9f. Properties of Ionic Crystals

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IONIC CONDUCTIVITY AND DIFFUSION IN IONIC CRYSTALS

9f-1. Ionic Conductivity and Diffusion. These phenomena are ascribed to the presence of ionic defects—vacancies where ions are missing from normally occupied positions and ions in interstitial positions in the structure. *Schottky defects* are com-

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[1] Ionic Conductivity and Diffusion.

[2] Dielectric Constants of Inorganic Crystals.

[3] Piezoelectric and Pyroelectric Properties; Ferroelectric and Antiferroelectric Properties.

binations of cation and anion vacancies, as in the alkali halides and alkaline earth oxides. *Frenkel defects* are combinations of vacancies and interstitial ions, for cations as in the silver halides, or for anions as in the alkaline earth halides. At high temperatures the defects exist in thermodynamic equilibrium in the crystal: for Schottky defects in MX crystals, for example, the concentration or mole fraction increases with temperature according to (ref. 23)

$$x = x_0 \exp\left(-\frac{1}{2}\frac{h_f}{kT}\right) \qquad x_0 = \exp\left(\frac{1}{2}\frac{s_f}{k}\right) \tag{9f-1}$$

where h_f and s_f are the enthalpy and entropy of formation of a pair of defects. At lower temperatures the mole fraction is usually controlled by the presence of aliovalent impurities.

The random jumping of a defect gives rise to a *microscopic diffusion coefficient* for the defect of

$$d = d_0 \exp\left(-\frac{\Delta h}{kT}\right) \qquad d_0 = \tfrac{1}{6}\nu a^2 \exp\left(\frac{\Delta s}{k}\right) \tag{9f-2}$$

where ν is an attempt frequency, a is the jump distance, and Δh and Δs are the activation enthalpy and entropy for the jump. (The factor $\frac{1}{6}$ is appropriate for a cubic lattice.) In an electric field there is also a drift *mobility*

$$\mu = \mu_0 \exp\left(-\frac{\Delta h}{kT}\right) \qquad \mu_0 = \left(\frac{q}{kT}\right) d_0 \tag{9f-3}$$

Here μ_0 has been obtained from d_0 with the *microscopic Einstein relation*

$$\frac{d}{\mu} = \frac{kT}{q} \tag{9f-4}$$

The conversion factor is $k/e = 0.862 \times 10^{-4}$ volt/K with d in cm^2/sec and μ in cm^2/volt-sec. Equations (9f-1) to (9f-3) are used to express the observed conductivity and diffusion coefficients in the following sections.

Ionic crystals covered in these tables include halides, simple inorganic radicals (such as nitrates and azides), binary oxides, and the other chalcogenides (sulfides, selenides, and tellurides). Excluded from consideration are III-V compounds, ternary oxides (such as spinels and perovskites), and glasses and zeolites. Conductivity and self-diffusion coefficients are given for pure crystals only, but some information from experiments on doped crystals is contained in Table 9f-2. The effect of high pressure on conductivity and data for mixed electronic and ionic conductors are also presented. Space limitations prevent any consideration of the extensive recent literature on dielectric and anelastic relaxation, thermoelectric phenomena, and effects of radiation and plastic deformation on conductivity and diffusion. Similarly the diffusion of all foreign ions is excluded because of the proliferation of results. Many of the excluded topics are discussed in some of the books and review articles given in the general references.

9f-2. Conductivity for Ionic Conductors. The conductivity can be determined by passage of direct current through the sample if sufficient precautions are taken. More recently, however, most measurements have been made with current pulses of the order of 10^{-2} to 10^{-3} sec duration or alternating currents at frequencies of 1 to 10 kHz, in order to avoid large polarization effects at the electrodes.

In most cases a plot of log σ vs. $1/T$ is approximately a straight line, at least for a limited temperature range, allowing an empirical representation of the data as

$$\sigma = \sigma_0 \exp\left(-\frac{W}{kT}\right) \tag{9f-5}$$

The parameters σ_0 and W are listed in Table 9f-1. The conductivity at the melting temperature has been calculated from Eq. (9f-5) if it is not given in the references.

The values for σ_0 and W are not always so accurate as the number of significant figures would indicate. With good single-crystal or polycrystalline samples of high purity a careful worker can reproduce results within a few percent, but data from different laboratories may differ by 5 to 10 percent, and discrepancies of 50 percent are not uncommon. Hence W may be reliable to a few percent in favorable circumstances or to perhaps 10 percent in less favorable cases, and a discrepancy of 50 percent in σ_0, which is very sensitive to the choice of W, is not surprising. For this reason several representative sets of data, if available, have been given for each substance.

9f-3. Concentration and Mobility of Defects in Ionic Crystals. The conductivity of a crystal containing several types of defects is

$$\sigma = N\Sigma_j q_j x_j \mu_j \tag{9f-6}$$

where N is the number of molecules per unit volume of the perfect crystal, and q_j is the magnitude of the charge of the jth defect. If only one type of defect makes an appreciable contribution to the conductivity, the use of Eqs. (9f-1) and (9f-3) gives the observed form of Eq. (9f-5). In the *intrinsic* region for temperatures near the melting point $W_{\text{intr}} = \frac{1}{2}h_f + \Delta h$ and $\sigma_0 = Nqx_0\mu_0$, and in the *extrinsic* region for lower temperatures $W_{\text{extr}} = \Delta h$ and $\sigma_0 = Nqc\mu_0$ since x is maintained constant at the impurity concentration c. This simple explanation corresponds to the frequent observation of two different temperature ranges with different slopes in the plot of log σ vs. $1/T$, especially for the initial observations on a substance, and the two slopes are often combined to obtain h_f and Δh from the expressions for W_{intr} and W_{extr}. This is presumably the extent of the analysis when only activation enthalpies are given in Table 9f-2. Recent work has shown, however, that such an analysis is at best only tentative because of contributions of other types of ions, association and precipitation of impurities, and overlapping of the different temperature regions.

In early work many transport number determinations were made by electrolysis in order to identify the ions carrying the current. When only one type of ion contributes to the conductivity, these experiments have, in fact, verified Faraday's laws of mass transport to an accuracy of 1 percent. When several types of ions, or both ions and electrons, however, make appreciable contributions, such experiments have not given very reliable results, presumably because of experimental difficulties at the electrodes and at the interfaces between the several samples involved. Hence only a handful of these experiments have been reported in the last ten years, and no separate table of results is provided.

In a few recent investigations of alkali halides an attempt has been made to separate cation and anion contributions to the conductivity by fitting a sum of two terms of the form of Eq. (9f-5) to the observed total conductivity, as indicated by Eq. (9f-6), and some results are given in this form in Table 9f-1. Often measurements of tracer diffusion coefficients allow evaluation of ionic transport numbers, but even these may not be completely unambiguous if vacancy pairs contribute noticeably to diffusion (ref. Ne1). The most reliable results are obtained from analysis of measurements on crystals intentionally doped with aliovalent impurities, with due account taken of mass-action laws, association of charged defects and impurities, and long-range Debye-Hückel interactions (ref. Be1). Most of the results in Table 9f-2 have been obtained in this way.

The temperature dependences of x and μ are given by Eqs. (9f-1) and (9f-3). It should be observed, however, that μ_0 contains a factor $1/T$, which is also carried over into σ_0. For this reason d_0 is listed rather than μ_0 in Table 9f-2: the conversion is obtained immediately from Eq. (9f-4). When the factor of $1/T$ is not explicitly removed from μ_0 or σ_0, the apparent activation energy is smaller than the correct value by kT, which is of the order of 0.05 to 0.15 eV for temperatures from 300 to 1500°C.

9f-4. Effect of Pressure on Conductivity. When the effect of high pressure is taken into consideration, Eqs. (9f-1) and (9f-3) are modified to give

$$x = x_0 \exp\left(-\frac{h_f + Pv_f}{2kT}\right) \qquad \mu = \mu_0 \exp\left(-\frac{\Delta h + P\,\Delta v}{kT}\right) \tag{9f-7}$$

where v_f is the change in volume of the crystal when a pair of Schottky defects is formed, and Δv is the activation volume when a defect moves from one position to another. If only one type of defect contributes appreciably to the conductivity, the pressure dependence of the conductivity is given by

$$\sigma = \sigma_0 \exp\left(-\frac{P\,\Delta V}{kT}\right) \tag{9f-8}$$

where $\Delta V_{\text{intr}} = \frac{1}{2}v_f + \Delta v$, for instance, in the intrinsic range.

The pressure dependence of the original data is expressed by a *pressure coefficient*

$$\alpha = -\left(\frac{\partial \ln \sigma}{\partial P}\right)_T \tag{9f-9}$$

The corresponding *free volume* from Eq. (9f-8) is

$$\Delta V = RT\alpha = 82.0 \times T \times \alpha$$

with ΔV in cm³/mole and α in atm⁻¹. Values of pressure coefficients and free volumes are given for a number of substances in Table 9f-3.

9f-5. Mixed Electronic and Ionic Conductors. Many ionic crystals have an appreciable electronic conductivity in addition to their ionic conductivity. Exclusive ionic conductivity occurs for nearly all halides (the cuprous halides being the only noteworthy exception) and for crystals with simple inorganic radicals. Beryllia also has mainly ionic conductivity, but the other alkaline earth oxides show progressively larger amounts of electronic conductivity, especially at higher temperatures. The only other predominantly ionic conductors are crystals with the fluorite structure such as calcia-stabilized zirconia and even sodium sulfide, perhaps some rare-earth-type trioxides such as scandia and neodymia, and a new class of complex sulfides typified by Ag_3SI. Appreciable, but not exclusive, ionic conductivity is displayed by the cuprous halides, some simple metal oxides such as alumina and tetragonal zirconia, and most rare-earth oxides such as ceria and dysprosia. Traces of ionic conductivity (a few percent) are present in the copper and silver chalcogenides. Electronic conductivity (by electrons or holes) is dominant in transition-metal oxides such as Cr_2O_3, and in all other divalent chalcogenides such as ZnO and PbS.

It should be clear that a fairly complicated situation exists when both electronic and ionic defects are present to an appreciable extent in a crystal. The treatment of the various interactions (refs. 21 and 22) shows that the defect structure may be profoundly influenced by the atmosphere surrounding the crystal or by deviations from stoichiometry of the crystal. Hence conductivity results are practically meaningless unless these conditions are specified, and similar remarks apply to diffusion. Fortunately much more attention has been devoted in recent years to control and measurement of the environment, and this information is provided where pertinent in Tables 9f-5 and 9f-6 in one of three ways: saturation of one constituent by contact with the metal or high vapor pressure of a volatile component, measurement of the oxygen partial pressure, or determination of the deviation from stoichiometry.

Several experimental techniques have been used to distinguish between electronic and ionic conductivity (ref. 56). (1) The earliest was direct determination of mass transport by electrolysis, but this has often been unreliable (ref. He1) and is seldom used at present. (2) Polarization effects are often observed; namely, the a-c conductivity at moderately high frequencies like 100 kHz is considerably less than the d-c conductivity. The simplest assumption is that the a-c value is due to the electronic conductivity only, whereas the d-c value represents the total conductivity (ref. Ve3). Despite the appeal of this interpretation the results are usually ambiguous, and much clarification is needed to make this method reliable (ref. Mc1). (3) If the potential drop between the electrodes is kept below the decomposition voltage of the sample, it may be assumed that an ionic current cannot flow to the electrode, and the remaining current is then ascribed to electronic conductivity (refs. Wa5, Wa6). This method appears to be fairly reliable in some cases, but note must be taken of the range of chemical potentials occurring in such experiments. (4) If the conductivity is completely ionic, an emf that can be calculated from thermodynamic data should be established when the ends of the sample are at different chemical potentials (ref. Wa2), and this has been amply verified for calcia-stabilized zirconia, for instance. If some electronic conductivity is also present, part of the emf is effectively short-circuited out, and hence the reduction of the observed emf below the thermodynamic value gives an indication of the amount of electronic transport (ref. Sc6). This method is the most commonly used, especially for oxides, and appears to give a reliable estimate of the average transport number if care is taken to establish a well-defined chemical potential at each end of the sample and to ensure thermodynamic equilibrium. An unfortunate aspect of this method is that it does not distinguish between electrons and holes for the electronic part of the conductivity, or between different types of ions for the ionic conductivity, but often other information is available. (5) The amount of ionic conductivity can be calculated from tracer diffusion coefficients with the Einstein relation if the charge on the defect and the correlation factor are known (see Sec. 9f-7). Since the last two items require a rather detailed knowledge of the diffusion mechanism, this approach is most often useful to establish an order of magnitude, especially when the ionic conductivity is very much smaller than the electronic part.

Table 9f-4 gives in most cases the *total conductivity*, which can often be determined more accurately than the transport numbers. Table 9f-5 gives the *ionic transport numbers*, which are defined as the fraction of the total current carried by ions. The two tables should be used together to obtain an estimate of the magnitude and nature of the conductivity for a particular substance. Substances have been listed only when there is some information about the ionic part of the conductivity; thus the numerous articles dealing solely with semiconducting behavior in ionic crystals such as ZnO and CdS are not included.

9f-6. Diffusion. The tracer diffusion coefficient for an ion which can diffuse by means of several types of defects is

$$D_T = \Sigma_j f_j x_j d_j \tag{9f-10}$$

where f_j is the correlation factor (see Sec. 9f-7) and x_j and d_j are given by Eqs. (9f-1) and (9f-2). When only a single mechanism is important, the temperature dependence is given by

$$D_T = D_0 \exp\left(-\frac{W}{kT}\right) \tag{9f-11}$$

and this form is usually used to represent experimental results. Empirically determined values of D_0 and W are given in Table 9f-6.

In the intrinsic region the parameters in Eq. (9f-11) are given by

$$D_0 = \tfrac{1}{6}\nu a^2 x_0 f \exp\left(\frac{\frac{1}{2}s_f + \Delta s}{k}\right) \quad \text{and} \quad W = \tfrac{1}{2}h_f + \Delta h \tag{9f-12}$$

Theoretical estimates indicate that W should be several electron volts, as observed, and that $\frac{1}{2}s_f + \Delta s$ should be at most a few entropy units, leading to a value of $D_0 \sim 10^{-3}$ to 10 cm²/sec. When an appreciably different value of D_0 is obtained empirically, it is usually an indication that some disturbing influence, such as impurities or grain-boundary diffusion, is dominating over the assumed thermodynamic equilibrium for volume diffusion.

Since the temperature dependence is the same for all types of defects, indirect methods must be used to distinguish a particular type of defect; this has been done with considerable success in many instances, as indicated in Table 9f-6. Some of these methods are (1) determination of the influence of aliovalent impurities in doped crystals, (2) study of correlation effects as described in Sec. 9f-7, and (3) observation of the effect of varying the stoichiometry or ambient pressure of one of the constituents of the crystal.

Among experimental methods for measuring diffusion coefficients with radioactive or isotopic tracers, *sectioning* is the most direct and reliable. *Surface counting, gaseous exchange,* and *solution exchange* are more sensitive but sometimes less reliable. Other methods of detection involve changes in *optical absorption, X-ray emission,* and *semiconducting properties* or observation of *additive coloration* or *electrotransport.* The line width in *nuclear magnetic resonance* allows a determination of the temperature dependence and an estimate of the magnitude of diffusion for stable nuclei. The rate of *oxidation* and *sintering* processes can also be used to evaluate diffusion coefficients when the process is sufficiently well understood.

The remarks concerning the accuracy of the results for ionic conductivity apply here with even more need for caution. For most halides pure single crystals are available, the melting points are not excessively high, and the influence of the surrounding atmosphere is often unimportant (ref. 50); hence in favorable cases an accuracy approaching that for the conductivity may be realized. For the usually semiconducting and often refractory chalcogenides, however, the situation is much less favorable. The high melting temperatures and difficulties of obtaining pure materials suggest that very few intrinsic properties have yet been observed for these substances (ref. 54). Furthermore the influence of grain boundaries is just beginning to be investigated, and yet a number of measurements have been made on sintered or pressed powder samples with porosities up to 5 or 10 percent. Finally the defect structure is strongly influenced by any excess or deficit of the constituents, as discussed in Sec. 9f-5. The data in Table 9f-6 may nonetheless be useful both as a survey of existing experimental efforts and as a stimulus to better understanding.

9f-7. Correlation Effects in Diffusion. Both the ionic conductivity and diffusion of a charged defect are caused by the jumping of the defect through the crystal, and the connection of these two phenomena is given by the microscopic Einstein relation in Eq. (9f-4). If a single type of defect is responsible for all the observed conductivity and diffusion, Eqs. (9f-6) and (9f-10) may be combined (without the correlation factor) to give a *macroscopic Einstein relation* that defines $D_{\text{conductivity}}$.

$$D_{\text{conductivity}} = \left(\frac{kT}{Nq^2}\right)\sigma \qquad \text{(9f-13)}$$

In many instances this relationship is at least approximately satisfied, but there are four ways in which deviations may occur. (1) There may be another contribution to the conductivity, such as an electronic part or another type of ionic defect. (2) There may be neutral complexes of defects, such as vacancy pairs in the alkali halides, which contribute to the diffusion but not to the conductivity. (3) In the diffusion of tracers there are correlations in the random-walk motion of tracer atoms that lead to correlation factors, as first described by Bardeen and Herring (ref. Ba2). (4) In interstitialcy mechanisms there are also different displacements for the tracer atom and for the charge of the defect. This displacement effect is usually included with the genuine correlation effects to give an overall correlation factor for interstitialcy mechanisms.

The *experimental correlation factor* is defined by

$$f = \frac{D_{\text{tracer}}}{D_{\text{conductivity}}}$$

Theoretical correlation factors may be calculated by considering the geometry of the diffusion mechanism and of the lattice (see refs. below). Comparison of experimental and theoretical values will then often point to a particular mechanism for diffusion. Experimental and theoretical correlation factors are presented in Table 9f-7.

