CHAPTER 5

Tables

These tables are from

Understanding the properties of matter

by Michael de Podesta.

The data from the tables is derived primarily, but not exclusively, from the following compilations:

- G. W. C. Kaye and T. H. Laby, *Tables of Physical and Chemical Constants*: 14th, 15th and 16th Editions, published by Longman (Harlow) in the UK and Wiley (New York) in the USA. This is referred to as *Kaye & Laby* in the text.
- Weast *CRC Handbook of Chemistry and Physics:* 65th *Edition* [also known as the 'Rubber Bible'], published by Chemical Rubber Publishing Company (Chicago, Ill)
- John Emsley, *The Elements*, published by Clarendon Press / Oxford University Press (Oxford).

For more details see **www.physicsofmatter.com**

Table 5.1 **The density of various gases at STP in units of kg m^{-3}. The lines in the table separate gases of monatomic, diatomic and polyatomic molecules.**

Gas	A (u)	Density (kg m^{-3})
Helium, He	4.0030	0.1786
Neon, Ne	20.180	0.9003
Argon, Ar	39.948	1.782
Krypton, Kr	83.800	3.739
Xenon, Xe	131.29	5.858
Hydrogen, H_2	2.0160	0.08995
Nitrogen, N_2	28.014	1.250
Oxygen, O_2	31.998	1.428
Chlorine, Cl_2	70.906	3.164
Methane, CH_4	16.043	0.7158
Ethane, C_2H_6	30.070	1.342
Propane, C_3H_8	44.097	1.968

Table 5.2 **The major components of *dry* atmospheric air. Typically water vapour is also present at a level of roughly 0.5%.**

Gas	Molecular mass	% by volume
Nitrogen, N_2	28.01	78.09
Oxygen, O_2	32.00	20.95
Argon, Ar	39.95	0.93
Carbon dioxide, CO_2	44.00	0.03

Table 5.3 **The molar volume of various gases at STP in units of 10^{-3} m^3. The lines in the table separate gases of monatomic, diatomic and polyatomic molecules.**

Gas	Molar density (m^{-3})	Mass of 1 mol ($\times 10^{-3}$ kg)	Molar volume ($\times 10^{-3}$ m^3)
Helium, He	44.6158	4.0030	22.4136
Neon, Ne	44.6152	20.180	22.4139
Argon, Ar	44.6162	39.948	22.4134
Krypton, Kr	44.6168	83.800	22.4131
Xenon, Xe	44.6174	131.29	22.4128
Hydrogen, H_2	44.6160	2.0160	22.4135
Nitrogen, N_2	44.6168	28.014	22.4131
Oxygen, O_2	44.6162	31.998	22.4134
Chlorine, Cl_2	44.6172	70.906	22.4129
Methane, CH_4	44.6170	16.043	22.4130
Ethane, C_2H_6	44.6178	30.070	22.4126
Propane, C_3H_8	44.6182	44.097	22.4124

Table 5.4 **Values of the expansivity coefficients β_V and β_P for gases whose initial pressure is 0.1333 MPa at 0 °C, valid in the temperature range 0 °C to 100 °C. The pressure 0.1333 MPa is a little greater than normal atmospheric pressure.**

Gas	β_V (°C^{-1})	β_P (°C^{-1})
Helium, He	3.6580×10^{-3}	3.6605×10^{-3}
Hydrogen, H_2	3.6588×10^{-3}	3.6620×10^{-3}
Nitrogen, N_2	3.6735×10^{-3}	3.6744×10^{-3}
Air	3.6728×10^{-3}	3.6744×10^{-3}
Neon, Ne	3.6600×10^{-3}	3.6617×10^{-3}

Table 5.5 **Comparison of experimental and theoretical expansivities of gases. See also Table 5.4.**

Gas	β_V (°C^{-1})	% difference between theory and experiment
Helium, He	3.6580×10^{-3}	− 0.082
Hydrogen, H_2	3.6588×10^{-3}	− 0.060
Nitrogen, N_2	3.6735×10^{-3}	+ 0.342
Air	3.6728×10^{-3}	+ 0.323
Neon, Ne	3.6600×10^{-3}	− 0.027

Table 5.6 The molar heat capacities at constant pressure C_P(J K^{-1} mol^{-1}) for the monatomic noble gases. These data are graphed in Figure 5.3.

