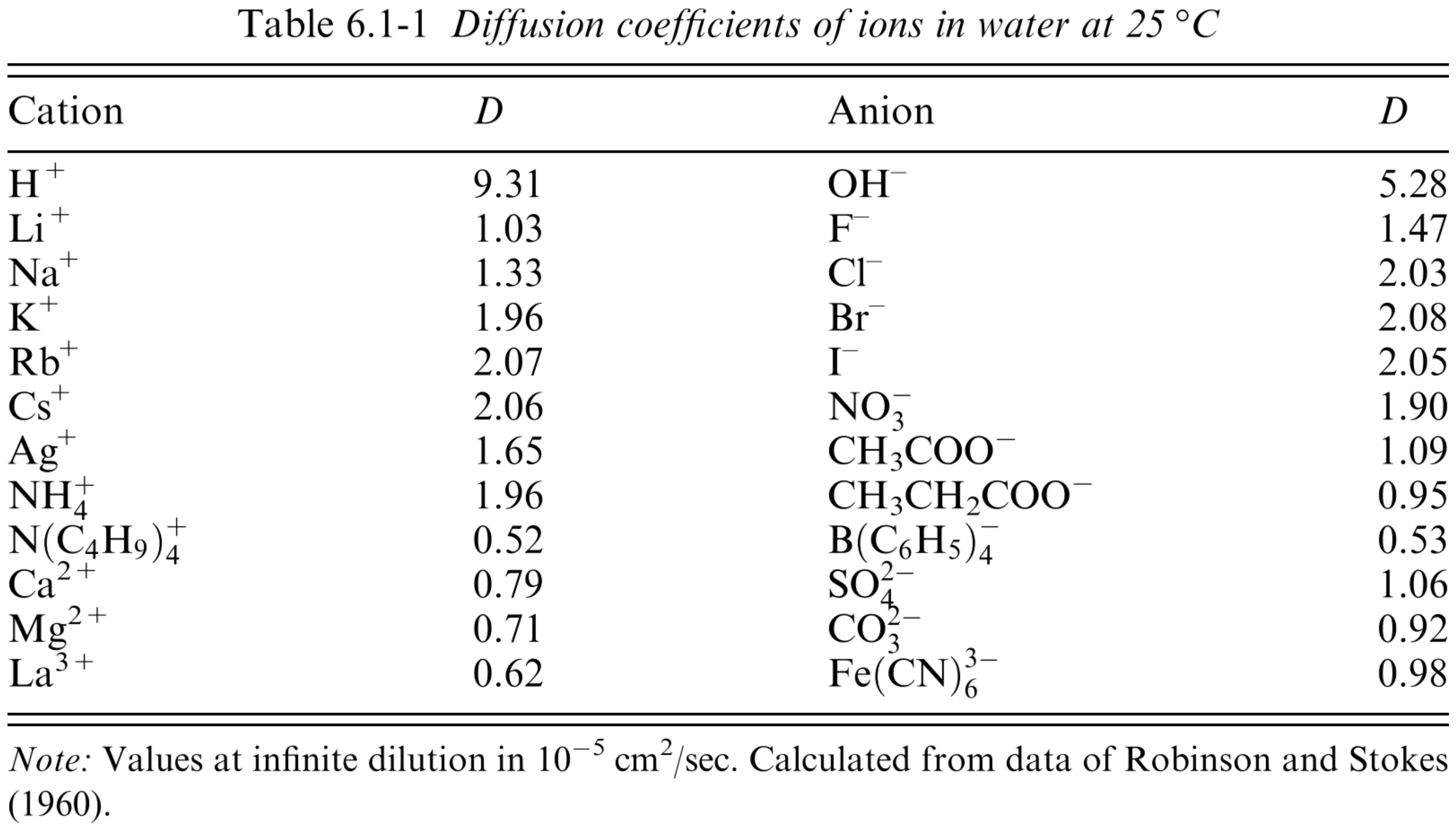


Table 6.1-1 *Diffusion coefficients of ions in water at 25 °C*

Cation	*D*	Anion	*D*
H^+	9.31	OH^-	5.28
Li^+	1.03	F^-	1.47
Na^+	1.33	Cl^-	2.03
K^+	1.96	Br^-	2.08
Rb^+	2.07	I^-	2.05
Cs^+	2.06	NO_3^-	1.90
Ag^+	1.65	CH_3COO^-	1.09
NH_4^+	1.96	$CH_3CH_2COO^-$	0.95
$N(C_4H_9)_4^+$	0.52	$B(C_6H_5)_4^-$	0.53
Ca^{2+}	0.79	SO_4^{2-}	1.06
Mg^{2+}	0.71	CO_3^{2-}	0.92
La^{3+}	0.62	$Fe(CN)_6^{3-}$	0.98

Note: Values at infinite dilution in 10^{-5} cm^2/sec. Calculated from data of Robinson and Stokes (1960).

$$J_T = -\left[\frac{(|z_1| + |z_2|)}{\left(\frac{|z_1|}{D_2} + \frac{|z_2|}{D_1}\right)}\right]\nabla c_T \qquad D_{eff} = \left[\frac{(|z_1| + |z_2|)}{\left(\frac{|z_1|}{D_2} + \frac{|z_2|}{D_1}\right)}\right] = 1.29 * 10^{-5}\ \text{cm}^2/\text{s}$$

Faster Cl^- but +3 charge on La^{+3}