Guide to references on theoretical correlation factors.
General treatment: 24, Ba2, Co2, Co3, Ho10
Vacancy mechanisms: Ba2, Co2, Fr1, Sc8
Interstitial and interstitialcy mechanisms: Co3, Fr2, Mc2
Vacancy pairs and impurity complexes: Co2, Ho10, Le1, Li1
Anisotropic lattices: Co2, Gh1, Hu1, Hu2, Md1, Mu3
Disordered lattices: Ri2, Yo3
Diffusion by nuclear magnetic resonance: Ei2, St5
Isotope effects: Le2, Th1

TABLE 9f-1. CONDUCTIVITY FOR IONIC CONDUCTORS

[The conductivity is given as $\sigma = \sigma_0 \exp(-W/kT)$.]

Substance	Form	T_m, °C	$\sigma(T_m)$, (ohm-cm)$^{-1}$	T range, °C	σ_0, (ohm-cm)$^{-1}$	W, eV	Specific reference	Other references
ALKALI HALIDES								
LiH	sc	688	4×10^{-2}	480–630	4×10^{7}	1.72	Pr1	
				240–480	1	0.53	Pr1	
LiD	sc	....	....	480–630	1×10^{7}	1.72	Pr1	
LiF	sc	842	2.4×10^{-3}	540–720	$6 \times 10^{9}/T$	2.07	Ja6	Be7, Be8, Ha19, Le5, St7
				340–540	$5 \times 10/T$	0.70	Ja6	
	sc	....	1.5×10^{-3}	560–750	$1.6 \times 10^{9}/T$	1.99	Ba7	
				330–560	$4.5 \times 10^{10}/T$	1.65	Ba7	
LiCl	sc	606	9×10^{-3}	480–570	2.5×10^{6}	1.47	Ha19	Le5
	pc	....	1.8×10^{-3}	400–550	2.5×10^{5}	1.42	Gi1	
				30–350	1.2	0.59	Gi1	
LiBr	sc	550	1.8×10^{-2}	440–540	1.4×10^{6}	1.29	Ha19	
	pc	....	1.4×10^{-2}	350–500	4.2×10^{5}	1.22	Gi1	
				30–300	3.3	0.56	Gi1	
	sc	....	....	160–360	8×10^{-2}	0.43	Al3	
LiI	sc	452	5×10^{-2}	340–420	9.6×10^{5}	1.05	Ha19	
	pc	....	7×10^{-2}	250–350	1.8×10^{5}	0.92	Gi1	
				30–150	1.4×10^{-1}	0.36	Gi1	
NaF	pc	992	3×10^{-3}	330–980	1.3×10^{3}	1.42	Ph1	Le5
NaCl	sc	800	1.0×10^{-3}	520–740	$4.7 \times 10^{8}/T$	1.86^c	Fu3	Bi2, Br5, Do6, Dr2, Et1, Ja4, Ka4, Ko1, La4, Ma6, Le1
				520–740	$1.2 \times 10^{9}/T$	2.07^a	Fu3	
			1.2×10^{-3}	720–800	$2.4 \times 10^{10}/T$	2.19	Ne1	
				550–650	$9.2 \times 10^{8}/T$	1.92	Ne1	
				275–425	$3/T$	0.65	Ne1	
NaBr	sc	755	1.2×10^{-3}	450–700	$2.1 \times 10^{8}/T$	1.68	Ma6	Le5, Ph1 Sc2
				300–450	$3.5 \times 10^{2}/T$	0.84	Ma6	
	sc	....	2.1×10^{-3}	610–730	$2.3 \times 10^{8}/T$	1.64	Ho8	
				490–570	$3 \times 10^{2}/T$	0.80	Ho8	
NaI	pc	661	2.1×10^{-3}	350–600	8.1×10^{3}	1.23	Ph1	Le5
				170–350	6×10^{-2}	0.60	Ph1	
KF	sc	846	6×10^{-4}	660–790	2×10^{7}	2.34	Ka1	Le5
				400–500	4×10^{-1}	1.02	Ka1	
KCl	sc	768	2.4×10^{-4}	570–750	$4.1 \times 10^{6}/T$	1.66^c	Fu4	As3, Be2, Bi4, Gr4, He4, Le5, Me2, Ph2, Pe1, Wa4
				570–750	$5.6 \times 10^{10}/T$	2.36^a	Fu4	
	sc	....	1.4×10^{-4}	340–640	$2.3 \times 10^{8}/T$	1.90	Mi4	
	sc	....	4.5×10^{-5}	480–680	$5.9 \times 10^{7}/T$	1.88	Al4	
KBr	sc	728	1.3×10^{-4}	300–700	$3.1 \times 10^{8}/T$	1.91^c	Da9	Gr4, Le5, Pe1, Ph2
				300–700	$7.1 \times 10^{9}/T$	2.21^a	Da9	
	sc	....	2.1×10^{-4}	440–680	1.1×10^{6}	1.93	Ro4	
	sc	....	1.0×10^{-4}	560–680	7.9×10^{5}	1.97	Ho9	
KI	sc	680	1.0×10^{-3}	430–600	$1.4 \times 10^{7}/T$	1.69^c	Pe1	Bi4, Ec1, He4, Le5, Ph2
				430–600	$1.6 \times 10^{12}/T$	2.31^a	Pe1	
	sc	....	2.1×10^{-4}	450–650	1.6×10^{6}	1.87	Ka1	
RbCl	sc	717	1.3×10^{-5}	550–700	$3.6 \times 10^{6}/T$	1.58^c	Fu3	Le5, Pi1
				550–700	$8.8 \times 10^{11}/T$	2.55^a	Fu3	
RbBr	sc	681	3.4×10^{-5}	....	1.8×10^{6}	2.03	Le5	
CsF	pc	684	1.1×10^{-2}	550–660	1.6×10^{5}	1.55	Ha6	
				330–550	2	0.85	Ha6	
CsCl (α)	sc	636	6.1×10^{-5}	480–610	$1.0 \times 10^{8}/T$	1.67	Ar3	Ar2
	pc	....	7×10^{-6}	470–580	1	0.95	Ha6	
CsCl (β)	sc	tr. 469	....	250–480	$8.0 \times 10^{7}/T$	1.33	Ar3	Ha6, Ha9, He4, Ho6
	sc	....	....	150–460	1.0×10^{2}	1.05	Mo7	
CsBr	sc	636	2.6×10^{-3}	475–590	2.5×10^{5}	1.44	Ly1	
				300–475	2.5×10^{4}	1.28	Ly1	
	pc	....	4×10^{-4}	340–620	1×10^{3}	1.15	Ha6	
CsI	sc	621	1.9×10^{-3}	480–595	2.2×10^{5}	1.43	Ly1	Be10, Ec1, Ha6
				300–480	1.4×10^{4}	1.25	Ly1	
	sc	....	2.1×10^{-3}	300–550	1.1×10^{5}	1.37	Ho7	
OTHER MONOVALENT HALIDES								
NH_4Cl	sc	....	....	40–170	4.4×10^{5}	1.15	He4	
NH_4Br	pp	....	....	70–150	2.6	0.83	He4	
NH_4I	pp	....	....	0–130	1.9×10^{7}	1.23	He4	

TABLE 9f-1. CONDUCTIVITY FOR IONIC CONDUCTORS (*Continued*)

Substance	Form	T_m, °C	$\sigma(T_m)$, (ohm-cm)$^{-1}$	T range, °C	σ_0, (ohm-cm)$^{-1}$	W, eV	Specific reference	Other references
OTHER MONOVALENT HALIDES (*Cont.*)								
AgCl	sc	455	3.5×10^{-2}	160–380	$3.9 \times 10^7/T$	0.99^c	Ab1	Ab2, Co4,
				160–380	$5.0 \times 10^4/T$	0.78^i	Ab1	Sh6, Wa9
	sc	....	4.6×10^{-2}	50–250	$2.8 \times 10^7/T$	0.97^c	Mu1	
				50–250	$7.1 \times 10^8/T$	0.78^i	Mu1	
	sc	....	1.3×10^{-1}	225–400	2.4×10^8	0.93	Eb1	
AgBr	sc	422	1.3×10^{-1}	20–180	$6.3 \times 10^7/T$	0.87^c	Mu1	Ku3, Lu1,
				20–180	$4.9 \times 10^6/T$	0.68^i	Mu1	Mi1, Te1,
	sc	....	7.0×10^{-1}	345–410	1.1×10^8	1.13	Fr2	Wa6, Wa10
				250–345	1.4×10^6	0.89	Fr2	
				140–250	2.1×10^4	0.70	Fr2	
AgI (α)	pc	555	2.7	220–530	5.5	0.051	Kv5	Li3
	pc	....	2.7	145–555	9.2	0.064^x	Bi3	
AgI (β)	sc^e	tr. 146	....	85–145	6×10^7	0.97	La2	Li3, Mr1
				15– 85	5×10^2	0.61	La2	
	sc^a	....	....	90–145	3×10^7	0.93	La2	
				20– 90	1.3	0.40	La2	
TlCl	sc	427	6.6×10^{-3}	375–425	$8.8 \times 10^6/T$	0.87	Fr4	Ha10, Le5,
				325–380	$2.3 \times 10^6/T$	0.80	Fr4	Ph2, Sa1
				235–330	$1.15 \times 10^6/T$	0.76	Fr4	
	sc	....	5.7×10^{-3}	200–350	$8.6 \times 10^5/T$	0.75	Ja8	
TlBr	pc	458	1.0×10^{-3}	295–420	3.8×10^4	1.10	He3	Le5, Mo6,
				175–295	4.0×10^2	0.80	He3	Sa1
	pc	....	2.0×10^{-3}	150–400	2.2×10^2	0.73	Ph2	
TlI(α)	pc	438	1.4×10^{-3}	163–400	4.2×10	0.63	Ph2	
TlI(β)	pc	tr. 163	....	90–163	2.5×10^{-2}	0.41	Ph2	Sa1
MIXED HALIDES								
Na_2CdCl_4	pc	....	....	230–350	2.8×10^3	0.86	Ja7	
KHF_2 (β)	pc	239	....	195–225	1.1×10^5	0.91	Da6	
KAg_4I_5	pc	253	3.4×10^{-1}	40–250	$3.1 \times 10^3/T$	0.13	Br2	Ow1
K_2BaCl_4	pc	662	....	500–635	1.6×10^6	1.54	Kr2	Sc10
K_2BaBr_4	pc	....	....	430–600	7.1×10^4	1.33	Ja7	
$RbAg_4I_5$	pc	228	8.6×10^{-1}	20–220	$1.1 \times 10^4/T$	0.14	Br3	Ow1
$(NH_4)_2SnCl_6$	sc	....	....	20–180	4.0×10^{-3}	0.30	He4	
NH_4PF_6	pp	....	....	20–160	7.7×10^3	1.03	He4	
Cu_2HgI_4 (α)	pp	....	....	67– 80	3.3×10^3	0.59	Su2	Ja2
Cu_2HgI_4 (β)	pp	tr. 67	....	15– 66	2.2×10^{-1}	0.39	Su2	
Ag_2HgI_4 (α)	pp	....	....	50– 80	7.5×10^3	0.44	Su2	Ne2
	pp	....	....	50– 84	1.8×10^6	0.61	We3	
Ag_2HgI_4 (β)	pp	tr. 50	....	10– 50	1.4×10^6	0.71	Su2	Ma5
	pp	....	....	22– 35	9.9×10^4	0.65	Ne2	
POLYVALENT HALIDES								
CaF_2	sc	1418	2.9	620–980	$1.1 \times 10^{10}/T$	2.13	Ba6	Ar4, As1,
	sc	....	2.7	560–1000	$5.6 \times 10^9/T$	2.04	Ur1	Ch2, Ni1,
				200–560	3×10^{-1}	0.80	Ur1	So3
SrF_2	sc	1190	1.6×10^{-1}	700–1010	$5.6 \times 10^9/T$	2.14	Ba6	Bo3, Cr1,
	sc	....	5×10^{-2}	510–800	2.6×10^4	1.65	Ar4	Ni1
				50–510	2×10^{-1}	0.9	Ar4	
$SrCl_2$	sc	873	5.0×10^{-2}	380–660	$1.8 \times 10^7/T$	1.25	Ba6	
	sc	....	2	650–780	$3 \times 10^{17}/T$	3.2	Ho5	
				400–500	$3 \times 10/T$	0.4	Ho5	
BaF_2	sc	1287	2.2	620–900	$6.8 \times 10^8/T$	1.64	Ba8	Ba6
				300–620	$7.2 \times 10^7/T$	1.49	Ba8	
			1.3×10^{-1}	50–800	1.3×10^3	1.24	Ar4	
$BaCl_2$	pp	950	6×10^{-4}	310–760	3.5×10^{-2}	0.43	Ja3	
$BaBr_2$	pc	847	1.4×10^{-3}	390–750	1.0×10^{-1}	0.41	Ja7	
$CdCl_2$	pc	568	1.1×10^{-1}	260–520	1.6×10^5	1.03	Ja7	Bi6
HgI_2 (α)	pc	....	....	127–150	1.1×10^7	0.43	Ja2	
HgI_2 (β)	pc	tr. 126	....	92–125	3.8×10^{14}	0.96	Ja2	
$PbCl_2$	sc	500	4.0×10^{-8}	340–440	2.5×10^3	0.89	De8	Sc9
				200–340	3.5×10^{-2}	0.30	De8	
	pc	....	....	175–350	8.7	0.40	Si1	
$PbBr_2$	sc	373	2.2×10^{-4}	230–330	$4.9 \times 10^4/T$	0.71	Ve1	
				60–140	$4.8/T$	0.36	Ve1	
PbI_2	sc	402	4.0×10^{-4}	210–270	2×10^5	1.30	Da8	
				170–210	2×10^{-1}	0.71	Da8	
	sc^c	....	1.2×10^{-6}	270–400	2.1×10^4	1.24	Se7	
	sc^a	....	9×10^{-5}	180–370	6×10^{-2}	0.38	Se7	

TABLE 9f-1. CONDUCTIVITY FOR IONIC CONDUCTORS (*Continued*)

Substance	Form	T_m, °C	$\sigma(T_m)$, (ohm-cm)$^{-1}$	T range, °C	σ_0, (ohm-cm)$^{-1}$	W, eV	Specific reference	Other references
POLYVALENT HALIDES (*Cont.*)								
$AlCl_3$	pc	189	2.4×10^{-6}	150–189	3.8×10^{13}	1.76	Bi5	
	pc	....	1.1×10^{-6}	160–189	2×10^{4}	0.85	Se11	
$GaCl_3$	pc	78	1.5×10^{-8}	60–70	2.5×10^{12}	1.21	Gr3	
$GaBr_3$	pc	122	1.5×10^{-6}	80–100	3.4×10	0.52	Gr3	
GaI_3	pc	211	6×10^{-5}	190–205	6.7×10^{18}	2.23	Gr3	
LaF_3	sc	1490	....	160–560	$3/T$	0.084	Sh3	
				20–80	$2 \times 10^{6}/T$	0.46	Sh3	
SIMPLE INORGANIC RADICALS								
Li_2SO_4	pc	860	3.0	575–800	1.2×10^{2}	0.36	Kv2	Kv1, Kv3
LiN_3	pp	....	....	172–280	4.3×10^{7}	1.87	Ga1	Ja1
				90–170	5.3×10^{-2}	0.53	Ga1	
$NaNO_2$	sc^e	....	....	163–190	1.4×10^{5}	1.15	As2	
		tr. 163	....	130–160	2.5×10^{12}	1.85	As2	
	sc^f	....	....	163–200	1.4×10	0.64	So1	
		tr. 163	....	40–163	1.0×10	0.68	So1	
$NaNO_3$	sc^c	306	5×10^{-6}	240–300	4.0×10^{13}	2.17	Ra2	Bi7
				20–230	1.3×10	0.94	Ra2	
	sc^c	....	5×10^{-6}	250–280	3×10^{22}	3.08	Ma7	
				40–240	3.6×10	0.87	Ma7	
$NaBrO_3$	sc	dec 315	....	182–298	1.6×10^{-9}	1.1	Ra1	
				50–162	9×10^{-6}	0.46	Ra1	
Na_2C_2	pp	dec 797	....	190–270	1.3×10^{4}	0.97	An3	
NaN_3	sc^c	....	....	270–330	2.5×10^{7}	1.82	To2	Ja1
				100–270	1.0×10^{-2}	0.87	To2	
	sc^a	....	....	230–400	1.0×10^{-1}	0.87	To2	
				130–230	1.0×10^{-4}	0.56	To2	
KNO_3	sc^c	334	....	130–165	1.0×10^{2}	0.80	As2	Cl1
		tr. 130	....	90–130	2.3	0.80	As2	
KCN	sc	634	1.0×10^{-4}	320–630	2.8×10^{3}	1.34	Lo2	
				160–320	3.4×10^{-1}	0.93	Lo2	
KCNS	sc	175	3×10^{-6}	120–175	3.1×10^{18}	2.13	Lo1	Pl1
				20–120	4.4×10^{7}	1.30	Lo1	
KN_3	pp	....	....	40–160	2.0×10^{7}	1.36	To1	
				120–230	4×10^{4}	1.30	Ja1	
$CsNO_3$	pc	404	2.0×10^{-3}	270–390	1.3×10^{5}	1.05	Bi8	
				220–270	2×10^{2}	0.74	Bi8	
	sc	....	....	160–210	6×10^{-5}	0.20	So2	
		tr. 154	....	35–130	8	0.72	So2	
NH_4NO_3	pp	....	....	125–143	3.8×10^{4}	0.68	Br6	
		tr. 125	....	48–124	3.1×10^{6}	0.96	Br6	
		tr. 84	....	48–84	4.8×10	0.75	Br6	
NH_4ClO_4	pp	....	....	50–110	3.5×10^{5}	1.15	Zi2	
$CuSO_4$	pp	dec 770	6×10^{-4}	500–570	2.8×10^{7}	2.21	Ja3	
$AgNO_3$	pc	208	5×10^{-1}	206–208	....	....	Ce2	
	pc	....	....	164–207	1×10^{12}	1.46	Da7	
Ag_2SO_3	pp	dec 100	....	40–80	5×10^{2}	0.80	Za1	
Ag_2SO_4 (α)	pp	656	6×10^{-2}	430–600	3.6×10^{3}	0.70	Ha12	Ja3
Ag_2SO_4 (β)	..	tr. 425	....	200–410	8.0×10^{-1}	0.42	Ha12	
$Ag_2C_2O_4$	pp	....	....	40–100	8.3×10^{-2}	0.70	Bo2	
	pp	....	....	....	1.0×10^{-6}	0.46	Fi1	
AgN_3	pp	....	....	180–250	2	0.46	Gr2	Ba10
	pp	....	....	25–110	3.3×10^{4}	0.82	Za2	
$Ca(N_3)_2$	pp	....	....	80–110	4.8	0.94	To1	
	pp	....	....	20–100	2.8×10^{-10}	0.23	Ja1	
$Sr(N_3)_2$	pp	....	....	30–110	2.0×10^{-11}	0.22	Ja1	
$Ba(N_3)_2$	sc^d	....	....	80–130	3×10^{-6}	0.56	To3	Ja1
	sc^e	....	....	70–110	2×10^{-7}	0.41	To3	
$ZnSO_4$	pp	761	1.4×10^{-6}	504–761	2.4	1.28	Ja3	
$PbSO_4$	pp	1080	8×10^{-4}	625–810	5.1×10^{2}	1.56	Ja3	

