# Carbondioxide ($CO_2$)

**1. Recommended electron collision cross sections**

*Source*: Y. Nakamura, *Aust. J. Phys.* **48**(1995)357

The following cross section set was compiled so that it can reproduce the drift velocity and the $ND_L$ measured in $CO_2$-Ar mixtures and the drift velocity, $ND_L$ and the Townsend's ionization coefficient measured in pure $CO_2$ gas by the multi-term Boltzmann code (Robson and Ness, *Phys. Rev. A* **26** (1986)2068).

**(1) Elastic momentum transfer cross section**

| Energy(eV) | Cross section(Å$^2$) | Energy(eV) | Cross section(Å$^2$) |
|---|---|---|---|
| 0.0000 | 600.00000 | 1.7000 | 3.20000 |
| 0.0010 | 578.00000 | 1.9000 | 3.30000 |
| 0.0020 | 407.00000 | 2.1000 | 3.50000 |
| 0.0030 | 328.00000 | 2.2000 | 3.60000 |
| 0.0050 | 254.00000 | 2.5000 | 4.00000 |
| 0.0070 | 214.00000 | 2.8000 | 4.40000 |
| 0.0085 | 195.00000 | 3.0000 | 4.70000 |
| 0.0100 | 182.00000 | 3.3000 | 5.20000 |
| 0.0150 | 148.00000 | 3.6000 | 5.80000 |
| 0.0200 | 128.00000 | 4.0000 | 6.00000 |
| 0.0300 | 104.00000 | 4.5000 | 5.50000 |
| 0.0400 | 91.00000 | 5.0000 | 5.10000 |
| 0.0500 | 81.00000 | 5.5000 | 5.00000 |
| 0.0700 | 67.00000 | 6.0000 | 5.20000 |
| 0.1000 | 53.50000 | 7.0000 | 6.10000 |
| 0.1200 | 46.00000 | 8.0000 | 7.30000 |
| 0.1500 | 37.00000 | 10.0000 | 8.80000 |
| 0.1700 | 32.00000 | 12.0000 | 10.00000 |
| 0.2000 | 27.00000 | 15.0000 | 11.00000 |
| 0.2500 | 20.00000 | 17.0000 | 11.00000 |
| 0.3000 | 15.00000 | 20.0000 | 10.70000 |
| 0.3500 | 12.40000 | 25.0000 | 10.00000 |
| 0.4000 | 10.50000 | 30.0000 | 9.10000 |
| 0.5000 | 8.00000 | 50.0000 | 6.20000 |
| 0.7000 | 5.70000 | 75.0000 | 4.00000 |
| 1.0000 | 4.20000 | 100.0000 | 3.00000 |
| 1.2000 | 3.70000 | 150.0000 | 6.00000 |
| 1.3000 | 3.40000 | 200.0000 | 4.00000 |
| 1.5000 | 3.30000 | | |

(2) **Vibrational excitation cross section (010)** Threshold = 0.083eV, Energy loss = 0.083eV

| Energy(eV) | Cross section(Å$^2$) | Energy(eV) | Cross section(Å$^2$) |
|---|---|---|---|
| 0.0830 | 0.00000 | 0.3500 | 1.13000 |
| 0.0844 | 0.85000 | 0.5000 | 0.86000 |
| 0.0862 | 1.16000 | 0.7000 | 0.68000 |
| 0.0932 | 1.85000 | 0.9000 | 0.57000 |
| 0.1035 | 2.30000 | 1.1000 | 0.51000 |
| 0.1208 | 2.60000 | 1.4000 | 0.45000 |
| 0.1382 | 2.68000 | 1.6000 | 0.42000 |
| 0.1700 | 2.40000 | 1.9000 | 0.44000 |
| 0.2000 | 2.00000 | 2.6000 | 0.70000 |
| 0.2500 | 1.55000 | 3.1000 | 1.32000 |

| | | | |
|---|---|---|---|
| 3.5000 | 2.64000 | 6.1000 | 0.61000 |
| 3.7000 | 3.15000 | 6.5000 | 0.55000 |
| 3.9000 | 3.50000 | 7.5000 | 0.48000 |
| 4.1000 | 3.56000 | 8.5000 | 0.45000 |
| 4.3000 | 3.52000 | 10.5000 | 0.20000 |
| 4.5000 | 3.35000 | 20.0000 | 0.00000 |
| 4.7000 | 2.74000 | 50.0000 | 0.00000 |
| 5.1000 | 1.85000 | 200.0000 | 0.00000 |
| 5.6000 | 0.80000 | | |