- The shaded figures correspond to data taken in the liquid or solid phase. For each gas the boiling temperature and melting temperature are separated by less than 5 K.
- The data between the two double lines is from a separate source from the rest of the table. Notice that the extra measurement resolution still shows agreement between the heat capacities of the different gases.

T(K)	He	Ne	Ar	Kr	Xe
50	—	—	24.8	25.1	25.1
100	—	—	20.8	31.6	28.2
150	—	—	20.8	20.8	33.6
200	—	—	20.8	20.8	20.8
298.15	20.786	20.786	20.786	20.786	20.786
400	20.8	20.8	20.8	20.8	20.8
600	20.8	20.8	20.8	20.8	20.8
800	20.8	20.8	20.8	20.8	20.8
1000	20.8	20.8	20.8	20.8	20.8
1500	20.8	20.8	20.8	20.8	20.8
2000	20.8	20.8	20.8	20.8	20.8
2500	20.8	20.8	20.8	20.8	20.8

Table 5.7 The molar heat capacities at constant pressure CP(J K–1 mol–1) for some diatomic gases. These data are graphed in Figure 5.4.

- The shaded figures correspond to data taken in the liquid or solid phase.

T(K)	H_2	0_2	N_2	F_2	Cl_2	Br_2	I_2
50	—	46.1	41.5	—	29.2	33.3	35.8
100	—	29.1	29.1	—	42.3	43.6	45.6
150	—	29.1	29.1	—	51.0	49.2	49.6
200	—	29.1	29.1	—	54.2	53.8	51.5
400	29.2	30.1	29.2	33.0	35.3	36.7	80.3
600	29.3	32.1	30.1	35.2	36.6	37.3	37.6
800	29.6	33.7	31.4	36.3	37.2	37.5	37.8
1000	30.2	34.9	32.7	37.0	37.5	37.7	37.9
1500	32.3	36.6	34.9	37.9	38.0	38.0	38.2
2000	34.3	37.8	36.0	38.4	38.3	38.2	38.5
2500	36.0	38.9	36.0	38.8	38.6	38.5	38.8

Table 5.8 The ratio of the principal heat capacities ($\gamma = C_P/C_V$) of some gases. The shaded results correspond to a pressure of 200 atmospheres (20 MPa). The notes below each section of the table summarise the results for that class of gases. There appears to be a trend towards a reduction in γ as the temperature is increased. Where no temperature shown, the temperature of the measurement is not known but is probably either 0 °C or close to 20 °C.

Gas	T(°C)	T(K)	γ	Gas	T(°C)	T(K)	γ
Monatomic gases				**Triatomic gases**			
He	0.0	273.20	1.630	O_3	—	—	1.290
Ar	0.0	273.20	1.667	H_20	100.0	373.20	1.334
Ne	19.0	292.20	1.642	CO_2	10.0	283.20	1.300
Kr	19.0	292.20	1.689	CO_2	300.0	573.20	1.220
Xe	19.0	292.20	1.666	CO_2	500.0	773.20	1.200
Hg	310.0	583.20	1.666	NH_3	—	—	1.336
All the above results are close to 1.66				N_20	—	—	1.324
Diatomic gases				H_2S	—	—	1.340
H_2	10.0	283.20	1.407	CS_2	—	—	1.239
N_2	20.0	293.20	1.401	SO_2	20.0	293.20	1.260
O_2	10.0	283.20	1.400	SO_2	500.0	773.20	1.200
CO	1800.0	2073.2	1.297	*All the above results are close to 1.3*			
NO	—	—	1.394	**Polyatomic gases**			
Most of the above results are close to 1.4				CH_4	—	—	1.313
C: Air				C_2H_6	—	—	1.220
Air	-79.3	193.90	1.405	C_3H_8	—	—	1.130
Air	10.0	283.20	1.401	C_2H_2	—	—	1.260
Air	500.0	773.20	1.357	C_2H_4	—	—	1.264
Air	900.0	1173.2	1.320	C_6H_6	20.0	293.20	1.400
Air	0.0	273.20	1.828	C_6H_6	99.7	372.90	1.105
Air	-79.3	193.90	2.333	$CHCl_3$	30.0	303.20	1.110
Most of the above results are close to 1.4 except for				$CHCl_3$	99.8	373.00	1.150
those shaded.				CCl_4	—	—	1.130
				The above results are between 1.1 and 1.4			

Table 5.9 The number of degrees of freedom *p* for the molecules of a variety of gases predicted from the measured value of γ according to Equation 5.48. Values are plotted only for those gases included in Table 5.8.