Form of Sample:

sc	single crystal
pc	polycrystalline
pp	pressed powder
tr.	transition
dec	decomposes

Crystal Directions:

sc^a ∥ a axis
sc^c ∥ c axis
sc^d ⊥ (100) plane
sc^e ⊥ (001) plane
cs^f ∥ ferroelectric axis

Activation Energy Notes:

^{a}Anion vacancy contribution
^{c}Cation vacancy contribution
^{i}Interstitial cation contribution
^{z} $\sigma = \sigma_0 \exp(-W/kT)\,[1 + \exp(-W/kT)]^{-1}$

TABLE 9f-2. CONCENTRATION AND MOBILITY OF DEFECTS IN IONIC CRYSTALS

Substance	T range, °C	x_0	h, eV	Defect	d_0, cm²/sec	Δh, eV	Defect	Method	Specific reference	Other references
ALKALI HALIDES										
LiH	240–630	...	2.38	Schottky	...	0.53	V_{Li}'	con	Pr1	Be9 Ei1, Ja6, St4
LiF	400–700	9.2×10	2.42	Schottky	1.6×10^{-1}	0.73	V_{Li}'	con	Ba7	
	460–840	5.0×10^{2}	2.68	Schottky	$5.2 \times 10^{-5} \times T$	0.65	V_{Li}'	con	Ha19	
	500–800	...	...	...	...	1.0	$V_{\mathrm{F}}^{\cdot}$	nmr	St7	
LiCl	310–570	1.7×10^{3}	2.12	Schottky	$2.8 \times 10^{-5} \times T$	0.41	V_{Li}'	con	Ha19	
LiBr	270–540	8.1×10^{2}	1.80	Schottky	$3.9 \times 10^{-5} \times T$	0.39	V_{Li}'	con	Ha19	
	160–360	...	2.0	Schottky	...	0.43	V_{Li}'	nmr	Al3	
LiI	180–420	5.0×10^{2}	1.34	Schottky	$5.6 \times 10^{-5} \times T$	0.38	V_{Li}'	con	Ha19	
NaF	250–650	...	3.0	Schottky	$\geq 2.0 \times 10^{-3}$	0.52	V_{Na}'	nmr	Pe2	Ma2
NaCl	250–720	2.2×10	2.12	Schottky	4.1×10^{-1}	0.80	V_{Na}'	con	Dr1	Bi2, Ch3, Et1, Ja5, Ka4, Ki3, Pi1, St10
	250–790	3.4	2.17	Schottky	3.7×10^{-1}	0.66	V_{Na}'	con	Al5	
	250–790	...	...	...	2.0×10^{2}	1.15	$V_{\mathrm{Cl}}^{\cdot}$	con	Al5	
	400–550	8	0.95	V_{Na}'	...	...	...	dis	Da4	
	630–760	3.0×10^{4}	1.30	$(V_{\mathrm{Na}}V_{\mathrm{Cl}})^{x}$	1.7×10^{-2}	1.25	Cl into $(V_{\mathrm{Na}}V_{\mathrm{Cl}})^{x}$	die	Ec3	
NaBr	490–730	8.3	1.68	Schottky	7.8×10^{-1}	0.80	V_{Na}'	con	Ho8	Ma6, Sc2
KF	400–790	...	2.64	Schottky	...	1.02	V_{K}'	con	Ka1	
KCl	400–700	3.5×10	2.22	Schottky	4.8×10^{-1}	0.84	V_{K}'	con	Dr1	Al4, Bi4, Ch3, Ka1, Ma12, Pe1, Wa4
	270–640	1.5×10	2.26	Schottky	1.1×10^{-1}	0.71	V_{K}'	con	Be1	
	270–640	...	...	...	9.1	1.04	$V_{\mathrm{Cl}}^{\cdot}$	con	Be1	
	560–760	4.4×10	2.31	Schottky	1.1	0.95	$V_{\mathrm{Cl}}^{\cdot}$	dif	Fu2	
	250–350	~1	0.7	V_{K}'	...	...	...	dis	Ka2	Ka3
	640–770	4.5×10^{5}	1.34	$(V_{\mathrm{K}}V_{\mathrm{Cl}})^{x}$	1.1×10^{-3}	1.04	Cl into $(V_{\mathrm{K}}V_{\mathrm{Cl}})^{x}$	die	Sa2	Ec2
KBr	440–680	1.4×10^{2}	2.53	Schottky	9.1×10^{-2}	0.66	V_{K}'	con	Ro4	Ch3, Ka1, Ma12, Pe1
	440–680	...	...	...	7.4×10^{-1}	0.87	$V_{\mathrm{Br}}^{\cdot}$	con	Ro4	
	410–680	7.7×10	2.40	Schottky	7.9×10^{-1}	0.83	V_{K}'	con	Ho9	
	600–730	5.5×10^{5}	1.41	$(V_{\mathrm{K}}V_{\mathrm{Br}})^{x}$	2.3×10^{-2}	1.19	Br into $(V_{\mathrm{K}}V_{\mathrm{Br}})^{x}$	die	Ec3	
KI	350–580	...	1.59	Schottky	...	1.21	V_{K}'	con	Ec1	Ch3, Pe1
RbI	230–260	...	2.00	Schottky	...	...	...	con	Ch3	
CsCl (α)	480–610	...	2.1	Schottky	...	0.7	$V_{\mathrm{Cl}}^{\cdot}$	con	Ar2	
CsCl (β)	280–460	...	1.86	Schottky	...	0.6	V_{Cs}'	dif	Ha9	Ar2, Mo7
	280–460	...	...	...	...	0.34	$V_{\mathrm{Cl}}^{\cdot}$	dif	Ha9	
CsBr	320–550	...	2.0	Schottky	...	0.58	V_{Cs}'	cdf	Ly1	
	320–550	...	...	...	...	0.27	$V_{\mathrm{Br}}^{\cdot}$	cdf	Ly1	
CsI	300–500	...	2.14	Schottky	...	0.67	V_{Cs}'	dif	Ho7	Be10, Ly1
	300–500	...	...	...	...	0.3	$V_{\mathrm{I}}^{\cdot}$	con	Ho7	
OTHER HALIDES										
AgCl	160–380	1.6×10^{2}	1.44	Ag Frenkel	5.7×10^{-3}	0.27	V_{Ag}'	con	Ab1	Ab2, Eb1, Mu1
	160–380	...	...	...	7.2×10^{-4}	0.055	$\mathrm{Ag}_i^{\cdot}$	con	Ab1	
	300–440	...	...	...	2.1×10^{-4}	0.008	collin. instlcy.	dif	We1	
	300–440	...	...	...	7.5×10^{-4}	0.13	noncoll. instlcy.	dif	We1	
	20–60	...	0.82	$(V_{\mathrm{Ag}}V_{\mathrm{Cl}})^{x}$	...	1.0	Cl into $(V_{\mathrm{Ag}}V_{\mathrm{Cl}})^{x}$	con	La6	
AgBr	200–300	5.3×10^{2}	1.13	Ag Frenkel	1.5×10^{-2}	0.30	V_{Ag}'	con	Te1	Ku3, Mu1
	200–300	...	...	...	1.2×10^{-2}	0.17	$\mathrm{Ag}_i^{\cdot}$	con	Te1	
	200–330	...	...	...	2.5×10^{-4}	0.058	collin. instlcy.	dif	We1	Fr2
	200–330	...	...	...	3.0×10^{-2}	0.27	noncoll. instlcy.	dif	We1	
	300–400	4×10^{-3}	1.62	Schottky	...	...	...	...	Kr1	

AgI (α)............	150– 250	....	0	Ag disorder	....	0.057	$Ag_i^{\cdot}$	con	Li3	
AgI (β)............	20– 140	....	0.69	Ag Frenkel	....	0.14	$Ag_i^{\cdot}$	con	Li3	Mr1
TlCl............	200– 330	5.5×10	1.36	Schottky	2.2×10^{-3}	0.44	V_{Tl}'	spc	Ja8	Ch8, Fr4
	280– 400	....	....	....	0.9×10^{-4}	0.105	$V_{Cl}^{\cdot}$	spc	Ja8	
CaF₂............	640– 920	6.0×10^{3}	2.81	F Frenkel	1.2×10^{1}	1.64	F_i'	con	Ur1	
	250– 650	....	....	....	$9 \times 10^{-8} \times T$	0.60	$V_F^{\cdot}$	con	Ur1	
	230– 980	6×10^{3}	2.4	F Frenkel	....	0.9	$V_F^{\cdot}$	con	Ba6	
SrF₂............	370–1010	....	2.3	F Frenkel	....	1.0	$V_F^{\cdot}$ or F_i'	con	Ba6	Bo3, Cr1
SrCl₂............	180– 660	1×10^{3}	1.8	Cl Frenkel	4×10^{-3}	0.4	$V_{Cl}^{\cdot}$	con	Ba6	
BaF₂............	350– 650	2.1×10	1.86	F Frenkel	5.5×10^{-3}	0.56	$V_F^{\cdot}$	con	Ba8	Ba6, Ma2,
	150– 500	....	....	....	3.5×10^{-1}	0.79	F_i'	con	Ba9	Ni1
PbCl₂............	160– 310	~~4.6×10^{-1}~~	1.16	Schottky	$1.4 \times 10^{-6} \times T$	0.60	V_{Pb}''	con	Sc9	De8
	160– 310	....	....	$V_{Pb}'' + 2V_{Cl}^{\cdot}$	$2.6 \times 10^{-7} \times T$	0.12	$V_{Cl}^{\cdot}$	con	Sc9	
PbBr₂............	60– 330	....	1.44	$V_{Pb}'' + 2V_{Br}^{\cdot}$	....	0.29	$V_{Br}^{\cdot}$	con	Ye1	
LaCl₃............	20– 440	5.8×10	0.28	$V_{La}^{x} + 3V_F^{x}$	....	0.42	$V_F^{\cdot}$	thx	Sh3	
SIMPLE INORGANIC RADICALS										
NaNO₃............	120– 300	....	2.46	Na Frenkel	....	0.94	$Na_i^{\cdot}$	con	Ra2	
NaN₃............	100– 330	....	1.90	Schottky	....	0.87	V_{Na}'	con	To2	
KNO₃............	130– 330	7×10^{-1}	1.04	K Frenkel	$8 \times 10^{-6} \times T$	0.40	V_K'	con	Cl1	
CsNO₃............	220– 390	....	0.62	....	....	0.74	....	con	Bi8	
Ag₂C₂O₄............	50– 110	....	....	Ag Frenkel	$7 \times 10^{-7} \times T$	0.82	V_{Ag}'	con	Bo2	
OXIDES										
SrO............	1040–1340	....	2.0	$\frac{1}{2}O_{2(g)} \rightarrow O_i' + h^{\cdot}$	....	0.6	O_i'	P1	Co8	
	700–1100	....	3.0	$V_O^{\cdot} + O_i'$	....	0.6	O_i'	P2	Co8	
ZnO............	900–1025	1.2×10^{3}	2.78	Zn Frenkel	$3.3 \times 10^{-6} \times T$	1.78	Zn_i'	dif	Sn2	
CdO............	630– 850	....	6.5	$2V_O^{\cdot\cdot} + Cd_{Cd}'' + 2Cd_C{}' + O_O^{x} + O_{2(g)}$	....	2.7	$V_O^{\cdot\cdot}$	dif	Ha17	
Al₂O₃............	1670–1900	....	6.8	$2V_{Al}''' + 3V_O^{\cdot\cdot}$	....	.....	....	dif	Oi1	
						2.2	V_{Al}'''	dif	Pa1	
TiO₂............	1000–1500	....	9.6	$Ti_i^{\cdot\cdot\cdot} + 3e' + O_{2(g)}$	....	.....	....	sem	Bl2	
Nb₂O₅ (α)............	800–1160	....	2.8	$V_O^{\cdot} + e' + \frac{1}{2}O_{2(g)}$	....	1.2	$V_O^{\cdot}$	con	Ch4	Ch3
Cr₂O₃............	1040–1550	....	3.9	$V_{Cr}''' + Cr_i^{\cdot\cdot} + h^{\cdot}$	....	1.3	V_{Cr}''' or $Cr_i^{\cdot\cdot}$	cdf	Ha1	
UO₂............	320– 850	....	3.1	$V_O^{\cdot\cdot} + O_i$	....	1.3	O_i'' instlcy.	dif	Be4	
	100– 800	....	....	....	....	2.3	V_U'''' or $U_i^{\cdot\cdot\cdot\cdot}$	con	Na1	
SULFIDES AND TELLURIDES										
Na₂S............	350– 800	....	1.77	Na Frenkel	....	0.76	V_{Na}' or $Na_i^{\cdot}$	cdf	Mo2	
	350– 800	....	....	....	....	1.17	$V_S^{\cdot\cdot}$	cdf	Mo2	
Cu₂S (β)............	130– 210	8×10^{-4}	0	V_{Cu}'	$3.6 \times 10^{-1} \times T$	0.26	V_{Cu}'	sem	Yo1	
CdTe............	700–1000	1.7×10^{-4}	1.04	$V_{Cd}' + Cd_i^{\cdot}$	....	.....	....	sem	De5	

Method:

cdf	Ionic conductivity and diffusion	nmr	Nuclear magnetic resonance	P1	$P_{O_2} = 10^{-3}$ to 1 atm
con	Ionic conductivity in doped samples	sem	Semiconducting properties	P2	$P_{O_2} = 10^{-12}$ to 10^{-4} atm
die	Dielectric relaxation	the	Ionic thermoelectric effect	P3	$P_{O_2} = 10^{-5}$ to 1 atm
dif	Diffusion with tracers	thx	Thermal expansion		
dis	Charged dislocations	spc	Space charge polarization		

TABLE 9f-3. EFFECT OF PRESSURE ON CONDUCTIVITY

I. PRESSURE COEFFICIENT $\alpha = -(\partial \ln \sigma / \partial P)_T$

Substance	Form	T range, °C	P range, kiloatm	$\alpha_3 \times 10^4$, atm^{-1}	Comments	Specific reference	Other references
NaCl	sc	600–700	0–5	3.7	intrinsic	Bi2	
	sc	220–510	0–10	1.33	extrinsic	Pi1	
KCl	sc	550–700	0–5	5.1	intrinsic	Bi4	
	sc	220–400	0–10	1.46	extrinsic	Pi1	Ta12
KI	sc	400–630	0–5	5.3	intrinsic	Bi4	
RbCl	sc	300	0–5	4.0	extrinsic	Pi1	
CuBr (β)	pc	380	0–0.15	0.29	Cu electrodes	Bi1	
CuBr (γ)	pc	250–380	0–0.15	1.2	Cu electrodes	Bi1	
AgCl	sc	144–336	0–8	1.3 to 2.6	intrinsic	Ab2	Ne3
	sc	200–350	0–1.5	3.6 to 4.5	Ag diffusion	Mu6	Sh7
AgBr	sc	202–406	0–2	1.2 to 2.1	intrinsic	Ku3	
	pc	250–350	0–0.15	3.3 to 3.9	....	Wa1	Sc3
AgI (α)	pc	191	0–0.15	0.37	....	Wa1	
		400	0–0.15	0.15	....	Wa1	Li3
AgI (β)	pc	110–130	0–0.03	−1.9 to −12	....	Li3	
	pc	110–135	0–0.15	−2.2 to − 2.8	....	Wa1	Pa8, Ri4, Sc7
	pp	90	0–2.0	−7.1	Ag diffusion	Mu5	
	pc	20	3–7	5.8 to 5.4	High P phases	Ne3	
Ag_2HgI_4 (α)	pp	65–85	0–4	−2.1	....	We3	
		65–85	4–8	5.0 to 4.3	High P phases	We3	
KNO_3	pp	200–320	0–0.5	2.0 to 2.8	....	Cl2	
ZrO_2 (monocl.)	pp	600–800	10–30	−1.1	....	Wh1	
		1000	0–5	−3.9	....	Wh1	

II. FREE VOLUMES

Substance	T range, °C	P range, kiloatm	$v_{formation}$, cm^3/mole	Defect	Δv_{motion}, cm^3/mole	Defect	Specific reference	Other references
NaCl	400–700	0–5	43	Schottky	9.5	V_{Na}'	Bi4	
	220–510	0–10	....	....	7.7	V_{Na}'	Pi1	Bi2, Sh8
KCl	400–700	0–5	67	Schottky	10	V_K'	Bi4	
	220–490	0–10	....	....	7.0	V_K'	Pi1	Ta12
	685, 745	7–17	....	....	11.7	$V_{Cl}^{\cdot}$	Ra3	
AgCl	30–350	0–8	16.7	Ag Frenkel	4.7	V_{Ag}'	Ab2	
	30–350	0–8	....	....	3.2	$Ag_i^{\cdot}$	Ab2	
AgBr	200–290	0–8	16	Ag Frenkel	7.4	V_{Ag}'	Ku3	
	200–290	0–8	....	....	2.6	$Ag_i^{\cdot}$	Ku3	
	350–410	0–5	43	Schottky	20	$V_{Br}^{\cdot}$	Ta10	
KNO_3	200–330	0–0.5	8 to 11	K Frenkel	4 to 9	V_K'	Cl2	