**(3) Vibrational excitation cross section (100)** Threshold = 0.167eV, Energy loss = 0.167eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 0.1670 | 0.00000 | 3.9000 | 3.50000 |
| 0.1720 | 0.30000 | 4.0500 | 3.52000 |
| 0.1800 | 0.33000 | 4.2000 | 3.45000 |
| 0.2000 | 0.35000 | 4.4000 | 3.16000 |
| 0.2500 | 0.32500 | 4.6000 | 2.30000 |
| 0.5000 | 0.11700 | 5.1000 | 1.58000 |
| 1.0000 | 0.05000 | 5.5000 | 0.71000 |
| 1.5000 | 0.04000 | 5.7000 | 0.60000 |
| 2.0000 | 0.06000 | 6.5000 | 0.37000 |
| 2.2000 | 0.08000 | 8.5000 | 0.25000 |
| 2.5000 | 0.20000 | 10.5000 | 0.21000 |
| 2.9000 | 0.57000 | 20.0000 | 0.00000 |
| 3.4000 | 2.53000 | 200.0000 | 0.00000 |
| 3.6000 | 3.10000 | | |

**(4) Vibrational excitation cross section (001)** Threshold = 0.291eV, Energy loss = 0.291eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 0.2910 | 0.00000 | 1.5000 | 0.76000 |
| 0.3000 | 0.76000 | 2.0000 | 0.64000 |
| 0.3100 | 1.36000 | 3.0000 | 0.49000 |
| 0.3200 | 1.58000 | 4.5000 | 0.44000 |
| 0.3300 | 1.67000 | 6.0000 | 0.41000 |
| 0.3500 | 1.73000 | 8.0000 | 0.48000 |
| 0.3800 | 1.82000 | 10.0000 | 0.26000 |
| 0.4000 | 1.83000 | 25.0000 | 0.13500 |
| 0.4500 | 1.78000 | 30.0000 | 0.10000 |
| 0.5000 | 1.67000 | 100.0000 | 0.00000 |
| 0.6000 | 1.46000 | 200.0000 | 0.00000 |
| 0.8000 | 1.17000 | | |
| 1.0000 | 1.00000 | | |

**(5) Vibrational excitation cross section (200)** Threshold = 0.339eV, Energy loss = 0.339eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 1.5000 | 0.00000 | 4.6000 | 0.61000 |
| 2.3000 | 0.12500 | 5.1000 | 0.27800 |
| 2.9000 | 0.36000 | 5.6600 | 0.00000 |
| 3.4000 | 0.81000 | 200.0000 | 0.00000 |
| 4.0600 | 1.30000 | | |

**(6) Vibrational excitation cross section (110)** Threshold = 2.50eV, Energy loss = 0.252eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 2.5000 | 0.00000 | 3.5000 | 0.63000 |

| | | | |
|---|---|---|---|
| 4.0600 | 1.06000 | 5.5600 | 0.06600 |
| 4.6000 | 0.61000 | 6.0000 | 0.00000 |
| 5.1000 | 0.29000 | 200.0000 | 0.00000 |

**(7) Vibrational excitation cross section (210)** Threshold = 2.50eV, Energy loss = 0.422eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 2.5000 | 0.00000 | 5.1000 | 0.00000 |
| 3.4000 | 0.21000 | 5.5600 | 0.00000 |
| 4.0600 | 0.44400 | 200.0000 | 0.00000 |
| 4.6000 | 0.18000 | | |