Gas	γ	T(K)	*p*	Gas	γ	T(K)	*p*
A: Some monatomic gases				**D: Some triatomic gases**			
He	1.630	273.20	3.17	O_3	1.290	—	6.90
Ar	1.667	273.20	3.00	H_20	1.334	373.20	5.99
Ne	1.642	292.20	3.12	CO_2	1.300	283.20	6.67
Kr	1.689	292.20	2.90	CO_2	1.220	573.20	9.09
Xe	1.666	292.20	3.00	CO_2	1.200	773.20	10.00
Hg	1.666	583.20	3.00	NH_3	1.336	—	5.95
				N_20	1.324	—	6.17
B: Some diatomic gases				H_2S	1.340	—	5.88
H_2	1.407	283.20	4.91	CS_2	1.239	—	8.37
N_2	1.401	293.20	4.99	SO_2	1.260	293.20	7.69
O_2	1.400	283.20	5.00	SO_2	1.200	773.20	10.00
CO	1.297	2073.2	6.73				
NO	1.394	—	5.08	**E: Some polyatomic gases**			
				CH_4	1.313	—	6.39
C: Air				C_2H_6	1.220	—	9.09
Air	1.405	193.90	4.94	C_3H_8	1.130	—	15.4
Air	1.401	283.20	4.99	C_2H_2	1.260	—	7.69
Air	1.357	773.20	5.60	C_2H_4	1.264	—	7.58
Air	1.320	1173.2	6.25	C_6H_6	1.400	293.20	5.00
Air	1.828	273.20	2.42	C_6H_6	1.105	372.90	19.0
Air	2.333	193.90	1.50	$CHCl_3$	1.110	303.20	18.2
				$CHCl_3$	1.150	373.00	13.3
				CCl_4	1.130	—	15.4

Table 5.10 (and Table 2.5) Illustration of the use of the term *accessibility* of quantum states. Notice that increasing the temperature always increases the number of 'accessible' quantum states.

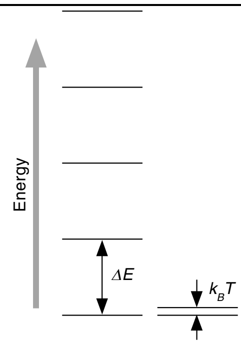
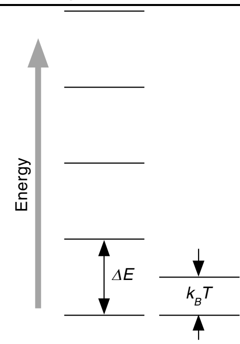
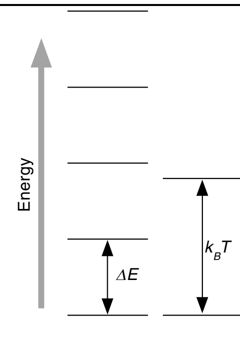
Inaccessible	**Marginal accessibility**	**Fully accessible**
		
$k_B T << \Delta E$	$k_B T \approx \Delta E$	$k_B T >> \Delta E$
e.g. $k_B T < 0.1\Delta E$	e.g. $0.1\ \Delta E < k_B T < 1.5\Delta E$	e.g. $k_B T > 1.5\Delta E$
In this case, only occasionally do molecules make transitions to the higher quantum state. We can consider the degrees of freedom associated with these transitions to be inaccessible.	In this case, molecules make transitions to the higher quantum state. Detailed calculations are required to assess the extent to which the quantum state can be considered accessible	In this case, molecules frequently make transitions to the higher quantum state. We can consider the degrees of freedom associated with these transitions to be fully accessible.
In colloquial terms, the process associated with transitions between quantum states occurs so infrequently that it may generally be ignored.		In colloquial terms, the process associated with transitions between quantum states occurs so frequently that the quantum nature of the states may generally be ignored.

Table 5.11 Measured values of the thermal conductivities of some gases. The units are 10^{-2} W m^{-1} K^{-1}. For example, the thermal conductivity of argon at 273.2 K is 1.63×10^{-2} W m^{-1} K^{-1}.