TABLE 9f-4. CONDUCTIVITY FOR MIXED CONDUCTORS

Total conductivity $\sigma = \sigma_0 \exp(-W/kT)$

Substance	Form	T_m, °C	T range, °C	σ_0, (ohm-cm)$^{-1}$	W, eV	Environment	Specific reference	Other references
HALIDES								
CuCl	sc	426	100– 400	6.3×10^6	1.06	Cu	Hs1	Tu2, Wa7
CuBr (α)	pc	491	470– 491	6.5	0.039	Cu	Bi3	
CuBr (β)	pc	tr. 470	379– 450	2.0×10	0.21	Cu.	Bi1	Wa7
CuBr (γ)	pc	tr. 379	230– 379	2.8×10^{10}	1.47	Cu	Bi1	Wa3, Wa7
CuI (α)	pc	602	402– 440	8	0.20	Cu	Bi1	Wa7
CuI (β)	pc	tr. 402	370– 400	2×10^7	1.09	Cu	Bi1	Wa7
CuI (γ)	pc	tr. 369	330– 369	1.8×10^{10}	1.52	Cu	Bi1	Wa7, We4
Ag_2HgI_4 (β)	pp	tr. 50	27– 48	7.5×10^8	0.89	Ag	We3	
OXIDES						P_{O_2} (atm)		
BeO	pc	.....	1100–1300	$1.6 \times 10^5/T$	2.52	air	De3	Br1, Pr3
			600–1100	$2.8 \times 10^{-2}/T$	0.69	air	De3	
	sp	.....	1380–1600	$4.7 \times 10^6/T$	3.12	air	Cl4	
MgO	sc	.....	930–1500	1.3^i	2.00^i	O_2, air	Mi3	Bu1, Da5
	sc	.....	770–1300	1.8×10^3	2.7	10^{-8}	Mi2	
	sc	.....	400– 750	1.3×10^3	2.8	10^{-7}	Le6	
CaO	sc	2550	1000–1300	2.9×10	1.73	$\sim 10^{-4}$	Gu2	Pa2
	sc	.....	770–1150	8×10^7	3.5	vacuum	Su3	
SrO	sp	.....	1040–1340	2.8×10^2	1.6	1	Co8	Su3
				$\sigma \propto P_{O_2}{}^{1/4}$	.....	10^{-3} to 1	Co8	
			790–1100	2.0×10^2	2.1	10^{-12} to 10^{-5}	Co8	
BaO	sc	.....	440– 730	4×10^{-2}	0.5	vacuum	Do2	
Al_2O_3	sc, pc	.....	750–1320	8×10^{-3}	1.9	air	Ma9	Ch1, Da3, Fl1, Ha7, Ha8, Pe4
	sc	.....	1625–1725	5.1×10^9	5.5	10^{-5}	Pa5	
			1300–1600	9.1×10	2.62	10^{-5}	Pa5	
Sc_2O_3	pp	.....	800–1300	....	1.70	air	No1	
Y_2O_3	sp	.....	1200–1600	8×10^2	1.94	10^{-1}	Ta8	No1
				$\sigma \propto P_{O_2}{}^{3/16}$	.....	10^{-1} to 10^{-7}	Ta8	
La_2O_3 (hex)	pp	2315	400– 700	4.6×10^6	0.67	air	Me1	No1
(cub)	.....	tr. 590	350– 580	1.5×10^{10}	1.05	air	Me1	
ZrO_2 (tetr)	sc	.....	1500–1780	2.1×10^6	3.3	air	An2	Mc1, Ve2
			1150–1340	6.7×10^{-2}	0.74	air	An2	
ZrO_2:CaO (15%)	sp	.....	100–1100	1.4×10^2	1.13	10^{-9}	Ve3	Di1, Jo1, Ki1, St9
ZrO_2:$YO_{1.5}$ (20%)	sp	.....	700–1350	1.8×10^2	0.83	air	St9	
HfO_2	sp	.....	1000–1600	9.3×10	1.45	1	Ro1	
				$\sigma \propto P_{O_2}{}^{0.19}$	.....	1 to 10^{-4}	Ro1	
HfO_2:CaO (12%)	sp	.....	800–2000	1.8×10^3	1.43	max. cond.	Jo1	
HfO_2:$YO_{1.5}$ (16%)	sp	.....	900–1600	8×10^2	1.12	max. cond.	Be11	
CeO_2	sc	.....	130–1000	1.5×10^3	1.28	air	Vi1	No1
ThO_2	sp	3050	800–1100	1.1×10	1.41	10^{-10} to 10^{-22}	La3	Da1
ThO_2:$YO_{1.5}$ (15%)	sp	.....	800–1100	3.1×10	0.92	10^{-6} to 10^{-22}	La3	
Pr_2O_3 (hex)	pp	.....	720– 850	....	0.86	dry H_2	Me1	No1
(cub)	pp	tr. 780	700– 780	....	0.84	dry H_2	Me1	
Nd_2O_3 (hex)	pp	.....	400– 700	....	0.75	air	Me1	No1
(cub)	pp	tr. 550	400– 540	....	1.26	air	Me1	
Sm_2O_3	pp	.....	800–1300	....	1.17	air	No1	
Eu_2O_3	pp	.....	800–1300	....	1.24	air	No1	
Gd_2O_3	pp	.....	800–1300	....	1.36	air	No1	
Tb_4O_7	pp	.....	800– 900	....	0.40	air	No1	
Dy_2O_3	pp	.....	800–1300	....	1.39	air	No1	
Er_2O_3	pp	.....	800–1300	....	1.40	air	No1	
Yb_2O_3	pp	.....	800–1300	....	1.53	air	No1	
SULFIDES, SELENIDES, AND TELLURIDES								
Na_2S	sp	1169	520– 800	3.4×10^7	1.64	H_2	Mo2	
			350– 520	8.0×10	0.75	H_2	Mo2	
Cu_2S (β)	....	tr. 470	110– 470	$9 \times 10^4/T$	0.24	....	Mi5	Ha16, We2
	pc	.....	400	$\sigma_i = 2.4$	.....	Pt, Cu	Yo2	Yo1
Cu_2Se	pc	.....	580– 750	3×10^i	0.17^i	$Cu_{1.96}Se$	Ce1	
Ag_2S (α)	pc	835	180– 300	$2.9 \times 10^4/T^i$	0.11^i	....	Ok1	He1
Ag_2S (β)	....	tr. 179	130– 160	1.3×10^8	0.71	Ag	Mi6	Ri1
			130– 170	1.4×10^6	0.69	S	Mi5	
Ag_3SBr	sp	.....	100– 250	8^i	0.24^i	Ag	Re4	
Ag_3SI (α)	sp	700	235– 400	2	0.04	Ag	Re4	Ta1
Ag_3SI (β)	sp	tr. 235	0– 80	2.9	0.14	Ag	Ta4	Ta5
Ag_2Se (α)	pc	.....	130– 300	$1.7 \times 10^4/T^i$	0.10^i	....	Ok1	Mi7
Ag_2Se (β)	pc	tr. 133	100– 130	3.4×10^i	0.39^i	Ag	Mi9	
Ag_2Te (α)	....	.....	165– 225	9×10^4	0.31	....	Mi8	
Ag_2Te (β)	pc	.....	80– 140	6×10^4	0.56	....	Mi9	Ta6

Form of Sample:
sc single crystal
pc polycrystalline
pp pressed powder
sp sintered powder

Conductivity:
[i] Ionic portion of conductivity.

TABLE 9f-5. TRANSPORT NUMBERS FOR MIXED CONDUCTORS

Substance	T, °C	Transport numbers			Form	Environment	Specific reference	Other references
HALIDES		$t_c = 1 - t_i$						
CuCl	150	[1]0.008	[2]0.04		[1]pc	Cu	[1]Ma3	Wa7
	250	0.027	0.85		[2]pc	Cu, Cu_2O	[2]Tu2	
	350	0.51	0.99					
CuBr (α)	470– 491	1.00			pc	Cu	Tu3	
CuBr (β)	390– 445	1.00			pc	Cu	Tu3	Wa7
CuBr (γ)	100	[1]0.004	[2]0.01	[3]0.005	[1]pc	Cu	[1]Ma3	Wa7
	200	0.042	0.10	0.032	[2]pc	Cu, Cu_2O	[2]Tu3	
	300	0.26	0.87	0.36	[3]pc	Cu, Cu_2O	[3]Ki4	
	390	0.25	1.00	0.65				
CuI (α)	402– 500	1.00			pc	Cu	Tu1	Wa7
CuI (β)	375– 400	0.99			pc	Cu	Tu1	Wa7
CuI (γ)	200	[1]0.003	[2]0.00		[1]pc	Cu, Cu_2O	[1]Ma3	Wa7, We4
	300	0.004	0.25		[2]pc	Cu	[2]Tu1	
Ag_2HgI_4 (α)	50– 84	0.97			pp	Ag, Pt	We3	
Ag_2HgI_4 (β)	27– 48	0.4			pp	Ag, Pt	We3	
Ag_2SO_4 (α)	602	$t_e = 3 \times 10^{-3}$			....	P_{O_2} = 10 to 700 torr	Hal2	
	446	$t_h = 1 \times 10^{-4}$			....	P_{O_2} = 0.1 to 700 torr	Hal2	
OXIDES		$t_c = 1 - t_e$			....	P_{O_2} (atm)		
Cu_2O	800–1000	$(2 \text{ to } 5) \times 10^{-4}$			pp	Cu	Gu1	
BeO	1000–1200		[2]1.00	[3]0.80 to 0.96	[1]sp	10 to 10^{-8}	[1]Cl3	
	1200–1300	[1]0.94		1.00	[2]pp	O_2, air	[2]Pa2	
	1400–1700	1.00			[3]pp	O_2, $CO - CO_2$	[3]Pa2	
MgO	900	[1]1.0		[3]0.57	[1]sc	O_2, air	[1]Mi3	Sc4
	1100	0.9		0.91	[2]sc	10^{-4}	[2]Sc6	
	1300	0.5	[2]0.87	0.63	[3]pp	O_2, $CO - CO_2$	[3]Pa2	

CaO	900		[2]0.57	[3]0.02	[1]pp	O_2, air	[1]Pa2	
	1100	[1]0.52	0.91	0.02	[2]pp	O_2, CO − CO_2	[2]Pa2	
	1300	0.61	0.63	0.02	[3]sc	$\sim 10^{-4}$	[3]Gu2	
SrO	1000	[1]0.03	[2]0.68		[1]pp	O_2, air	[1]Pa2	
	1150	0.08	0.89		[2]pp	O_2, CO − CO_2	[2]Pa2	
BaO	200- 700	0.0			sc	vacuum	Do2	
		$t_i = 1 - t_e - t_h$			....	P_{O_2} (atm)		
Al_2O_3	800-1300	0.9 to 0.0			sc	O_2, air	Ma9	
	1100-1300	1.0 to 0.0			sp	1 to 10^{-11}	Sc6	
Sc_2O_3	800-1000	1.0			sp	10^{-12}, 10^{-17}	Sc6	
Y_2O_3	700- 800	0.3 to 0.15			sp	10^{-15}	Ta8	
	1200-1600	0.00			sp	10^{-1} to 10^{-17}	Ta8	
	825	≥ 0.5			sp	6×10^{-5} to 3×10^{-22}	Ta11	
La_2O_3	400-1000	~ 1			pp	air	Me1	
		$t_a = 1 - t_e - t_h$			....	P_{O_2} (atm)		
ZrO_2 (tetr)	1300-1600	0.9 to 0.4			sp	10^{-5} to 10^{-11}	Ve2	
	1140-1340	0.6 to 0.2			sp	10^{-11} to 10^{-14}	Me1	
ZrO_2 (monocl)	990	4.5×10^{-3}			sc	0.4	Ma1	Ta7
ZrO_2:CaO (15%)	1000	≥ 0.99			sp	1 to 10^{-15}	St1	Ve3
	800	[1]$t_h = 10^{-2.5}$ to $10^{-3.3}$	[2]$t_e = 10^{-6.6}$ to $10^{-4.9}$		[1]sp	1 to 10^{-6}	Pa6	
	1000	$t_h = 10^{-1.7}$ to $10^{-3.4}$	$t_e = 10^{-6.0}$ to $10^{-2.7}$		[2]sp	10^{-10} to 10^{-20}	Pa6	
ZrO_2:$YO_{1.5}$ (20%)	900-1100	$t_e \leq 0.01$			sp	air or H_2	Br4	Sm1, Tr1
HfO_2	1000	0.71 to 0.94			sp	10^{-6} to 10^{-15}	Ro1	St1
	1000	0.01 to 0.03			....	1 to 10^{-3}	Ro1	
	1400	0.06 to 0.13			....	1 to 10^{-3}	Ro1	
	1000-1500	0.00			sp	1 to 10^{-18}	Ta9	
HfO_2:$YO_{1.5}$ (16%)	800-1050	1.0			sp	10^{-10} to 10^{-15}	Be11	Vo1
$Nb_2O_5(\alpha)$	1000-1200	0.03			sp	1 to 10^{-5}	El1	

TABLE 9f-5. TRANSPORT NUMBERS FOR MIXED CONDUCTORS (*Continued*)

Substance	T, °C	Transport numbers	Form	Environment	Specific reference	Other references
		$t_c = 1 - t_e - t_h$	....	P_{O_2} (atm)		
Cr_2O_3	980–1550	5.7×10^{-4} to 1.2×10^{-3}	sp	N_2	Ha1	
MnO	1010	1×10^{-5}	sp	Mn	Bo1	
FeO	720–1020	1.4×10^{-5} to 2.6×10^{-4}	pc	$Fe_{0.887}O$	De6	Ha11
		$t_a = 1 - t_e - t_h$	....	P_{O_2} (atm)		
CeO_2	450–1300	$0 < t_a < 1$	sp	air	Ho4	No2, Vi2
CeO_2: $LaO_{1.5}$ (30%)	1000–1100	1.00	sp	air	Ne4	Ta3
ThO_2	1000	0.06 to 0.93	sp	1 to 10^{-9}	La3	Da1, St1
	1000	1.00 to 0.96	sp	10^{-12} to 10^{-21}	La3	
ThO_2: $YO_{1.5}$ (15%)	1000	≥ 0.99	sp	10^{-5} to 10^{-24}	St1	La3, Su1, Wi1
	800	[1]$t_h = 10^{-2.7}$ to $10^{-3.2}$ [2]$t_e = 10^{-5.7}$	[1]sp	1 to 10^{-10}	Pa6	
	1000	$t_h = 10^{-4.7}$ to $10^{-2.7}$ $t_e = 10^{-4.4}$	[2]sp	10^{-5} to 10^{-25}	Pa6	
UO_2	900–1100	4×10^{-6} to 1.2×10^{-4}	sp	$UO_{2.0003}$	Do3	Ii1

		$t_i = 1 - t_e - t_h$	....	P_{O_2} (atm)		
Nd_2O_3	800-1000	1.00	pp	10^{-12}, 10^{-17}	Sc6	
Sm_2O_3	800-1000	1.00	pp	10^{-12}, 10^{-17}	Sc6	
Gd_2O_3	800-1100	$0 < t_i < 1$	....	....	Ra4	
Dy_2O_3	800-1100	$0 < t_i < 1$	....	....	Ra4	
Yb_2O_3	800-1000	1.00	pp	10^{-12}, 10^{-17}	Sc6	
SULFIDES, SELENIDES, AND TELLURIDES		$t_c = 1 - t_e$				
Na_2S	350- 800	1.00	sp	....	Mo2	
Cu_2S	134- 207	0.05 to 0.15	....	....	Yo1	Hi2, Ku4, Wa8, We2
	400	0.86	pc	Pt, Cu	Yo2	
Cu_2Se	580- 750	0.06 to 0.11	pc	$Cu_{1.96}$ Se	Ce1	
Cu_2Te	335- 410	1×10^{-4}	....	....	Re3	
Ag_2S (α)	200	$t_c = 10^{-2}$ to 10^{-3} $t_a = 10^{-8}$	....	....	Wa2	
Ag_2S (β)	130- 160	0.011	....	Ag	Mi6	Bu3
	130- 170	0.59	....	S	Mi6	Hel
Ag_3SBr	100- 250	0.98 to 0.93	sp	Ag	Re4	
Ag_3SI (α)	300	0.95	sp	Ag	Re4	Ta1, Ta2
Ag_3SI (β)	100- 200	0.995 to 0.986	sp	Ag	Re4	Ta4
Ag_2Se (α)	220	2×10^{-3}	....	Ag	Mi7	Bu2
Ag_2Se (β)	124	1×10^{-7}	pc	Ag	Mi9	
Ag_2Te (α)	270	0.010	pc	Ag	Yo2	Mi8
Ag_2Te (β)	100	4×10^{-7}	....	Ag	Mi9	Ta6
ZnSe	200- 400	0.08 to 0.13	sc	Fe − FeO, Cu − Cu_2O	Ki4	

Form of Sample:

sc	single crystals
pc	polycrystalline
pp	pressed powder
sp	sintered powder

Transport Numbers:

t_i	Ionic	t_e	Electron
t_c	Cation	t_h	Hole
t_a	Anion		

TABLE 9f-6. DIFFUSION IN IONIC CRYSTALS

[The diffusion coefficient is given as $D = D_0 \exp(-W/kT)$.]