**(8) Vibrational excitation cross section (300)** Threshold = 2.50eV, Energy loss=0.505eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 2.5000 | 0.00000 | 5.1000 | 0.00000 |
| 3.4000 | 0.31000 | 5.5600 | 0.00000 |
| 4.0600 | 0.59000 | 200.0000 | 0.00000 |
| 4.6000 | 0.28000 | | |

**(9) Vibrational excitation cross section** Threshold = 2.50eV, Energy loss=2.50eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 2.5000 | 0.00000 | 4.6000 | 0.32000 |
| 3.4000 | 0.35000 | 5.0000 | 0.00000 |
| 4.1000 | 0.49000 | 200.0000 | 0.00000 |

**(10) Electronic excitation 1** Threshold = 7.0eV, Energy loss=7.0 eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 7.0000 | 0.00000 | 11.0000 | 0.00000 |
| 8.0000 | 0.50000 | 200.0000 | 0.00000 |
| 8.5000 | 0.50000 | | |

**(11) Electronic excitation 2** Threshold = 10.5eV, Energy loss=10.5eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 10.5000 | 0.00000 | 25.0000 | 1.95000 |
| 12.0000 | 0.76000 | 30.0000 | 2.54000 |
| 13.0000 | 0.83000 | 40.0000 | 3.60000 |
| 14.0000 | 0.90000 | 60.0000 | 4.80000 |
| 15.0000 | 0.97000 | 80.0000 | 5.60000 |
| 17.0000 | 1.14000 | 100.0000 | 6.30000 |
| 20.0000 | 1.40000 | 200.0000 | 6.30000 |

**(12) Electron attachment** Threshold = 3.85eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 3.8500 | 0.00000 | 8.2000 | 0.00450 |
| 4.3000 | 0.00140 | 8.4000 | 0.00420 |
| 4.5000 | 0.00140 | 8.9000 | 0.00100 |
| 5.1000 | 0.00000 | 9.7000 | 0.00000 |
| 6.6000 | 0.00000 | 200.0000 | 0.00000 |
| 7.2000 | 0.00070 | | |

**(13) Ionization** Threshold = 13.3 eV, Energy loss = 13.3eV

| Energy(eV) | Cross section(Å $^2$) | Energy(eV) | Cross section(Å $^2$) |
|---|---|---|---|
| 13.3000 | 0.00000 | 16.0000 | 0.18800 |
| 14.5000 | 0.06000 | 18.0000 | 0.35900 |
| 15.0000 | 0.10400 | 20.0000 | 0.53200 |

| | | | |
|---|---|---|---|
| 30.0000 | 1.63000 | 70.0000 | 3.43000 |
| 40.0000 | 2.28000 | 100.0000 | 3.79000 |
| 50.0000 | 2.79000 | 200.0000 | 3.40000 |