	Temperature (K)				
Gas	**73.2**	**173.2**	**273.2**	**373.2**	**1273**
Monatomic gases					
Helium, He	5.95	10.45	14.22	17.77	41.90
Neon, Ne	1.74	3.37	4.65	5.66	12.80
Argon, Ar	—	1.09	1.63	2.12	5.00
Krypton, Kr	—	0.57	0.87	1.15	2.90
Xenon, Xe	—	0.34	0.52	0.70	1.90
Radon, Ra	—	—	0.33	0.45	—
Diatomic gases					
Hydrogen, H_2	5.09	11.24	16.82	21.18	—
Fluorine, Fl_2	—	1.56	2.54	3.47	—
Chlorine, Cl_2	—	—	0.79	1.15	—
Bromine, Br_2	—	—	0.40	0.60	—
Nitrogen, N_2	—	1.59	2.40	3.09	7.40
Oxygen, O_2	—	1.59	2.45	3.23	8.60
Carbon monoxide, CO	—	1.51	2.32	3.04	—
Air, N_2/O_2	—	1.58	2.41	3.17	7.60
Polyatomic gases					
Ammonia, NH_4	—	—	2.18	3.38	—
Carbon dioxide, CO_2	—	—	1.45	2.23	7.90
Ethane, C_2H_6	—	1.80	—	—	—
Ethene, C_2H_4	—	1.40	—	—	—
Methane, CH_4	—	1.88	3.02	—	—
Sulpur dioxide, SO_2	—	—	0.77	—	—
Water/Steam, H_20	—	—	1.58	2.35	—

Table 5.12 Calculated and experimental values for κ for argon at various temperatures. Also shown is the inferred value(*a*) for the molecular diameter.

T (K)	Data ($W\ m^{-1}\ K^{-1}$)	Prediction ($W\ m^{-1}\ K^{-1}$)	Ratio	*a* (nm)
173.2	1.09×10^{-2}	5.23×10^{-3}	2.08	0.21
273.2	1.63×10^{-2}	6.57×10^{-3}	2.48	0.19
373.2	2.12×10^{-2}	7.68×10^{-3}	2.76	0.18
1273	5.00×10^{-2}	14.19×10^{-3}	3.52	0.16

Table 5.13 Results from an analysis of the thermal conductivity data assuming the data has the form $\kappa = AT^{x}$. The significance of *a* is discussed in the text.

Gas	*A*	*x*	*a* (nm)
Helium, He	30.91×10^{-4}	0.685	0.108
Neon, Ne	9.14×10^{-4}	0.695	0.198
Argon, Ar	2.34×10^{-4}	0.754	0.391
Krypton, Kr	0.93×10^{-4}	0.806	0.620
Xenon, Xe	0.42×10^{-4}	0.857	0.923
Radon, Ra	0.12×10^{-4}	0.994	1.73

Table 5.14 The speed of sound in a selection of gases listed in order of increasing molecular mass *M* in atomic mass units *u*. The shaded entries in the table are gases that have a 'partner' gas in the table with the same molecular mass. See the text for more details.

Gas	*M*	*T*(K)	c_{sound} (ms^{-1})
Hydrogen, H_2	2.0	273.2	1286
Helium, He	4.0	273.2	971.9
Deuterium, D_2	4.0	273.2	890
Methane, CH_4	16.0	273.2	430
Ammonia, NH_3	18.0	273.2	415
Water (steam), H_2O	18.0	373.2	473
Water (steam), H_2O	18.0	407.2	494
Fluorine, F_2	19.0	373.2	332
Heavy Water (steam), D_2O	20.0	373.2	451
Neon, Ne	20.2	273.2	434
Acetylene, C_2H_2	26.0	273.2	329
Nitrogen, N_2	28.0	273.2	337
Carbon monoxide, CO	28.0	273.2	337
Ethylene, C_2H_4	28.0	273.2	318
Ethane, C_2H_6	30.0	283.2	308
Ethane, C_2H_6	30.0	304.2	316
Nitric oxide, NO	30.0	283.2	324
Nitric oxide, NO	30.0	289.2	334
Oxygen, O_2	32.0	303.2	332
Methanol, CH_3OH	32.0	370.2	335
Hydrogen sulphide, H_2S	33.1	273.2	310
Hydrogen chloride, HCl	36.5	273.2	296
Argon, Ar	40.0	273.2	307.8
Nitrous oxide, N_2O	44.0	298.2	268
Propane, C_3H_8	44.0	273.2	238
Carbon dioxide, CO_2	44.0	273.2	259
Ethanol, C_2H_5OH	46.0	326.2	258
Sulphur dioxide, SO_2	64.0	273.2	211
Chlorine, Cl_2	70.9	293.2	219
Carbon disulphide, CS_2	76.0	273.2	192
Benzene, C_6H_6	78.0	273.2	177
Bromine, Br_2	79.9	331.2	149
Hydrogen bromide, HBr	80.9	273.2	200
Krypton, Kr	83.8	273.2	213
Cyclohexane, C_6H_{12}	84.0	303.2	181
Hydrogen iodide, HI	127.9	273.2	157
Xenon, Xe	131.3	273.2	170
Sulphur hexafluoride, SF_6	146.0	284.2	133
Carbon tetrachloride, CCl_4	153.8	370.2	145
Iodine, I_2	263.8	453.2	138