Substance	Form	Isotope	T range, °C	D_0, cm²/sec	W, eV	Defect	Method	Environment	Comments	Specific reference	Other references
ALKALI HALIDES											
LiF	sc	^{7}Li	560–770	2.3	1.81	V_{Li}'	nmr			Ei1	Ma2, St6
			360–560	4.5×10^{-7}	0.71	V_{Li}'	nmr	…	…	Ei1	
NaF		^{19}F	600–790	6.1×10	2.2	$V_F^{\cdot}$	nmr	…	…	Ei1	St7
	pw	^{23}Na	550–650	1.6×10	2.0	V_{Na}'	nmr	…	…	Pe2	Ma2
			250–400	2.3×10^{-7}	0.52	V_{Na}'	nmr	…	…	Pe2	
NaCl	sc	^{22}Na	600–720	2.9×10	1.97	V_{Na}'	sct	…	…	Be5	Ba4, Do6, Ei3, La5, Ma6
	sc	^{22}Na	670–770	1.8×10	2.10	V_{Na}'	sct	single vacancy		Ne1	
			670–770	1.1×10^{3}	2.35	$(V_{Na}V_{Cl})^x$	sct	vacancy pair		Ne1	
	sc	^{36}Cl	520–745	2.2	2.07	$V_{Cl}^{\cdot}$	sct	single vacancy		La4 Fu3	Ba5, La5
			520–745	9.9×10^{2}	2.50	$(V_{Na}V_{Cl})^x$	sct	vacancy pair			
NaBr	sc	^{24}Na	425–700	6.7×10^{-1}	1.53	V_{Na}'	sct	…	…	Ma6	
	sc	^{82}Br	450–690	5.0×10^{-3}	2.02	$V_{Br}^{\cdot}$	sct	…	…	Sc2	Do1
KF	pp	^{42}K	580–840	2	1.78	V_K'	sct	…	…	La5	
KCl	sc	^{42}K	450–750	4×10^{-2}	1.48	V_K'	sct	…	…	La5	Ar6, Wi3
	sc	^{36}Cl	560–760	3.6×10	2.10	$V_{Cl}^{\cdot}$	sct	single vacancy		Fu2	Ba3, La5, Ra3
			560–760	8.6×10^{3}	2.65	$(V_K V_{Cl})^x$	sct	vacancy pair		Fu2	
KBr	sc	^{42}K	470–730	1×10^{-2}	1.26	V_K'	sct	…	…	La5	
	sc	^{82}Br	400–700	3×10^{4}	2.61	$V_{Br}^{\cdot}$	gax	…	…	Da10	Do1, La5
KI	sc	^{42}K	430–690	1×10^{-6}	0.64	V_K'	sct	…	…	No6	La5
	sc	^{131}I	430–690	1.2×10^{-8}	1.12	$V_I^{\cdot}$	sct	…	…	No6	La5
RbCl	sc	^{86}Rb	600–760	3.3×10	1.99	V_{Rb}'	sct	…	…	Ar1	Ma4
CsF	pc	^{137}Cs	480–640	3.1	1.67	$\{V_{Cs}'\}$	sct	…	…	La5	
CsCl (α)	pp	^{137}Cs	465–620	1×10^{-1}	1.39	$\{V_{Cs}'\}$	sct	…	…	La5	
	pp	^{36}Cl	465–620	7×10^{-1}	1.56	$\{V_{Cl}^{\cdot}\}$	sct	…	…	La5	
CsCl (β)	sc	^{137}Cs	280–460	2.4×10	1.53	V_{Cs}'	sfc	…	…	Ha9	La5
	sc	^{36}Cl	280–460	1.5	1.27	$V_{Cl}^{\cdot}$	sfc	…	…	Ha9	Ho6, La5
CsBr	sc	^{134}Cs	320–550	1.5×10	1.54	V_{Cs}'	sct	…	…	Ly1	
	sc	^{82}Br	415–530	3.9	1.42	$V_{Br}^{\cdot}$	sct	…	…	Ly1	
CsI	sc	^{134}Cs	320–550	1.4×10	1.53	V_{Cs}'	sct	…	…	Ly1	Ho7, Kl5
	sc	^{131}I	410–540	2.1	1.37	$V_I^{\cdot}$	sct	…	…	Ly1	Kl5
OTHER MONOVALENT HALIDES											
CuI (α,β)	pp	^{131}I	370–500	7.5	1.48	$\{V_I^{\cdot}\}$	sfc	…	…	No3	
CuI (γ)	pp	^{131}I	350–370	5.0×10^{4}	1.96	$\{V_I^{\cdot}\}$	sfc	…	…	No3	
AgCl	sc	^{110}Ag	380–440	6.5×10^{2}	1.13	$V_{Ag}' + Ag_i^{\cdot}$	sct	interstitialcy		We1	Co4, Re1
			300–380	1.8	0.92	$V_{Ag}' + Ag_i^{\cdot}$	sct	interstitialcy		We1	
	sc	^{36}Cl	300–450	8.5×10	1.57	$V_{Cl}^{\cdot}$	sct	…	…	La1	Co4, No5

AgBr	sc	^{110}Ag	345– 410	6.8×10^{2}	1.10	$V_{Ag}' + Ag_i^{\cdot}$	sct	interstitialcy		Fr2	Mi1, Mu4, Se6, St2, St3
			250– 345	5.7×10	0.97	$V_{Ag}' + Ag$	sct	interstitialcy		Fr2	
			140– 250	1.3	0.79	$V_{Ag}' + Ag_i$	sct	interstitialcy		Fr2	
	sc	^{82}Br	370– 415	9.4×10^{5}	2.53	$V_{Br}^{\cdot}$	sct	....	....	Ta10	
			332– 370	3.0×10^{4}	1.93	$V_{Br}^{\cdot}$	sct	....	....	Ta10	
AgI (α)	pp	^{110}Ag	145– 220	1.6×10^{-4}	0.097	V_{Ag}'	sct	cation disorder		Jo3	Ba1, Zi1
	pp	^{131}I	145– 540	4.4×10^{-4}	0.70	$\{V_I^{\cdot}\}$	sfc	....	....	No4	Jo3, Jo4
AgI (β)	pp	^{110}Ag	20– 145	3.2×10^{-1}	0.62	$\{V_{Ag}' + Ag_i^{\cdot}\}$	slx	....	....	Jo3	Mu5, Zi1
	sc	^{131}I	80– 140	4.7×10^{-10}	0.29	$\{V_I^{\cdot}\}$	sct	....	‖ *a* axis	La2	
		^{131}I	50– 140	$D = (8.2 \text{ to } 3.4) \times 10^{-4}$	.....	$\{V_I^{\cdot}\}$	sct	....	‖ *c* axis	La2	
AgI (γ)	pp	^{110}Ag	20– 147	5×10^{-4}	0.37	$\{V_{Ag}' + Ag_i^{\cdot}\}$	slx	....	....	Jo3	
Ag$_2$HgI$_4$ (α)	pc	^{111}Ag	40– 110	1.8	0.47	V_{Ag}'	sfc	cation disorder		Zi1	
		^{203}Hg	50– 160	5×10^{-3}	0.89	V_{Hg}''	sfc	cation disorder		Zi1	
TlCl	sc	^{204}Tl	290– 390	6.2×10^{-1}	1.10	V_{Tl}'	sct	....	....	Fr4	Fr3
	sc	^{36}Cl	270– 420	3.1×10^{-2}	0.77	$V_{Cl}^{\cdot}$	sct	....	....	Fr4	
POLYVALENT HALIDES											
CaF$_2$	sc	^{45}Ca	800–1250	1.3×10^{2}	3.75	$\{V_{Ca}''\}$	sct	....	....	Ma11	Sh9
	sc	^{18}F	670– 950	1.9×10	1.91	$V_F^{\cdot} + F_i'$	sfc	....	....	Ma10	
		^{18}F	360– 670	1.1×10^{-4}	0.91	$V_F^{\cdot}$	sfc	....	....	Ma10	
CaCl$_2$	sc	^{90}Sr	800	$D = 3 \times 10^{-10}$	.....	$\{V_{Ca}''\}$	sfc	....	....	Ho5	
		^{36}Cl	700	$D = 3 \times 10^{-7}$	.....	$V_{Cl}^{\cdot}$ or Cl_i'	sfc	(see next table)		Ho5	
PbCl$_2$	pp	^{212}Pb	180– 270	1.2×10^{2}	1.65	$\{V_{Pb}''\}$	sfc	....	....	He5	
PbI$_2$	sc	^{212}Pb	260– 320	2.0×10^{6}	1.37	$\{V_{Pb}''\}$	sfc	....	....	Se7	He5
LaF$_3$	sc	^{19}F	0– 230	7.1×10^{-4}	0.50	$\{V_F^{\cdot}\}$	nmr	....	....	Lu3	Le3
SIMPLE INORGANIC RADICALS											
Li$_2$SO$_4$	pc	^{6}Li	640– 790	1.9×10^{-3}	0.34	V_{Li}'	sct	cation disorder		Kv4	Ku5, Lu2
LiOH	sc	^{6}Li	25	$D = 7.3 \times 10^{-11}$	.....	....	......	....	....	Ku5	
Ag$_2$SO$_4$ (α)	sp	^{111}Ag	430– 600	2.5	1.15	$\{V_{Ag}' + Ag_i^{\cdot}\}$	sfc	....	....	Jo2	Li4
Ag$_2$SO$_4$ (β)	sp	^{111}Ag	100– 430	6.7×10^{-5}	0.58	$\{V_{Ag}' + Ag_i^{\cdot}\}$	sfc	....	....	Jo2	Ja3
CaCO$_3$	sc	^{13}C	606– 848	4.5×10^{-4}	2.51	....	gsx	....	....	Ha13	
MONOVALENT OXIDES								P_{O_2} (atm)			
Cu$_2$O	pc	^{64}Cu	800–1050	4.4×10^{-2}	1.57	V_{Cu}'	sct	1.3×10^{-8}	....	Mo3	Ca4, Sh4
	sc	^{18}O	1020–1120	5.4×10^{-4}	1.70	$O_i^{\cdot\cdot}$	gsx	1.3×10^{-1}	$D \propto P_{O_2}^{\,1}$	Eb2	Mo4, Sl1
Ag$_2$O	pp	^{110}Ag	20– 160	5.4×10^{-8}	0.30	$\{V_{Ag}'\}$	sfc	....	....	Ro7	
DIVALENT OXIDES								P_{O_2} (atm)			
BeO	sc	^{7}Be	1720–1960	1.2×10^{-6}	1.56	V_{Be}''	sct	Ar	....	Au2	Au1, Au3
			1500–1760	1.3×10^{-3}	2.78	V_{Be}''	sct	Ar	....	Au2	
	pc	^{7}Be	1100–1800	3.2×10^{-3}	2.73	V_{Be}''	sct	vacuum	....	De3	De2
	sp	^{7}Be	1500–2130	5.9×10^{-6}	2.12	V_{Be}''	sct	....	$D_c/D_a = 1.3$	Co7	
	sc	^{18}O	1560–1730	3.0×10^{-6}	2.97	....	gsx	4.1×10^{-1}	....	Ho1	Au2
MgO	sc	^{28}Mg	1400–1600	2.5×10^{-1}	3.42	....	sct	air	....	Li13	Hi3, Se4
	sc	^{18}O	1000–1150	4.3×10^{-6}	3.56	$O_i^{\cdot\cdot}$	gsx	$(1 - 120) \times 10^{-8}$	....	Ro6	Oi2
			750–1000	4.8×10^{-14}	1.31	$O_i^{\cdot\cdot}$	gsx	$(1 - 120) \times 10^{-3}$	....	Ro6	
	pc	^{18}O	1650	$D < 10^{-14}$	.....	....	ard	1.6×10^{-1}	....	Ho2	

Table 9f-6. Diffusion in Ionic Crystals (*Continued*)

Substance	Form	Isotope	*T* range, °C	D_0, cm²/sec	*W*, eV	Defect	Method	Environment	Comments	Specific reference	Other references
								P_{O_2} (atm)			
CaO	sc	^{45}Ca	1000–1400	8.8×10^{-8}	1.50	$\{V_{Ca}''\}$	sct	1.3×10^{-4}	....	Gu2	Li6
BaO	sc	^{140}Ba	1080–1230	1×10^{29}	11	$\{Ba_i^x\}$	sct	....	....	Re2	Be12, De1
				1×10^{31}	12	$\{V_{Ba}''\}$	sct	....	....	Re2	
			330–1080	1×10^{-9}	0.44	$\{Ba_i^x\}$	sct	....	....	Re2	
				3×10^{-10}	0.3	$\{V_{Ba}''\}$	sct	....	....	Re2	
ZnO	sc	O	800–1300	2.5×10^{3}	2.8	V_O^x	adc	Ba(g)	....	Sp2	
	pw	^{65}Zn	720– 840	4×10^{-1}	3.32	$Zn_i^{\cdot\cdot}$	gsx	Zn(g)	$D \propto P_{Zn}^{0.66}$	Se5	Le4, Li5, Pa4, Ro2, Ro3, Se1, Se2, Se4, Sp1
	sc	^{65}Zn	940–1025	5.0	3.25	....	sfc	....	....	Mu2	
			850– 940	3.0×10^{-9}	0.87	....	sfc	....	....	Mu2	
	sc	^{65}Zn	1000–1250	1.3×10^{-5}	1.9	$\{Zn_i^{\cdot\cdot}\}$	sct	O_2	....	Mo5	
	sc	^{18}O	1100–1300	6.5×10^{11}	7.15	{disloc}	gsx	1 (to 10^{-1})	$D \propto P_{O_2}^{\frac{1}{2}}$	Mo5	
CdO	sc	^{18}O	630– 855	3.8×10^{6}	3.99	$V_O^{\cdot\cdot}$	gsx	1 (to 10^{-3})	$D \propto P_{O_2}^{-\frac{1}{6}}$	Ha17	Ha14, Ha15
SnO$_2$	sp	^{119}Sn	980–1380	1×10^{4}	5.14	....	sfc	air	....	Li10	Si4
PbO (α)	pp	^{210}Pb	600– 680	4×10^{9}	3.5	....	sfc	air	....	Da2	Li8
	pw	^{18}O	500– 650	5.4×10^{-6}	0.93	....	gsx	O_2	....	Th3	
PbO (β)	pc	^{212}Pb	200– 460	1.6×10^{-11}	0.56	....	sfc	air	....	Li9	
POLYVALENT OXIDES											
								P_{O_2} (atm)			
Al$_2$O$_3$	sp	^{26}Al	1670–1905	2.8×10	4.95	V_{Al}'''	sct	air			
	sc	^{18}O	1500–1780	1.9×10^{3}	6.6	$V_O^{\cdot\cdot}$	gsx	2.0×10^{-1}	....	Pa1	
			1200–1620	6.3×10^{-8}	2.5	$V_O^{\cdot\cdot}$	gsx	2.0×10^{-2}	....	Oi1	Co1, He6
In$_2$O$_3$	pf	In	308– 407	7.8×10^{-3}	1.35	$In_i^{\cdot\cdot\cdot}$	oxy	5×10^{-4}	....	Oi1	
Bi$_2$O$_3$	pp	^{210}Bi	720– 780	4.5×10^{-1}	2.00	V_{Bi}'''	sfc	air	on InSb	Ro5	
			600– 700	4.3×10^{-6}	0.90	V_{Bi}'''	sfc	air	....	Pa3	
Y$_2$O$_3$	sp	^{91}Y	1400–1800	2.4×10^{-4}	1.90	....	sct	vacuum	....	Pa3	
	sp	O	1000–1500	7.2	2.54	....	oxy	air	....	Be6	
TiO$_2$	sc	^{18}O	710–1300	2.0×10^{-3}	2.60	$V_O^{\cdot\cdot}$	gsx	$(2-6) \times 10^{-1}$	....	Wi2	
ZrO$_2$	sc	^{18}O	800–1000	9.7×10^{-3}	2.43	$V_O^{\cdot\cdot}$	gsx	4×10^{-1}	$D_\perp / D_\parallel = 1.6$	Ha18	Ha16
	pf	O	300– 390	9×10^{-4}	1.24	$V_O^{\cdot\cdot}$	oxy	1	....	Ma1	De4, Do4
ZrO$_2$:CaO (16%)	pc	^{95}Zr	1700–2150	3.5×10^{-2}	4.01	V_{Zr}''''	sct	H_2	....	Sm2	
		^{45}Ca	1700–2100	4.4×10^{-1}	4.35	V_{Ca}''	sct	H_2	....	Rh1	Mo1
ZrO$_2$:CaO (14%)	sc	^{18}O	780–1100	1.8×10^{-2}	1.35	$V_O^{\cdot\cdot}$	sct	air	....	Rh1	Mo1
Nb$_2$O$_5$ (α)	sc	^{18}O	850–1200	1.2×10^{-3}	2.14	$V_O^{\cdot\cdot}$	gsx	1 (to 10^{-2})	O disorder	Si3	Ha2, Sm1
	sc	^{18}O	850, 900	$D_\parallel / D_\perp = 60, 190$	.....	O_2	ard	10^{-17}, 10^{-2}	$D \propto P_{O_2}^{-\frac{1}{6}}$	Ch6	Ch4, Do5, Sh2
Nb$_2$O$_5$ (γ)	pf	O	540– 840	1.0	1.85	$\{V_O^{\cdot\cdot}\}$	oxy	1 to 10^{-8}	[010] axis	Sh1	
									....	Sb2	