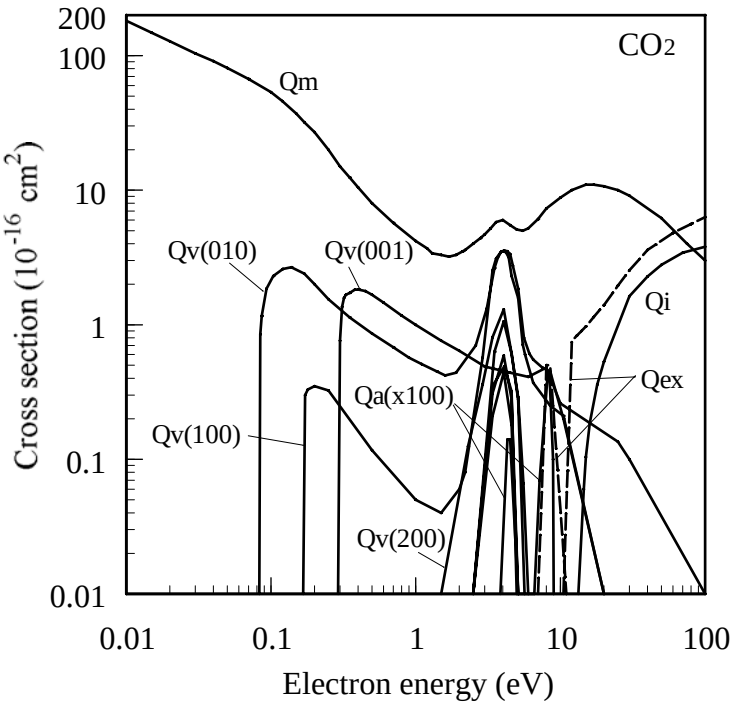


**Fig.1 Recommended electron collision cross sections for $CO_2$**

**2. Related electron swarm data**

**(1) Electron drift velocity, W, in pure $CO_2$**

| E/N (Td) | W ($10^6$ cm/s) | | E/N (Td) | W ($10^6$ cm/s) | |
|---|---|---|---|---|---|
| 0.25 | 0.0446[1] | | 8.0 | 1.560 | 1.543 |
| 0.3 | 0.0535 | | 10.0 | 2.043 | 2.049 |
| 0.35 | 0.0612 | | 12.0 | 2.682 | 2.669 |
| 0.4 | 0.0705 | 0.0712[2] | 14.0 | 3.446 | 3.443 |
| 0.5 | 0.0885 | 0.0890 | 16.0 | | 4.355 |
| 0.6 | 0.1061 | 0.1067 | 17.0 | 4.847 | |
| 0.7 | 0.1237 | 0.1245 | 18.0 | | 5.332 |
| 0.8 | 0.1410 | 0.1423 | | | |
| 1.0 | 0.1774 | 0.1779 | 20.0 | 6.270 | 6.258 |
| 1.2 | 0.2122 | 0.2133 | 22.0 | | 7.071 |
| 1.4 | 0.2474 | 0.2489 | 24.0 | | 7.742 |
| 1.7 | 0.3009 | 0.3025 | 25.0 | 8.014 | |
| 2.0 | 0.3530 | 0.3559 | 26.0 | | 8.268 |
| 2.5 | 0.4425 | 0.4453 | 28.0 | | 8.694 |
| 3.0 | 0.5253 | 0.5355 | 30.0 | 8.950 | 9.003 |
| 3.5 | 0.6235 | | 35.0 | 9.658 | 9.667 |
| 4.0 | 0.7176 | 0.7196 | 40.0 | 10.15 | 10.11 |
| 5.0 | 0.9053 | 0.9095 | 45.0 | | 10.66 |
| 6.0 | 1.103 | 1.108 | 50.0 | 10.87 | 11.02 |
| 7.0 | 1.308 | 1.319 | 60.0 | 11.57 | |

| | | | |
|---|---|---|---|
| 70.0 | 12.33 | 140.0 | 17.39 |
| 80.0 | 12.90 | 170.0 | 19.48 |
| 100.0 | 14.44 | 200.0 | 21.36 |
| 120.0 | 15.82 | 250.0 | 25.68 |

[1] Y. Nakamura, *Aust. J. Phys.* **48** (1995) 357-363, 300K
[2] M. T. Elford and G. N. Haddad, *Aust. J. Phys.* **33** (1980) 517-530, 293K