Table 5.15 Details of gases whose molecules have relative molecular mass of 4 and 28. The table enables a detailed comparison of theoretical expectations and experimental results for the dependence of the speed of sound upon molecular complexity.

Gas	*M*	Number of atoms per molecule	Expected γ	*T*(K)	C_{sound} (theoretical) $\sqrt{(\gamma RT/M)}$	C_{sound} (experimental) Table 5.14
He	4.0	1	1.667 (p=3)	273.2	972.8	971.9
D_2	4.0	2	1.400 (p=5)	273.2	891.5	890.0
N_2	28	2	1.400 (p=5)	273.2	336.9	337.0
CO	28	2	1.400 (p=5)	273.2	336.9	337.0
CH_2CH_2	28	6	1.2 (p=10?)	273.2	≈312	318.0

Table 5.16 The relative dielectric permittivity ε of various gases at atmospheric pressure (1.013×10^5 Pa). For pressures below atmospheric pressure ε varies linearly with pressure. The relative permittivity of vacuum is exactly 1, and all the gases in the table have values of ε within 1% of unity. The table shows the value of $10^4 (\varepsilon - 1)$, which clearly shows the variation between gases. The table also shows the relative molecular mass of the molecules of the gas.

Different experimenters find different values of ε and the data for $10^4 (\varepsilon - 1)$ should all be treated as accurate to only about 10%. The entry for ethanol has two alternative values to indicate two particularly divergent values for $10^4 (\varepsilon - 1)$. For other entries I have taken averages of tabulated results, or ignored entries in tables that were clearly in error.

The data refer to values obtained with electric fields oscillating at radio frequencies, $\approx 10^6$ Hz. The shaded entries in the table, i.e. helium, hydrogen, argon, oxygen, nitrogen, and air, are typical results for ε valid from DC up to optical frequencies $\approx 10^{15}$ Hz. The variation over that range is within ±2 of the least significant figure in the table.

Gas	M	T (°C)	$10^4(\varepsilon - 1)$
Monatomic gases			
Helium, He	4.0	20	0.65
Neon, Ne	20.2	0	1.3
Argon, Ar	40.0	20	5.16
Mercury, Hg	200.6	180	7.4
Mercury, Hg	200.6	180	7.4
Diatomic gases			
Hydrogen, H_2	2.0	0	2.72
Hydrogen, H_2	2.0	20	2.54
Nitrogen, N_2	28.0	20	5.47
Oxygen, O_2	32.0	20	4.94
Air (dry, no CO_2)	28.8	20	5.36
Carbon monoxide, CO	28.0	23	6.92
Triatomic gases			
Carbon dioxide, CO_2	44.0	0	9.88
Carbon dioxide, CO_2	44.0	20	9.22
Carbon dioxide, CO_2	44.0	100	7.23
Nitrous oxide, N_2O	44.0	25	11
Water (steam) H_2O	18.0	100	60
Polyatomic gases			
Ethane, C_2H_6	30.0	0	15
Benzene, C_6H_6	65.0	100	32.7
Methanol, CH_3OH	32.0	100	57
Ethanol, C_2H_5OH	44.0	100	61 or 78
Ammonia, NH_3	18.0	0	8.34
Ammonia, NH_3	18.0	100	4.87