TRANSITION METAL OXIDES								P_{O_2} (atm)			
Cr_2O_3	sp	^{51}Cr	1040–1550	1.4×10^{-1}	2.64	V_{Cr}''' or $Cr_i^{\cdot\cdot\cdot}$	sct	N_2	....	Ha1	Fe1, Li11
	sc	^{51}Cr	1300	$D \propto (P_{H_2O}/P_{H_2})^{0.4}$	.....	V_{Cr}'''	sct	$P_{H_2O}/P_{H_2} = 2$ to 18	....	Wa1	
	pc	^{18}O	1100–1450	1.6×10	4.38	....	gsx	1.6×10^{-1}	....	Ha3	Ha5
MnO	sp	^{54}Mn	900–1150	7.4×10^{-7}	0.79	V_{Mn}''	sct	10^{-12} (to 10^{-14})	$D \propto P_{O_2}^{1/4}$	Bo1	
FeO	pc	^{59}Fe	700–1120	1.1×10^{-2}	1.31	V_{Fe}''	sct	$Fe_{0.917}O$	....	De6	De7, He2, Hi1
	pc	^{55}Fe	700–1000	1.4×10^{-2}	1.31	V_{Fe}''	sct	$Fe_{0.921}O$	....	Ca2	
Fe_2O_3 (α)	sp	^{59}Fe	950–1050	1.3×10^{6}	4.35	....	sct	air	....	Iz2	Li7
	pc	^{18}O	900–1250	2.0	3.38	$\{V_O^{\cdot\cdot}\}$	gsx	1.6×10^{-1}	....	Ha4	Ki2
Fe_3O_4	pc	^{55}Fe	750–1000	5.2	2.38	V_{Fe}''	sfc	$Fe_{2.993}O_4$	....	Hi1	Iz1
	sc	^{55}Fe	850–1075	6×10^{5}	3.64	....	sct	Ar	....	Kl1	
	sp	^{59}Fe	1115	$D \propto (P_{CO_2}/P_{CO})^{0.3}$	.....	V_{Fe}''	sfc	$P_{CO_2}/P_{CO} = 10$ to $10^{3.5}$	....	Sc5	
	sc	^{18}O	300– 550	3.2×10^{-14}	0.74	....	gsx	$H_2O(g)$	....	Ca5	
CoO	pc	^{60}Co	1010–1340	2.2×10^{-3}	1.50	V_{Co}''	sct	1	$D \propto P_{O_2}^{0.3}$	Ca2	Ca3, Pr2
	sc	^{18}O	1150–1500	9×10	4.2	....	gsx	2.1×10^{-1}	....	Ch5	Ho3, Th2
Co_3O_4	pc	^{18}O	830– 860	2.4×10^{22}	7.6	....	gsx	....	....	Th2	
NiO	sc	^{63}Ni	1000–1470	1.8×10^{-3}	1.98	V_{Ni}''	sct	air	....	Ch7	Kl2
	sc	^{63}Ni	1000–1400	4.4×10^{-4}	1.92	V_{Ni}''	sfc	air	....	Sh5	Li12
	sc	^{18}O	1100–1500	6.2×10^{-4}	2.49	$[O_i'']$	gsx	7×10^{-2}	....	Ok2	
RARE EARTH OXIDES								P_{O_2} (atm)			
Pr_2O_3	pw	O	700– 990	4.5×10^{-2}	1.82	$V_O^{\cdot\cdot}$	oxy	vacuum	....	Ku2	
Nd_2O_3	pc	^{18}O	700–1000	1.3×10^{-4}	1.34	....	gsx	4×10^{-2} to 4×10^{-1}	....	St8	
Sm_2O_3	pc	^{18}O	700–1000	6.0×10^{-6}	0.93	....	gsx	4×10^{-2} to 4×10^{-1}	....	St8	
Er_2O_3	pw	O	850–1250	1.2	2.07	....	oxy	air	....	Wi2	
UO_2	sc	^{233}U	1450–1700	4×10^{-7}	3.04	$\{V_U''''\}$	sec	H_2	....	Al1	Be4, Li2, Li14, Ya1
	sp	^{235}U	1500	$D = 1.6 \times 10^{-11} \times y^{1.9}$	.....	UO_{2+y}	sfc	$y = 0.007$ to 0.17	....	Ma8	
	pw	^{18}O	550– 850	1.2×10^{3}	2.83	O_i''	gsx	$UO_{2.002}$	interstitialcy	Be4	Ar7, Be3, Do3, Th4
			320– 500	2.1×10^{-3}	1.29	O_i''	gsx	$UO_{2.063}$	interstitialcy	Be4	
MONOVALENT CHALCOGENIDES											
Na_2S	sp	^{22}Na	520– 700	8.3×10^{2}	1.66	....	sfc	H_2	....	Mo2	
			400– 520	1.6×10^{-3}	0.77	....	sfc	H_2	....	Mo2	
	sp	^{35}S	420– 800	3.8×10^{-3}	1.77	....	sfc	H_2	....	Mo2	
Cu_2S	...	^{64}Cu	140– 450	2×10^{-4}	<0.2	....	......	no effect	....	Pa7	We2
Cu_2Se	pc	Cu	580– 750	9×10^{-4}	0.27	Cu disorder	smc	$Cu_{1.96}Se$	....	Ce1	
Ag_2S (α)	pc	^{110}Ag	200– 400	2.8×10^{-4}	0.15	Ag disorder	sct	no effect	....	Al2	Ok1
	pc	^{35}S	650–1000	2.4×10^{-4}	1.04	$V_S^{\cdot\cdot}$	sct	....	....	Is1	Ja3, Sh4
Ag_2S (β)	pc	^{110}Ag	95– 175	6×10^{-3}	0.45	$\{Ag_i^{\cdot}\}$	sct	....	....	Al1	
	pw	^{110}Ag	25– 70	9.3×10^{-3}	0.40	....	slx	....	....	Pe3	
	pw	^{35}S	120– 141	2.4×10^{-1}	1.07	....	slx	....	....	Pe3	
$AgSbS_2$	pc	Ag	400	$D = 4 \times 10^{-7}$	.....	elt	S_2	....	....	Ri3	
	...	Sb	400	$D = 3 \times 10^{-11}$	....	oxy	S_2	....	....	Ri3	
Ag_2Se	pc	^{110}Ag	150– 280	2.1×10^{-4}	0.12	Ag disorder	sct	no effect	....	Ok1	
Tl_2Se	pc	^{204}Tl	150– 300	1.2×10^{-3}	0.61	....	sct	vacuum	....	Ak1	
		^{75}Se	150– 300	2.2×10^{-5}	0.58	....	sct	vacuum	....	Ak1	

TABLE 9f-6. DIFFUSION IN IONIC CRYSTALS (*Continued*)

Substance	Form	Isotope	T range, °C	D_0, cm²/sec	W, eV	Defect	Method	Environment	Comments	Specific reference	Other references
DIVALENT CHALCOGENIDES								P (atm)			
ZnS	sc	^{65}Zn	1030–1075	1×10^{16}	6.5	$\{V_{Zn}''\}$	gsx	$P_{Zn} = 1$	....	Se3	
			940–1030	1.5×10^4	3.25	$\{Zn_i^{\cdot\cdot}\}$	gsx	$P_{Zn} = 1$	....	Se3	
	sc	^{35}S	700– 890	2.9×10^4	3.4	....	sct	$P_S = 5 \times 10^{-1}$	....	Bl1	
	sc	^{35}S	740–1100	8×10^{-5}	2.2	....	ard	$P_S = 5 \times 10^{-1}$	....	Go1	
ZnSe	sc	^{75}Se	1000–1150	2.3×10^{-1}	2.7	Se_i^x	sct	P_{Se_2} max	....	Wo2	
ZnTe	sc	^{65}Zn	730– 950	1.4×10	2.69	V_{Zn}^x or Zn_i^x	sct	no effect	....	Re5	
	sc	^{123}Te	780– 950	1.9×10^4	3.78	Te_i^x	sct	Te(g)	or $(V_{Zn}V_{Te})^x$	Re5	
CdS	sc	^{115}Cd	700–1130	3	2.0	V_{Cd}^x	sct	Cd sat.	....	Wo1	
CdSe	sc	^{75}Se	700–1000	1.3×10^6	4.43	Se_i^x	sct	$P_{Cd} = 10^{-1}$ (to 10^{-7})	$D \propto P_{Cd}^{-1}$	Wo2	
	sc	^{75}Se	700–1000	2.6×10^{-3}	1.55	Se_i^x	sct	P_{Se_2} max	....	Wo2	
CdTe	sc	^{109}Cd	660– 920	3.3×10^2	2.67	$V_{Cd}^x + Cd_i^x$	sct	Cd sat.	....	Bo6	
			640– 850	1.6×10	2.44	$V_{Cd}^x + Cd_i^x$	sct	Te sat.	....	Bo6	
	sc	^{123}Te	660– 900	8.5×10^{-7}	1.42	Te_i^x	sct	Cd sat.	....	Bo6	Wo2
		^{123}Te	510– 780	1.7×10^{-4}	1.38	Te_i^x	sct	Te sat.	....	Bo6	
PbS	sc	^{210}Pb	500– 800	8.6×10^{-5}	1.5	$V_{Pb}^x + Pb_i^x$	sct	stoich.	....	Si2	An1, Scl, Se9
			500– 800	2.6×10^{-5}	1.4	Pb_i^x	sct	Pb 10^{18} cm^{-3}	....	Si2	
			500– 800	5.5×10^{-7}	1.0	V_{Pb}^x	sct	S excess	....	Si2	
	sc	^{35}S	500– 750	6.8×10^{-5}	1.38	....	sct	stoich.	....	Se10	
			500– 750	1.9×10^{-6}	1.16	$\{(V_{Pb}V_S)^x\}$	sct	Pb 10^{18} cm^{-3}	....	Se10	
			500– 750	4.6×10^{-6}	1.2	$\{S_i^x\}$	sct	S 10^{18} cm^{-3}	....	Se10	
PbSe	sc	^{210}Pb	400– 800	5.0×10^{-6}	0.83	$V_{Pb}^x + Pb_i^x$	sct	vacuum	....	Se8	Bo5
	sc	^{75}Se	650– 800	2.1×10^{-5}	1.2	$\{V_{Se}^x\}$	sct	vacuum	....	Bo5	
PbTe	sc	^{210}Pb	310– 820	3×10^{-3}	1.51	$\{Pb_i^x\}$	sct	....	....	Ca1	Bo4, Go2
		^{127}Te	500– 800	2.7×10^{-6}	0.75	$\{V_{Te}^x\}$	sct	vacuum	....	Bo5	Go2
BiSe	pc	^{75}Se	100– 200	2.5×10^{-9}	0.67	....	sct	vacuum	....	Ku1	
Bi$_2$Se$_3$	pc	^{75}Se	100– 200	8.5×10^{-9}	2.17	....	sct	vacuum	....	Ku1	
FeS	sc	Fe	350– 700	3.2×10^{-2}	0.97	V_{Fe}^x	......	Fe$_{0.85}$S	....	Co6	Co5, Me3
	sc	S	900–1060	1×10^{33}	10.4	....	......	Fe$_{0.85}$S	....	Co6	Co5
CoTe (γ)	pc	^{60}Co	400– 800	$D = 1.5 \times 10^{-7}$	.....	....	sct	....	D at 805°	Ar5	
		^{125}Te	400– 800	$D = 1.6 \times 10^{-9}$	.....	....	sct	....	D at 410°	Ar5	
NiS	sc	^{63}Ni	725– 880	1.1×10^{-2}	1.11	$V_{Ni}^x + Ni_i^x$	sct	Ni$_{0.97}$S	∥ c axis	Kl3	Fu1, Kl4
			725– 880	8.5×10^{-3}	1.11	$V_{Ni}^x + Ni_i^x$	sct	Ni$_{0.97}$S	⊥ c axis	Kl3	
	sc	^{35}S	800– 880	2.5×10^2	2.84	V_S^x	sct	Ni$_{0.97}$S	∥ c axis	Kl3	Kl4
			800– 880	2.2×10^6	3.79	V_S^x	sct	Ni$_{0.97}$S	⊥ c axis	Kl3	

Form of Sample

sc	single crystal
pc	polycrystalline
pf	polycrystalline film
pw	powder
pp	pressed powder
sp	sintered powder

Defect

V_{Ba}''	Ba ion vacancy
V_{Zn}^x	Zn vacancy, neutral
$V_{Br}^{\cdot}$	Br ion vacancy
$(V_{Na}V_{Cl})^x$	Vacancy pair, neutral
$Ag_i^{\cdot}$	Interstitial Ag ion
Te_i^x	Interstitial Te atom
{ }	Tentative assignment

Method

sct	sectioning
sfc	surface counting
gsx	gaseous exchange
slx	solution exchange
adc	additive coloration
ard	autoradiography
elt	electrotransport
nmr	nuclear magnetic resonance
oxy	oxidation or weight loss
smc	semiconducting properties

TABLE 9f-7. CORRELATION EFFECTS IN DIFFUSION
[The correlation factor is $f = D_{\text{tracer}}/D_{\text{conductivity}}$.]

Substance	Isotope	T range, °C	f_{expt}	Specific reference	Other references	Defect and lattice	f_{theor}	Reference
NaCl..........	$^{22}Na + {}^{36}Cl$	580– 680	0.9 –1.0	Do6	Ma6	$V_{Na}' + V_{Cl}^{\cdot}$, fcc	0.781	Ba2, Co2
	$^{22}Na + {}^{36}Cl$	640– 790	0.85–1.00	Ne1				
NaBr..........	^{24}Na	450– 700	1.0	Ma6	....	V_{Na}', fcc	0.781	Ba2, Co2
KCl..........	^{42}K	500– 700	1.0	As3	Wi3	V_{K}', fcc	0.781	Ba2, Co2
CsCl (β)........	$^{137}Cs + {}^{36}Cl$	280– 460	1.4 –1.5	Ha9	....	$V_{Cs}' + V_{Cl}^{\cdot}$, sc	0.653	Ba2, Co2
CsBr..........	$^{134}Cs + {}^{82}Br$	330– 530	0.83–0.88	Ly1	....	$V_{Cs}' + V_{Br}^{\cdot}$, sc	0.653	Ba2, Co2
CsI..........	$^{134}Cs + {}^{131}I$	330– 530	0.68–0.86	Ly1	....	$V_{Cs}' + V_{I}^{\cdot}$, sc	0.653	Ba2, Co2
AgCl..........	^{110}Ag	300– 440	0.48–0.54	We1	Co4, Mu6	$V_{Ag}' + Ag_i^{\cdot}$, fcc	0.33–0.78	Co3, Mc2
AgCl: Cd........	^{110}Ag	130– 230	0.78–0.74	Gr1	Co4, Lu4	V_{Ag}', fcc	0.781	Ba2, Co2
AgBr..........	^{110}Ag	140– 410	0.47–0.65	Fr2	Mi1, Mu4	$V_{Ag}' + Ag_i^{\cdot}$, fcc	0.33–0.78	Co3, Fr2
AgBr: Cd........	^{110}Ag	100– 200	0.80	Mi1	St2	V_{Ag}', fcc	0.781	Ba2, Co2
AgI (β)........	^{110}Ag	90– 110	6 –11	Mu5	....	{Ag ring}		
AgI..........	^{110}Ag	90– 110	2 –8	Mu5	....	High P phase		
TlCl..........	$^{204}Tl + {}^{36}Cl$	290– 390	0.75–0.70	Fr4	....	$V_{Tl}' + V_{Cl}^{\cdot}$, sc	0.653	Ba2, Co2
$CaCl_2$..........	^{36}Cl	650– 700	0.6	Ho5	....	$V_{Cl}^{\cdot}$ or Cl_i', sc		
		200– 500	2.0 –2.6	Ho5				
Li_2SO_4..........	^{6}Li	600– 800	0.9 –0.7	Kv4	Kv2	Li disorder		
BeO..........	^{7}Be	1100–1250	0.4 –0.8	De3	....	V_{Be}'', hcp	0.783	Co2, Mu3
	^{7}Be	1550	0.8	Cl5				
ZrO_2: CaO (15%)	^{18}O	780–1100	0.5 –0.8	Si3	Ki1	$V_{O}^{\cdot\cdot}$, sc	0.653	Ba2, Co2
Na_2S..........	^{22}Na	400– 700	1.0	Mo2	....	V_{Na}', sc	0.653	Ba2, Co2
Ag_2S (α)........	^{110}Ag	180– 280	0.26–0.30	Ok1	....	Ag disorder	0.3	Yo3
	^{110}Ag	200– 400	0.27–0.38	Ri1	....	Ag disorder	0.5	Ri2
Ag_2Se (α)......	^{110}Ag	140– 280	0.33–0.40	Ok1	....	Ag disorder	0.3 –0.5	Ri2, Yo3

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The literature has been surveyed to about the middle of 1968. Most of the references cover only the period 1958 to 1968; some earlier articles have been included, especially when more recent work is not available. The *specific references* in the tables provide the most complete or reliable information, but the *other references* also contain either appreciable data or extensive discussion.

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Diffusion, general discussion: 54, 55, 58, 59, 60, 62, 66, 67
Diffusion and ionic conductivity: 36, 38, 48, 50, 57, 69
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DIELECTRIC PROPERTIES

9f-8. Dielectric Constants of Crystalline Solids. The dielectric constants of inorganic compounds are listed in Table 9f-8; the chemical formula is given in the second column. The column headed t, °C gives the temperature of the measurements in degrees Celsius; the column headed ν, Hz gives the frequency of the measurement in Hz; the column headed ϵ/ϵ_v gives the dielectric constant (relative capacitance); and the final column gives the reference to the source of the information.

Discrepancies in the dielectric constant of the order of 10 percent are frequently found in the literature.