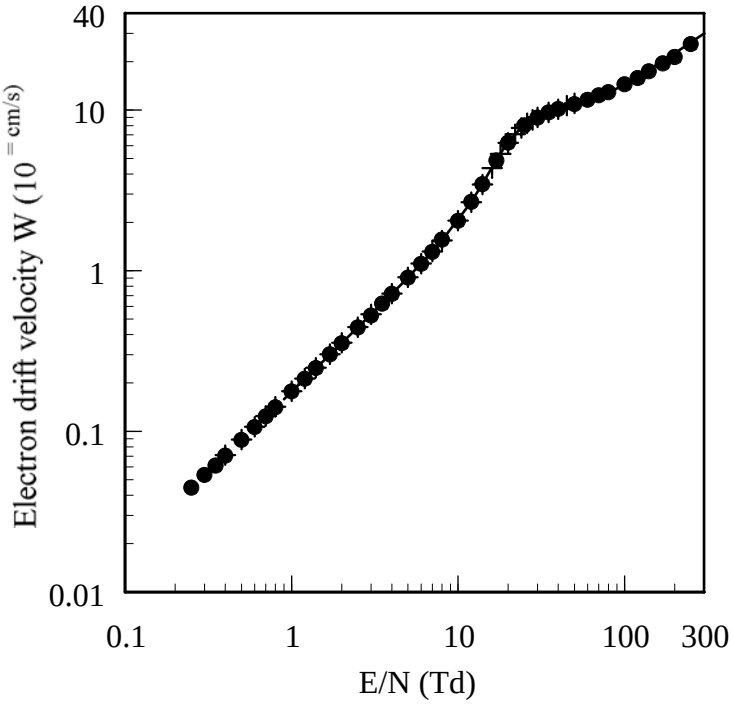


**Fig.2 Electron drift velocity in pure $CO_2$. Solid curve, using the recommended cross section data, solid circles, Nakamura (300K), and +, Elford et al. (293K).**

**(2) Product of longitudinal diffusion coefficient and gas number density, $ND_L$ in pure $CO_2$**

| E/N (Td) | $ND_L$ ($10^{20}$ $cm^{-1}.s^{-1}$) | E/N (Td) | $ND_L$ ($10^{20}$ $cm^{-1}.s^{-1}$) |
|---|---|---|---|
| 0.7 | 4.826[3] | 14.0 | 64.17 |
| 0.8 | 4.839 | 17.0 | 119.7 |
| 1.0 | 5.048 | 20.0 | 151.0 |
| 1.2 | 4.921 | 25.0 | 147.6 |
| 1.4 | 4.956 | 30.0 | 129.1 |
| 1.7 | 5.046 | 35.0 | 121.5 |
| 2.0 | 5.118 | 40.0 | 120.4 |
| 2.5 | 5.168 | 50.0 | 123.6 |
| 3.0 | 5.287 | 60.0 | 139.3 |
| 3.5 | 5.750 | 70.0 | 158.9 |
| 4.0 | 6.075 | 80.0 | 182.6 |
| 5.0 | 6.775 | 100 | 228.5 |
| 6.0 | 8.372 | 120 | 263.0 |
| 7.0 | 10.15 | 140 | 281.2 |
| 8.0 | 11.81 | 170 | 304.8 |
| 10.0 | 20.45 | 200 | 327.2 |
| 12.0 | 35.82 | 250 | 351.7 |

300 420.1

[3] Y. Nakamura, unpublished (1994), 300K

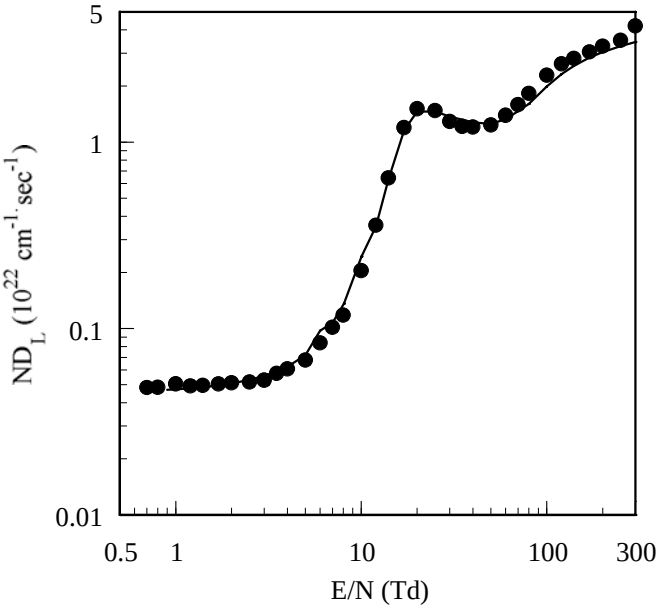


**Fig.3 $ND_L$ in pure $CO_2$. Solid curve, using the recommended cross section data, and solid circles, Nakamura (300K).**