Table 5.17

Thompson's description	What is happening
Starting from the cathode (negative terminal) there is a thin layer of luminosity (1) spread over its surface.	The luminosity is caused by positive ions striking the surface of the cathode.
Next to this there is a comparatively dark space called 'Crookes dark space' (2), the width of which depends on the pressure of the gas, increasing as the pressure diminishes — it also depends, under some conditions on the intensity of the current. The boundary of the dark space is approximately the surface traced out by normals of constant length drawn to the surface of the cathode.	In this region electrons liberated from the cathode (by the impact of positive ions) are being accelerated by the electric field in the tube. They are colliding with atoms and ions in this region but give off no light because they do not have sufficient energy to excite the atoms. The boundary of the region has this form because electrons have travelled in straight lines for a distance of around one ionic mean free path from the cathode.
Beyond the dark space there is a luminous region (3) called the 'negative glow'.	Now electrons *do* have sufficient energy to excite the atoms.
Beyond this again is another comparatively dark region (4) called by some writers the 'second negative dark space' and by others the 'Faraday dark space'. Its length is very variable, even when the pressure is constant.	Having collided inelastically with atoms of the gas in region (3), the electrons lost kinetic energy and are now being accelerated again.
Beyond this again there is a luminous column (5) reaching right up to the anode and called the positive column. When the current and pressure are within certain limits this column exhibits remarkable alternations of dark and bright spaces: these are called striations. In long tubes the positive column constitues by far the greater part of the discharge, for the Crookes space, negative glow and Faraday dark space do not depend markedly on the length of the tube. So that when the length of the discharge is increased, the increase is practically only in the length of the positive column. Thus for example in a tube about 15 metres used by one of us, the positive column occupied the whole of the tube with the exception of two or three centimetres close to the cathode.	The striations are caused by alternating regions of the gas in which: • electrons and ions are accelerated and do not yet have sufficient energy to ionise/excite the atoms of the gas: these are the non-luminous dark regions • electrons and ions accelerated in the above 'dark' regions now have sufficient energy to ionise/excite the atoms of the gas; these are the luminous regions. In some circumstances where the geometry of the acceleration is not very well defined, or where the cathode is heated to created a spread of initial electron velocities, the dark and light striations become blurred and overlap one another.

Table 5.18 The refractive index of various gases as $10^6(n_{light}–1)$ together with the molecular weight of the molecules of the gas. The data refer to gases at STP (P = 0.1013 MPa: T = 0 °C). The refractive index is that appropriate to the bright yellow 'D' lines in the emission spectrum of sodium vapour and varies slightly with frequency.

Gas	*M*	$(n_{light}–1) \times 10^6$
Hydrogen, H_2	2	132
Helium, He	4	36
Methane, CH_4	18	444
Water vapour, H_2O	18	254
Ammonia, NH_4	18	376
Neon, Ne	20	67
Nitrogen, N_2	28	297
Carbon monoxide, CO	28	338
Air	29	293
Nitric oxide, NO	30	297
Oxygen, O_2	32	271
Methanol, CH_3OH	32	586
Hydrogen sulphide, H_2S	34	633
Hydrogen chloride, HCl	36	447
Fluorine, F_2	38	195
Argon, Ar	40	281
Nitrous oxide, N_2O	44	516
Carbon dioxide, CO_2	44	451
Ethanol, C_2H_5OH	46	878
Sulphur dioxide, SO_2	64	686
Chlorine, Cl_2	71	773
Carbon disulphide, CS_2	76	481
Benzene, C_6H_6	78	1762
Hydrogen bromide, HBr	81	570
Krypton, Kr	84	427
Hydrogen iodide, HI	128	906
Xenon, Xe	131	702
Bromine, Br_2	160	1132

Table 5.19 Comparison of the experimental values of the refractive index of gases with the prediction of their refractive index based on Equation 2.17. Before comparing the data, the dielectric constant data have been corrected to STP using factors discussed in §5.6.2. The first three entries in the table are for non-polar gases and the last two are for polar gases. Notice the good agreement between theory and experiment for the non-polar gases, and the massive disagreement for water vapour.

Gas	$10^4(\varepsilon - 1)$	T	Correction factor	$10^4(\varepsilon - 1)$ (STP)	Prediction $10^6(\sqrt{\varepsilon} - 1)$	Experiment $10^6(n_{light} - 1)$
Non-polar gases						
He	0.65	20	293/273	0.70	35	36
Ne	1.3	0	1	1.3	65	67
Ar	5.16	20	293/273	5.54	277	281
Polar gases						
NH_3	8.34	0	1	8.34	416	376
H_2O	60	100	$(293/273)^2$	69.1	3449	254