TABLE 9f-8. INORGANIC SOLIDS—CRYSTALLINE

Name	Formula	t, °C	ν, Hz	ϵ/ϵ_v	Ref.
Alums:					
Ammonium alum	$Al(NH_4)(SO_4)_2 \cdot 12H_2O$	r.t.	10^{12}	6	34
Cesium alum	$CsAl(SO_4)_2 \cdot 12H_2O$	....	10^{12}	5.0	34
Potassium alum	$KAl(SO_4)_2 \cdot 12H_2O$	....	aud.	6.5	15
Rubidium alum	$RbAl(SO_4)_2 \cdot 12H_2O$	....	10^{12}	5.1	34
Rubidium chrome alum	$RbCr(SO_4)_2 \cdot 12H_2O$	....	10^{12}	5.0	34
Aluminum antimonide	$AlSb$	....	....	11.2	66
Aluminum oxide	Al_2O_3	25	10^2 to 8×10^9	$9.34\perp$	58
				$11.54\parallel$	38
Aluminum fluosilicate (topaz)	$Al_2(F_2SiO_4)$	24	7×10^3	6.62a	64
				6.58b	
				6.95c	
Aluminum phosphate	$AlPO_4$	r.t.	10^3	6.05	37
Ammonium bromide	NH_4Br	r.t.	10^{12}	7.3	34
Ammonium chloride	NH_4Cl	r.t.	2×10^6	6.96	28
Ammonium iodide (CsCl structure)	NH_4I	r.t.	6.15×10^3	7.3	23
Ammonium iodide (NaCl structure)	NH_4I	....	....	9.8	23
Ammonium sulfate	$(NH_4)_2SO_4$	20	10^3	9.8	61
Ammonium uranyl oxalate	$(NH_4)_2UO_2(C_2O_4)_2$	....	....	8.14	20
Ammonium uranyl oxalate trihydrate	$(NH_4)_2UO_2(C_2O_4)_2 \cdot 3H_2O$	....	....	6.06	20
Ammonium tartrate	$(NH_4)_2(C_4H_4O_6)$	r.t.	10^3	6.45	37
Antimonous sesquioxide	Sb_2O_3	....	$1.5 - 2 \times 10^3$	12.8	24
Barium carbonate	$BaCO_3$	18	2×10^5	8.53	51
Barium chloride	$BaCl_2$	....	....	9.81	30
Barium chloride dihydrate	$BaCl_2 \cdot 2H_2O$	....	....	9.00	30
Barium fluoride	BaF_2	....	2×10^6	7.33	28
Barium formate	$Ba(COOH)_2$	r.t.	10^3	7.9	37
Barium nitrate	$Ba(NO_3)_2$	19	2×10^5	4.95	51
Barium oxide	BaO	−25 to 60	60~ to 6×10^7	34	5
Barium peroxide	BaO_2	r.t.	2×10^6	10.7	24
Barium stannate	$BaSnO_3$	25	25×10^5	18	6
Barium sulfate	$BaSO_4$	15	10^8	11.4	
Barium sulfide	BaS	....	7.25×10^6	19.230	52
Beryllium aluminum silicate (beryl)	$Be_3Al_2(Si_6O_{18})$	24	7×10^3	5.95	64
				6.86	64
Beryllium carbonate	$BeCO_3$	18	2×10^5	9.7	51
Beryllium oxide	BeO	18	2×10^6	7.35	28
Bismuth trioxide	Bi_2O_3	r.t.	2×10^6	18.2	24
Bismuth titanate	$Bi_4Ti_3O_{12}$	r.t.	10^3	135–220	59
Boron nitride	BN	....	....	7.1	66
Cadmium arsenide	Cd_3As_2	−269	....	$18.5\parallel$	36
Cadmium sulfide	CdS	....	....	9.4(11)	43
				10.3(33)	43
Cadmium fluoride	CdF_2	27	10^5–10^7	8.33 ± 0.08	67
Cadmium bromide	$CdBr$	20	5×10^5	8.6	18
Cadmium malonate	$Cd(C_3H_2O_4)$	20	5×10^5	4.5	18
Calcium carbonate	$CaCO_3$	....	10^8	$8.5\perp$	48
				$8.0\parallel$	
Calcium fluoride	CaF_2	....	10^6	6.76	29, 34, 45, 46
			aud.	6.85	15, 44, 56, 40
Calcium nitrate	$Ca(NO_3)_2$	19	2×10^5	6.54	51
Calcium oxide	CaO	10	2×10^6	11.8	28
Calcium sulfide	CaS	....	7.25×10^6	6.699	52
Calcium sulfate (gypsum)	$CaSO_4 \cdot 2H_2O$	....	....	5.10*a*	17
				5.24*b*	
				10.30*c*	
Cadmium telluride	$CdTe$	24	....	10.60 ± 0.15	35
		−196	10^4	9.65	4
Ceric oxide	CeO_2	r.t.	2×10^6	7.0	24
Cesium bromide	$CsBr$	....	2×10^6	6.51	28
Cesium carbonate	Cs_2CO_3	18	2×10^5	6.53	51
Cesium chloride	$CsCl$	19	2×10^5	6.34	51
Cesium iodide	CsI	25	10^6	5.65	28, 27
Cesium nitrate	$CsNO_3$	r.t.	5×10^5	9.4*a*	8
				8.3*c*	

TABLE 9f-8. INORGANIC SOLIDS—CRYSTALLINE (*Continued*)

Name	Formula	t, °C	ν, Hz	ϵ/ϵ_v	Ref.
Chromic sesquioxide	Cr_2O_3	25.5	10^3	13.3*a*	21
Cupric oxide	CuO			11.9*c*	
Cupric sulfate pentahydrate	$CuSO_4 \cdot 5H_2O$	r.t.	2×10^6	18.1	24
Cuprous bromide	$CuBr$	....	....	6.60	30
Cuprous chloride	$CuCl$	20	5×10^5	8.0	18
Cuprous oxide	Cu_2O	....	10^3	9.8	3
Dextrose sodium bromide	$C_6H_{12}O_6 \cdot NaBr$	r.t.	10^5	7.60 ± 0.06	40.1
Diamond	C	....	10^3	4.0	37
Europium sulfide	EuS	....	....	5.5	49
Ferrous oxide	FeO	−193	$5 \times (10^2\text{–}10^6)$	13.10 ± 0.04	10
Gallium arsenide	$GaAs$	r.t.	2×10^6	14.2	24
Gallium antimonide	$GaSb$	....	....	13.13	66
Gallium phosphide	GaP	....	....	15.69	66
Hexamine cobalt (III) chloride	$[Co(NH_3)_6]Cl_3$	....	....	10.18	66
Ice I (1 bar)	H_2O	....	10^6	7.31	39
(1600 bar)		−23.4	....	97.5	11
Indium antimonide	$InSb$			100.8	
Indium arsenide	$InAs$	....	....	17.88	66
Indium phosphide	InP	....	....	14.55	66
Iodic acid	HIO_3	....	....	12.37	66
Iodine	I_2	....	10^3	7.5	37
		....	5×10^4	6*a*	53
			to	3*b*	
Lead acetate	$Pb(C_2H_3O_2)_2$		5×10^7	40*c*	
Lead bromide	$PbBr_2$	17–22	10^6	2.6	
Lead carbonate	$PbCO_3$	20	$0.5\text{–}3 \times 10^6$	>30	18
Lead chloride	$PbCl_2$	15	10^8	18.6	
Lead fluoride	PbF_2	20	$0.5\text{–}3 \times 10^6$	33.5	18
Lead iodide	PbI_2	r.t.	....	26.3	7
Lead molybdate (wulfenite)	$PbMoO_4$	20	$0.5\text{–}3 \times 10^6$	20.8	18
Lead nitrate	$Pb(NO_3)_2$	....	3×10^4	26.8∥	49
Lead oxide	PbO	....	$0.5\text{–}3 \times 10^6$	16.8	18
Lead selenide	$PbSe$	r.t.	2×10^6	25.9	24
Lead sulfate	$PbSO_4$	....	....	280	66
Lead sulfide	PbS	17–22	10^6	14.3	
Lead telluride	$PbTe$	....	....	205	66
Lithium bromide	$LiBr$	....	....	400	66
Lithium chloride	$LiCl$	....	2×10^6	12.1	28
Lithium carbonate	Li_2CO_3	....	2×10^6	11.05	18
Lithium fluoride	LiF	18	2×10^5	4.9	51
		20	10^6	9.27	28
		25	$10^2\text{–}10^7$	9.00	63
Lithium iodide	LiI	80	$10^2\text{–}10^7$	9.11	63
Lithium sulfate monohydrate	$Li_2SO_4 \cdot H_2O$	....	2×10^6	11.03	28
Lithium trisodium chromate	$LiNa_3CrO_4 \cdot 6H_2O$	....	10^3	5.6	37
Lithium trisodium molybdate	$LiNa_3MoO_4 \cdot 6H_2O$	....	10^3	8.0	37
Magnesium borate monochloride	$Mg_3B_7O_{13}Cl$	....	10^3	8.1	37
Magnesium carbonate	$MgCO_3$	r.t.	5×10^5	14.1*a*	54
Magnesium malonate	$Mg(C_2H.O_4)$	18	2×10^5	8.1	51
Magnesium mica (phlogopite)	$(K,H)_3Mg_3Al(SiO_4)_3$	20	5×10^5	5.8	18
Magnesium oxalate	$Mg(C_2O_4)$	r.t.	5×10^4	275	1
Magnesium oxide	MgO	20	5×10^5	5.2	18
Magnesium sulfate	$MgSO_4$	25	$10^2\text{–}10^8$	9.65	63
Magnesium sulfate heptahydrate	$MgSO_4 \cdot 7H_2O$	20	5×10^5	8.2	18
Manganese dioxide	MnO_2	....	....	5.46	30
Manganese monoxide	MnO	25	....	10^4	68
Mercuric chloride	$HgCl_2$	r.t.	10^6, 273×10^6	18.0 ± 0.5	14
Mercurous chloride	$HgCl$	....	10^{12}	6.5	34
Mercurous selenide	$HgSe$	....	10^{12}	14.0⊥	34
Mercurous sulfide	HgS	r.t.	$10^4\text{–}10^6$	25.6	32
Mica—ruby, muscovite	....	r.t.	$10^4\text{–}10^6$	30.6	32
Mica—Canadian	....	26	$10^2\text{–}3 \times 10^7$	5.4	63
		25	$10^2\text{–}10^4$	6.9⊥	63
Nickel sulfate hexahydrate	$NiSO_4 \cdot 6H_2O$	25	10^4	7.3∥	63
Phosphorus, red	P	....	10^3	6.2	37
yellow	....	....	10^8	4.1	
		....	10^8	3.6	49

TABLE 9f-8. INORGANIC SOLIDS—CRYSTALLINE (*Continued*)

Name	Formula	t, °C	ν, Hz	ϵ/ϵ_v	Ref.
Potassium bromate	$KBrO_3$	r.t.	2×10^6	7.3	57
Potassium bromide	KBr	r.t.	2×10^6	4.78	28
Potassium carbonate	K_2CO_3	18	2×10^5	4.96	51
Potassium chlorate	$KClO_3$	r.t.	2×10^6	5.1	57
Potassium chloride	KCl	29.5	10^6	4.64	27
		80	10^6	4.80	27
Potassium chromate	K_2CrO_4	....	6×10^7	7.3	
Potassium cyanide	KCN	r.t.	2×10^6	6.15	57
Potassium dihydrogen arsenate	KH_2AsO_4	r.t.	2×10^6	31	57
Potassium dihydrogen phosphate	KH_2PO_4	....	10^8	46	37
Potassium fluoride	KF	....	2×10^6	6.05	28
Potassium iodate	KIO_3	r.t.	2×10^6	16.85	57
Potassium iodide	KI	....	2×10^5	4.94	28
Potassium nitrate	KNO_3	20	2×10^5	4.37	51
Potassium perchlorate	$KClO_4$	r.t.	2×10^6	5.9	57
Potassium orthophosphate	K_3PO_4	r.t.	2×10^6	7.75	57
Potassium monohydrogen orthophosphate	K_2HPO_4	r.t.	2×10^6	9.05	57
Potassium dihydrogen orthophosphate	KH_2PO_4	r.t.	2×10^6	>31	57
Potassium sulfate	K_2SO_4	r.t.	2×10^6	6.4	57
Potassium tantalate–niobate (KTN)	$KTa_{0.66}Nb_{0.34}O_3$	−1	10^4	6,000	12
		0	....	34,000	
		20	....	6,000	
Potassium thiocyanate	$KSCN$	r.t.	2×10^6	7.9	57
Potassium thionates:					
Potassium trithionate	$K_2S_3O_6$	20	1.8×10^6	5.7	50
Potassium tetrathionate	$K_2S_4O_6$	20	1.8×10^6	5.5	50
Potassium pentathionate	$K_2S_5O_6 \cdot H_2O$	20	1.8×10^6	7.8	50
Potassium hexathionate	$K_2S_6O_6$	20	1.8×10^6	7.8	50
Rubidium bromide (NaCl structure)	$RbBr$	r.t.	....	4.9	25
Rubidium bromide (CsCl structure)	$RbBr$	r.t.	....	6.5	25
Rubidium carbonate	Rb_2CO_3	19	2×10^5	6.73	51
Rubidium chloride	$RbCl$	....	2×10^6	5.0	28
Rubidium fluoride	RbF	....	2×10^6	5.91	28
Rubidium iodide	RbI	....	2×10^6	5.0	28
Rubidium indium sulfate	$RbIn(SO_4)_2$	....	....	6.85	19
Rubidium nitrate	$RbNO_3$	130–215	10^6	20–380	16
		215–265	10^6	30	16
Selenium	Se	25	3×10^9	11.0	63
		25	3×10^9	10.4	63
Selenium, amorphous	Se	25	2×10^{10}	7.5	63
Silicon monoxide	SiO	25	10^2–10^{10}	6.00	63
Silicon dioxide (α-quartz)	SiO_2	r.t.	10^8	5.8	22
		r.t.	....	4.5⊥	
				4.6∥	9
Silicon carbide	SiC	....	10^5	10.2∥	26
Silicon nitride	Si_3N_4	r.t.	10^8	4.2	22
Silver bromide	$AgBr$	....	2×10^6	13.1	28, 18
Silver chloride	$AgCl$	....	2×10^6	12.3	28, 18
Silver cyanide	$AgCN$	....	10^6	5.6	
Silver nitrate	$AgNO_3$	20	5×10^5	9.0	18
Sodium ammonium tartrate tetrahydrate	$NaNH_4(C_4H_4O_6) \cdot 4H_2O$	....	10^8	9.0	37
Sodium bromide	$NaBr$	....	2×10^6	5.99	28
Sodium carbonate	Na_2CO_3	18	2×10^5	8.75	51
Sodium carbonate decahydrate	$Na_2CO_3 \cdot 10H_2O$	....	6×10^7	5.3	30
Sodium chlorate	$NaClO_3$	....	....	5.28	31
Sodium chloride	$NaCl$	20	2×10^5	5.62	28
		25	10^2–10^7	5.9	63
		85	10^4–10^7	5.98	63
Sodium cyanide	$NaCN$	20	10^5	7.55	58
Sodium fluoride	NaF	19	2×10^6	6.0	28

TABLE 9f-8. INORGANIC SOLIDS—CRYSTALLINE (*Continued*)

Name	Formula	t, °C	ν, Hz	ϵ/ϵ_v	Ref.
Sodium iodide	NaI	....	2×10^6	6.60	28
Sodium nitrate	$NaNO_3$	19	2×10^5	6.85	51
Sodium nitrite	$NaNO_2$	r.t.	5×10^5	6.8*a*	55
		r.t.	5×10^5	6.4*b*	
		r.t.	5×10^4	7.8*c*	
Sodium perchlorate	$NaClO_4$	....	10^3	5.76	37
Sodium sulfate	Na_2SO_4	....	....	7.90	30
Sodium sulfate decahydrate	$Na_2SO_4 \cdot 10H_2O$	....	....	5.0	30
Sodium uranyl oxalate	$Na_2UO_2(C_2O_4)_2$	....	....	5.18	20
Stannic dioxide	SnO_2	r.t.	10^4–10^{10}	9.0 ± 0.5∥	60
		r.t.	10^4–10^{10}	14 ± 2⊥	60
Strontium carbonate	$SrCO_3$	18	2×10^5	8.85	51
Strontium chloride	$SrCl_2$	....	....	9.19	30
Strontium chloride hexahydrate	$SrCl_2 \cdot 6H_2O$	....	....	8.52	30
Strontium fluoride	SrF_2	....	2×10^6	7.69	28
Strontium formate dihydrate	$Sr(COOH)_2 \cdot 2H_2O$	....	10^3	6.1	37
Strontium nitrate	$Sr(NO_3)_2$	19	2×10^5	5.33	51
Strontium oxide	SrO	....	2×10^6	13.3	28
Strontium sulfide	SrS	....	7.25×10^6	11.310	52
Strontium titanate	$SrTiO_3$	25	10^3	332	65
		−195	10^3	2,080	65
Sulfur (100)	S	25	10^2–10^3	3.75	63
(010)	....	25	10^2–10^3	3.95	63
(001)	....	25	10^2–10^3	4.44	63
Sublimed	....	25	10^2–10^3	3.69	63
Tantalum pentoxide (α)	Ta_2O_5	−196	10^3	30⊥	42
		−196	10^3	65∥	42
Tantalum pentoxide (β)	Ta_2O_5	19	10^3	24	42
Thallous bromide	TlBr	25	10^3–10^7	30.3	63
Thallous chloride	TlCl	....	2×10^6	31.9	28
Thallous iodide (orthorhombic)	TlI	20	10^4	21.2 ± 0.2	47
(cubic)	TlI	20	10^4	29.6 ± 0.5	47
(orthorhombic)	TlI	193	10^7	37.3	63
Thallous nitrate	$TlNO_3$	20	5×10^5	16.5	18
			$27\text{–}37 \times 10^9$	13.5	33
Thallous sulfate	Tl_2SO_4	20	5×10^5	25.5	18
Thorium dioxide	ThO_2	....	3×10^5	18.9 ± 0.4	2
		r.t.	2×10^6	10.6	24
Tin antimonide	SnSb	r.t.	10^4–10^6	147	32
Titanium dioxide (rutile)	TiO_2	r.t.	....	89 *a*	41
		r.t.	....	173 *c*	41
Uranium dioxide	UO_2	....	....	24	2
Ytterbium sesquioxide	Yb_2O_3	r.t.	10^3	5.0	22
Zinc malonate	$Zn(C_3H_2O_4)$	20	5×10^6	5.6	
Zinc monoxide	ZnO	....	....	8.14	13
Zinc selenide	ZnSe	25	10^4	9.12	4
Zinc sulfide	ZnS	25	10^4	8.37	4
Zinc telluride	ZnTe	25	10^4	10.10	4
Zirconium dioxide	ZrO_2	r.t.	2×10^6	12.5	24