**(3) Characteristic energy, $D_T/\mu$, in pure $CO_2$**

| E/N (Td) | $D_T/\mu$ ($10^{-2}$ V) | E/N (Td) | $D_T/\mu$ ($10^{-2}$ V) |
|---|---|---|---|
| 0.3 | 2.55[4] | 5.0 | 3.50 |
| 0.35 | 2.55 | 6.0 | 3.84 |
| 0.4 | 2.56 | 7.0 | 4.27 |
| 0.5 | 2.57 | 8.0 | 4.84 |
| 0.6 | 2.58 | 10.0 | 6.49 |
| 0.7 | 2.59 | 12.0 | 9.19 |
| 0.8 | 2.60 | 14.0 | 14.53 |
| 1.0 | 2.62 | 17.0 | 27.5 |
| 1.2 | 2.65 | 20.0 | 43.8 |
| 1.4 | 2.68 | 25.0 | 73.6 |
| 1.7 | 2.73 | 30.0 | 99.3 |
| 2.0 | 2.78 | 35.0 | 121.5 |
| 2.5 | 2.88 | 40.0 | 139.8 |
| 3.0 | 3.00 | 50.0 | 171.3 |
| 3.5 | 3.12 | 60.0 | 197.4 |
| 4.0 | 3.25 | | |

[4] J. A. Rees, *Aust. J. Phys.* **19**, 629- (1966)

**(4) Ionization coefficient, $\alpha/N$, in pure $CO_2$**

| E/N (Td) | $\alpha/N$ ($10^{-18}$ $cm^2$) | 109 | 0.96 |
|---|---|---|---|
| 84.0 | 0.18[5] | 121 | 1.55 |
| 97.2 | 0.52 | 136 | 2.5 |

| | | | |
|---|---|---|---|
| 152 | 3.5 | 106 | 0.92 |
| | | 122 | 1.58 |
| E/N (Td) | $\alpha$/N ($10^{-18}$ cm$^2$) | 137 | 2.86 |
| 76.0 | 0.15[6] | 152 | 3.35 |
| 91.2 | 0.27 | | |

[5] V. J. Conti and A. W. Williams, *J. Phys. D* **8**, 2198-2207 (1975)
[6] S. R. Alger and J. A. Rees, *J. Phys. D* **9**, 2359-2367 (1976)

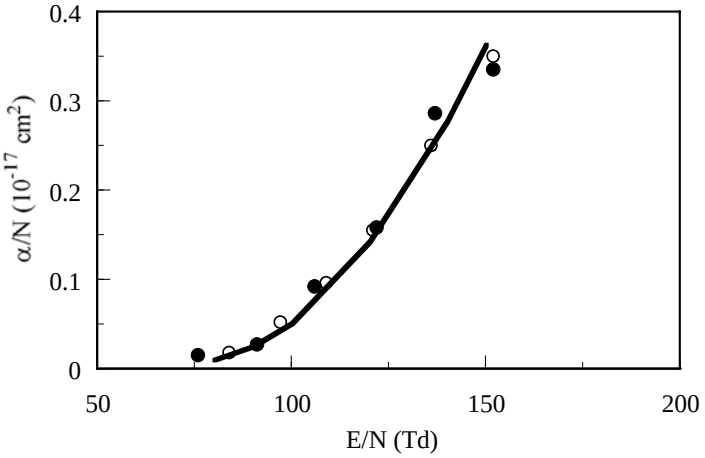


**Fig. 4 Ionization coefficient in pure $CO_2$. Solid curve, using the recommended cross section data, solid circles, Alger and Rees (1976), and open circles, Conti and Williams (1975).**

**(5) Electron drift velocity, W, in $CO_2$-Ar mixtures**[1]

**0.203% $CO_2$-Ar mixture**

| E/N (Td) | W ($10^6$ cm/s) | E/N (Td) | W ($10^6$ cm/s |
|---|---|---|---|
| 0.035 | 0.4976 | 0.7 | 0.7808 |
| 0.04 | 0.6012 | 0.8 | 0.7530 |
| 0.05 | 0.8198 | 1.0 | 0.7355 |
| 0.06 | 1.027 | 1.2 | 0.7468 |
| 0.07 | 1.213 | 1.4 | 0.7763 |
| 0.08 | 1.362 | 1.7 | 0.8081 |
| 0.1 | 1.566 | 2.0 | 0.8460 |
| 0.12 | 1.651 | 2.5 | 0.8794 |
| 0.14 | 1.667 | 3.0 | 0.8631 |
| 0.17 | 1.615 | 3.5 | 0.8388 |
| 0.2 | 1.530 | 4.0 | 0.8023 |
| 0.25 | 1.365 | 5.0 | 0.7750 |
| 0.3 | 1.225 | 6.0 | 0.8083 |
| 0.35 | 1.118 | 7.0 | 0.8567 |
| 0.4 | 1.028 | 8.0 | 0.9087 |
| 0.5 | 0.9017 | 10 | 1.0829 |
| 0.6 | 0.8277 | | |

**1.97% CO2-Ar mixture**

| E/N (Td) | W ($10^6$ cm/s) | E/N (Td) | W ($10^6$ cm/s) |
|---|---|---|---|
| 0.04 | 0.1999 | 0.07 | 0.3595 |
| 0.05 | 0.2519 | 0.08 | 0.4147 |
| 0.06 | 0.3046 | 0.1 | 0.5295 |

| | | | |
|---|---|---|---|
| 0.12 | 0.6560 | 1.7 | 2.518 |
| 0.14 | 0.7951 | 2.0 | 2.326 |
| 0.17 | 1.012 | 2.5 | 2.189 |
| 0.2 | 1.243 | 3.0 | 2.171 |
| 0.25 | 1.659 | 3.5 | 2.196 |
| 0.3 | 2.068 | 4.0 | 2.280 |
| 0.35 | 2.451 | 5.0 | 2.377 |
| 0.4 | 2.801 | 6.0 | 2.420 |
| 0.5 | 3.263 | 7.0 | 2.416 |
| 0.6 | 3.510 | 8.0 | 2.387 |
| 0.7 | 3.563 | 10 | 2.312 |
| 0.8 | 3.497 | 12 | 2.300 |
| 1.0 | 3.269 | 14 | 2.306 |
| 1.2 | 2.985 | 17 | 2.395 |
| 1.4 | 2.729 | | |

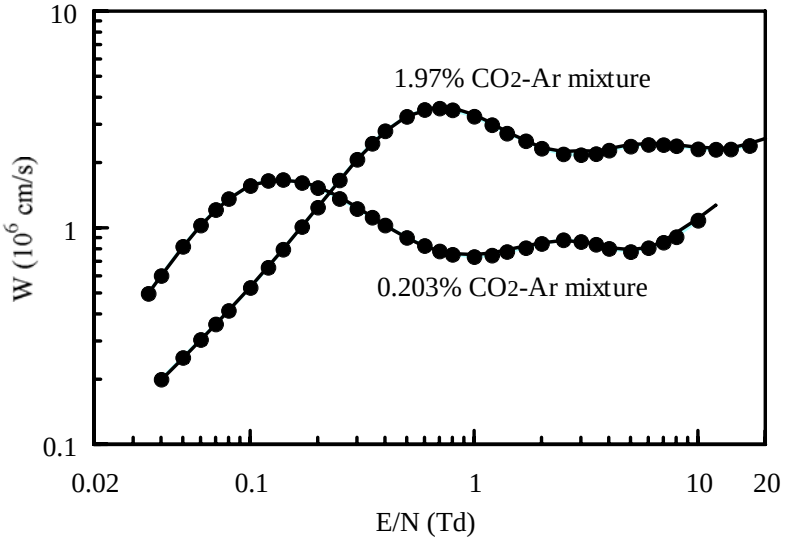


**Fig.5 Electron drift velocity in $CO_2$-Ar mixtures. Solid curves show the calculations using the recommended cross section data.**

**(6) Product of longitudinal diffusion coefficient and gas number density, $ND_L$ in $CO_2$-Ar mixtures**[1]

**0.203% $CO_2$-Ar mixture**

| E/N (Td) | $ND_L$ ($10^{22}$ $cm^{-1}.s^{-1}$) | E/N (Td) | $ND_L$ ($10^{22}$ $cm^{-1}.s^{-1}$) |
|---|---|---|---|
| 0.035 | 10.46 | 0.3 | 4.100 |
| 0.04 | 13.21 | 0.35 | 3.442 |
| 0.05 | 16.40 | 0.4 | 2.702 |
| 0.06 | 18.05 | 0.5 | 2.227 |
| 0.07 | 17.01 | 0.6 | 2.038 |
| 0.08 | 17.64 | 0.7 | 2.051 |
| 0.1 | 14.71 | 0.8 | 2.076 |
| 0.12 | 12.61 | 1.0 | 2.024 |
| 0.14 | 9.476 | 1.2 | 2.236 |
| 0.17 | 8.130 | 1.4 | 2.090 |
| 0.2 | 6.651 | 1.7 | 2.286 |
| 0.25 | 4.796 | 2.0 | 2.059 |

| | | | |
|---|---|---|---|
| 2.5 | 1.596 | 6.0 | 1.410 |
| 3.0 | 1.316 | 7.0 | 1.909 |
| 3.5 | 1.150 | 8.0 | 2.227 |
| 4.0 | 1.041 | 10 | 2.469 |
| 5.0 | 1.138 | | |

**1.97% CO2-Ar mixture**

| E/N (Td) | $ND_L$ ($10^{22}$ $cm^{-1}.s^{-1}$) | E/N (Td) | $ND_L$ ($10^{22}$ $cm^{-1}.s^{-1}$) |
|---|---|---|---|
| 0.04 | 1.366 | 1.0 | 3.193 |
| 0.05 | 1.392 | 1.2 | 2.634 |
| 0.06 | 1.612 | 1.4 | 2.081 |
| 0.07 | 1.818 | 1.7 | 2.019 |
| 0.08 | 1.873 | 2.0 | 1.853 |
| 0.1 | 2.192 | 2.5 | 1.948 |
| 0.12 | 2.746 | 3.0 | 2.245 |
| 0.14 | 2.891 | 3.5 | 2.342 |
| 0.17 | 3.418 | 4.0 | 2.356 |
| 0.2 | 3.954 | 5.0 | 2.219 |
| 0.25 | 5.414 | 6.0 | 2.159 |
| 0.3 | 6.234 | 7.0 | 1.902 |
| 0.35 | 6.677 | 8.0 | 2.013 |
| 0.4 | 6.923 | 10 | 1.950 |
| 0.5 | 6.708 | 12 | 2.005 |
| 0.6 | 5.210 | 14 | 2.152 |
| 0.7 | 4.623 | 17 | 2.686 |
| 0.8 | 4.149 | | |

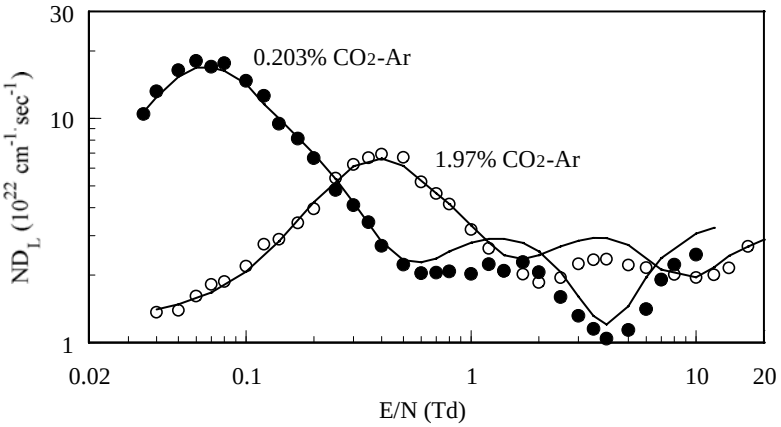


**Fig. 6 $ND_L$ in $CO_2$-Ar mixtures. Solid curves show the calculation using the recommended cross section data.**