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9f-9. Piezoelectric and Pyroelectric Constants

TABLE 9f-9. PIEZOELECTRIC STRAIN CONSTANTS*

Substance	Formula	d_{11}	d_{14}	d_{25}	d_{36}	Ref.
1. Aluminum phosphate	$AlPO_4$	±3.3	+1.5	......	......	29*
		+1.4	Small	......	......	12*
2. Ammonium dihydrogen arsenate	$NH_4H_2AsO_4$	....	+41	......	+31	12*
3. Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	....	−1.5	......	+48	12*
			+1.5	......	−45.6	40
			+1.7	......	+49	29*
4. Ammonium ditartrate	$NH_4HC_4H_4O_6$	....	−1.6	7.0	−0.4	35
5. Barium formate	$Ba(HCOO)_2$	....	±4.0	±2.7	±4.7	29*
6. Benzil	$C_{14}H_{10}O_2$	+8.0	....	......	......	42
7. Benzophenon	$(C_6H_5)_2CO$	....	+12.3	+2.0	+20.3	45
8. Beryllium sulfate tetrahydrate	$BeSO_4{:}4H_2O$	....	7	......	......	12*
9. Cadmiumtelluride	CdTe (−196°C)	....	+1.7	......	......	9*
10. Cesium tartrate	$Cs_2C_4H_4O_6$	2.7	0.17	......	......	12*
11. Deutero ammonium dideuterium phosphate	$ND_4D_2PO_4$	....	10	......	75	31
12. Dextrose plus sodium bromide	$C_6H_{12}O_6 + 2NaBr$	−3.7	−1.8	......	......	29*
13. Dextrose plus sodium chloride	$C_6H_{12}O_6 + 2NaCl$	−7.0	+0.3	......	......	29*
14. Dextrose plus sodium iodide	$C_6H_{12}O_6 + 2NaI$	−3.8	+0.7	......	......	29*
15. Galliumarsenide	GaAs	....	+2.6	......	......	15
16. Heavy rochelle salt	$KNaC_4D_2H_2O_6{\cdot}4D_2O$	....	Very large (see Table 9f-10)	−73	+13.3	30
17. Hexamethylentetramine	$(CH_2)_6N_4$	....	+17.5	......	......	18*
18. Iodic acid	HIO_3	....	±18.9	±15.3	±23.5	29*
19. Lithium ammonium tartrate monohydrate	$LiNH_4C_4H_4O_6{\cdot}H_2O$	....	±4.4	±6.5	±4.9	29*
			7.7	−5.3	6.8	35
20. Lithium potassium tartrate monohydrate	$LiKC_4H_4O_6{\cdot}H_2O$	....	+3.2	+11.2	±7.6	29*
			+2.0	−9.4	+6.6	35
21. Magnesium sulfate heptahydrate	$MgSO_4{\cdot}7H_2O$		2.1	10.0	6.8	12*
		....	−2.1	−2.7	−3.8	40
22. Mercury sulfide	HgS	+19.1	~1.7	......	......	11*
23. Nickel sulfate heptahydrate	$NiSO_4{\cdot}7H_2O$	....	−2.0	−2.9	−3.2	40
24. Nickel sulfate hexahydrate	$NiSO_4{\cdot}6H_2O$	....	−5.3	......	......	40
			±6.0	......	......	29*
25. Patchouli camphor	$C_{15}H_{26}O$	+0.05	....	......	......	42
26. Potassium dideuterium phosphate	KD_2PO_4	....	....	......	+51.7	2*
					+58	37
27. Potassium dihydrogen arsenate	KH_2AsO_4	....	+23.5	......	+22	12*
28. Potassium dihydrogen phosphate	KH_2PO_4		26.6	......	22.4	33
		....	+1.3	......	−20.9	40
			1.4	......	23	29*
			+1.3	......	+21	12*
29. Potassium ditartrate	$KHC_4H_4O_6$	....	−4.3	3.4	−1.0	35
30. Potassium dithionate	$K_2S_2O_6$	1.4	2.0	......	......	12*
31. Quartz	SiO_2	+2.31	−0.73	......	......	4
		+2.3	−0.67	......	......	13, 40
		−2.25	+0.85	......	......	29*
32. Rochelle salt	$KNaC_4H_4O_6{\cdot}4H_2O$	....	Very large (see Table 9f-10)	−56	+11.8	29*
				−53	+11.7	13
33. Rubidium dihydrogen phosphate	RbH_2PO_4	....	4.5	......	37	12*
34. Rubidium tartrate	$Rb_2C_4H_4O_6$	+2.7	....	......	......	42
35. Selenium	Se	65	....	......	......	17
36. Sodium ammonium tartrate tetrahydrate	$NaNH_4C_4H_4O_6{\cdot}4H_2O$	....	+18.7	−49.8	+9.4	28
			±19	±31.7	±10.3	29
37. Sodium bromate	$NaBrO_3$	....	−2.6	......	......	4
			−2.4	......	......	40
38. Sodium chlorate	$NaClO_3$		+2.7	......	......	29*
		....	−1.75	......	......	4, 40
			+2.0	......	......	29*
39. Strontium formate dihydrate	$Sr(HCOO)_2{\cdot}2H_2O$	....	±8.5	±11.5	±2.3	29*
40. Zinc selenide	ZnSe	....	+1.1	......	......	9*
41. Zinc sulfide (zincblende)	ZnS	....	−3.2	......	......	24
			+3.2	......	......	9*
42. Zinc telluride	ZnTe	....	+0.9	......	......	9*
43. Zinc sulfate heptahydrate	$ZnSO_4{\cdot}7H_2O$	....	−1.9	−3.5	−3.1	40

TABLE 9f-9. PIEZOELECTRIC STRAIN CONSTANTS* (*Continued*)

Substance	Formula	d_{15}	d_{22}	d_{24}	d_{31}	d_{32}	d_{33}	Ref.
44. Aluminium nitride	AlN	......	......		......	....	5.0	23*
45. Ammonium pentaborate tetrahydrate	$NH_4B_5O_8 \cdot 4H_2O$	+6.7	......	+13	−1.9	−6.6	+6.9	16*
46. Antimony sulfoiodide	SbSI	......	......	......	~150	....	1,300	10*
47. Barium antimonyl tartrate	$Ba(SbO)_2(C_4H_4O_6)_2 \cdot H_2O$	......	......	......	......	....	+3.7	42*
48. Barium titanate	$BaTiO_3$	392	......	......	−37	....	84	14*
					−34.5	....	85.6	7*
49. Barium titanate ceramic	$BaTiO_3$	270			−79	....	191	7*
50. Beryllium oxide	BeO	......	......	......	−0.12	....	+0.24	1*
51. Boracite	......	......	......	......	......	....	+0.6	39
52. Cadmium selenide	CdSe	−10.5	......	......	−3.9	....	+7.8	9*
53. Cadmium sulfide	CdS	−14.3	......	......	−3.7	....	+10.7	22*
54. Cesium nitrate	$CsNO_3$	......	......	......	......	....	+0.5	38
55. Lithium gallium oxide	$LiGaO_2$	+5.9	......	+5.1	−2.8	−2.4	......	11*
56. Lithium niobate	$LiNbO_3$	+74	+20.8	......	−0.86	....	+16.2	43
57. Lithium trisodium chromate hexahydrate	$LiNa_3(CrO_4)_2 \cdot 6H_2O$	......	±2.9	......	......	......	......	29*
58. Lithium trisodium molybdate hexahydrate	$LiNa_3(MoO_4)_2 \cdot 6H_2O$		±2.5	......	±1.3	....	±1.0	29*
59. Potassium lithium sulfate	$KLiSO_4$	+0.9	......	......	−2.35	....	+5.2	12*
60. Potassium pentaborate tetrahydrate	$KB_5O_8 \cdot 4H_2O$	+1.7	......	+9.5	<1	−5.4	+5.6	16*
61. Resorcinol	$C_6H_4(OH)_2$	+18.0	......	+18.4	−4.1	−4.3	+5.6	26
62. Sodium calcium aluminosilicate	$(Na_2Ca)_4(AlSiO_4)_5$ $CO_3(H_2O)_{0-3}$	+9.0	......	......	+0.7	....	+4.3	27
63. Sodium lithium sulfate	$NaLiSO_4$	......	0.85	......	+0.01	....	+0.3	12*
64. Sodium nitrite	$NaNO_2$	+9.3	......	−20.2	−1.2	−2.8	+1.7	19
65. Terpine monohydrate	$C_{10}H_{18}(OH)_2 \cdot H_2O$	+4.3	......	+5.8	−2.2	+3.5	+2.2	36
66. Tourmaline	variable	+3.7	−0.23	......	+0.25	....	+1.9	34
		−3.6	−0.33	......	−0.34	....	−1.8	29*
67. Zinc oxide	ZnO	−10 to −13	......	......	−4.7	....	+12	22*

Substance	Formula	d_{14}	d_{16}	d_{21}	d_{22}	d_{23}	d_{25}	d_{34}	d_{36}	Ref.
68. Anthracene	$C_{14}H_{10}$	......	......	−0.07	+0.16	−0.08	......	......	......	44
69. Cane sugar	$C_{12}H_{22}O_{11}$	+1.2	−2.4	+1.5	−3.4	+0.7	−0.9	−4.2	+0.4	20
70. Diammonium tartrate	$(NH_4)_2C_4H_4O_6$	+3.1	−2.8	+5.9	−8.7	+0.6	−2.0	−4.7	+1.9	40
		+3.3	+1.7	−6.7	+8.6	−0.6	+2.4	+1.8	+2.0	12*
71. Dipotassium tartrate hemihydrate	$K_2C_4H_4O_6 \cdot \frac{1}{2}H_2O$	+7.9	+3.5	−0.8	+4.5	−5.3	−6.5	−12.3	−23.2	6*
72. Ethylene diamine tartrate	$C_6H_{14}O_6N_2$	−10.0	−12.2	+10.1	+2.2	−11.3	−18.0	−17.0	−18.4	3*
73. Guanidine tartrate	$C_5H_{11}O_6N_3$	......	......	+2.6	......	−3.9	+3.3	......	......	12*
74. Lithium sulfate monohydrate	$Li_2SO_4 \cdot H_2O$	+0.76	−2.0	−3.6	+16.3	+1.7	−5.0	−2.1	−4.2	5*
75. Rhamnose	$C_6H_{12}O_5 \cdot H_2O$	+0.7	+5.0	+2.7	−3.0	−5.0	+12.2	−12.0	+1.1	32
76. Sorbitol hexacetate	$C_{18}H_{26}O_{12}$	1.4	23	0.5	−8	0.8	......	2	2	12
77. Tartaric acid	$C_4H_6O_6$	−13.2	+9.5	+2.0	−2.2	+0.65	+1.3	+9.3	−8.0	41
		+8.0	+5.3	−0.8	−2.2	−2.1	+0.4	−10.8	+11.7	29*
78. Triglycine sulfate	$(CH_2NH_2COOH)_3$ H_2SO_4	2.8	−4.6	23.6	7.9	25.3	24.3	−3.2	2.8	25
				23	22.0	84.0				21

Substance	Formula	d_{11}	d_{12}	d_{13}	d_{15}	d_{24}	d_{26}	d_{31}	d_{32}	d_{33}	d_{35}	Ref.
79. Lithium trihydrogen selenite	$LiH_3(SeO_3)_2$	+23.2	−22.3	−12.1	−46.6	−12.8	−14.6	−18.4	+5.5	+19.9	+53.2	8*

ADDENDUM

Substance	Formula	d_{14}	Ref.
80. Aluminum antimonide	AlSb	1.64	46
81. Indium antimonide	InSb	2.35	46
82. Indium arsenide	InAs	1.14	46
83. Gallium antimonide	GaSb	2.9	46

* According to the standards on piezoelectric crystals of the IRE [*Proc. IRE* **37**, 1378 (1949)] we define the piezoelectric strain constants $d_{ik} = (\partial D_i)/(\partial T_k)_E$ or $d_{ik} = (\partial S_k)/(\partial E_i)_T$, where $i = 1, 2, 3$, and $k = 1$ to 6; T_k = stress; S_k = strain; D_i = electric displacement; and E_i = electric field. The units are coulomb/newton or meter/volt (rationalized mks). The listed numbers have to be multiplied by 10^{-12}. In all cases marked by an asterisk the IRE convention of tension being a positive stress has been followed. For the other values quoted, the convention used is somewhat uncertain, although pressure is usually taken as positive.

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TABLE 9f-10. TEMPERATURE DEPENDENCE OF SOME PIEZOELECTRIC STRAIN CONSTANTS
($\times 10^{-12}$ in coulomb/newton or meter/volt)

Substance	Formula	d_{ij}	123 K	153 K	193 K	243 K	258 K	273 K	293 K	307 K	321 K	343 K	390 K	423 K	473 K	Ref.
Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	d_{36}	......	−83	−69	−55	−51	−48	−46	.....	....	....	.....	...	...	8
Barium titanate	$BaTiO_3$	d_{31}	......	....	....	....	.....	.....	−37	−38	−39	−42	−170	0	0	4
Barium titanate ceramics	$BaTiO_3$	d_{31}	......	....	....	−60	−65	−75	−85	−69	−64	−55	.....	...	...	2
Heavy rochelle salt	$KNaC_4H_2D_2O_6\cdot 4D_2O$	d_{14}	......	....	....	....	195	140	193	2,800	213	....	.....	...	...	3
Potassium dihydrogen phosphate	KH_2PO_4	d_{36}	20,000	135	50	29	26	23	21	.....	....	....	.....	...	...	1
Rochelle salt	$KNaC_4H_4O_6\cdot 4H_2O$	d_{14}	......	....	....	96	700	765	780	250	....	....	.....	...	...	7
					5.5	22	1,200	2,250	2,700	250	....	....	.....	...	...	8
						150	2,100	350	740	320	120	....	.....	...	...	2
Sodium bromate	$NaBrO_3$	d_{14}	......	....	....	....	.....	.....	2.7	2.8	3.0	3.2	3.7	4.1	5.1	5
Sodium chlorate	$NaClO_3$	d_{14}	......	....	....	....	.....	.....	2.0	2.2	2.3	2.5	3.1	3.8	5.4	5

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TABLE 9f-11. TEMPERATURE COEFFICIENT OF SOME PIEZOELECTRIC STRAIN CONSTANTS AT ROOM TEMPERATURE

Substance	Formula	α_{11}	α_{14}	α_{25}	α_{36}	Ref.
Iodic acid	HIO_3		+3.5	−3.5	−0.9	3
Lithium ammonium tartrate monohydrate	$LiNH_4C_4H_4O_6 \cdot H_2O$		+39	−50	+31	3
Quartz	SiO_2	~−10				2
		−2.15	12.9			1
Rochelle salt	$NaKC_4H_4O_6 \cdot 4H_2O$		See Table 9f-10.	+49	+10.9	4
Sodium ammonium tartrate tetrahydrate	$NaNH_4C_4H_4O_6 \cdot 4H_2O$		+2.1	−19	+12.1	3
Strontium formate dihydrate	$Sr(HCOO)_2 \cdot 2H_2O$		−8	−3.8	−14.7	3

Temperature coefficient α is defined as $\alpha_{ik} = \frac{1}{d_{ik}} \frac{\partial d_{ik}}{\partial \theta}$ where θ is the temperature. α_{ik} is measured in degrees^{-1}. The listed numbers have to be multiplied by 10^{-4}.

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TABLE 9f-12. TABLE OF PYROELECTRIC CONSTANTS*

Substance	Formula	p	References
1. Barium titanate (ceramic)	$BaTiO_3$	20	5
2. Calamine	$2ZnO \cdot SiO_2 \cdot H_2O$	2.0	2, 6
3. Cane sugar	$C_{12}H_{22}O_{11}$	0.18	4
4. Colmanite	$CaB_3O_4(OH)_3 \cdot H_2O$	0.03–0.3	3
5. Diammonium tartrate	$(NH_4)_2C_4H_4O_6$	0.95	1, 4
6. Dipotassium tartrate hemihydrate	$K_2C_4H_4O_6 \cdot \frac{1}{2}H_2O$	2.0	1, 4
7. Lithium selenate monohydrate	$Li_2SeO_4 \cdot H_2O$	5.7	1, 4
8. Lithium sodium sulfate	$LiNaSO_4$	0.75	1, 4
9. Lithium sulfate monohydrate	$Li_2SO_4 \cdot H_2O$	7.7	1, 4
10. Lithium trisodium selenate hexahydrate	$LiNa_3(SeO_4)_2 \cdot 6H_2O$	1.8	1, 4
11. Potassium lithium sulfate	$KLiSO_4$	1.6	1, 4
12. Resorcinol	$C_6H_6O_2$	2.6	4
13. Rhamnose	$C_6H_{12}O_5 \cdot H_2O$	1.2, 0.17	4
14. Scolecite	$CaAl_2Si_3O_{10} \cdot 3H_2O$	0.33	4
15. Strontium ditartrate tetrahydrate	$Sr(HC_4H_4O_6)_2 \cdot 4H_2O$	0.24, 2.7	1, 6
16. Tartaric acid	$C_4H_6O_6$	2.5	4
17. Tourmaline	Variable	0.35–0.44	1

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* The pyroelectric constant is defined as $p = (\partial D/\partial \theta)_{E=0}$, where D is the electric displacement, and θ the temperature. The units for p are coulomb/meter^2 degree (rationalized mks). The listed numbers have to be multiplied by 10^{-5}. They include both the true and the false pyroeffect.

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TABLE 9f-13. TEMPERATURE DEPENDENCE OF SOME PYROELECTRIC CONSTANTS*
($\times 10^{-5}$ in coulomb/meter^2 degree)

Substance	Formula	23 K	38 K	198 K	253 K	274 K	293 K	352 K	372 K	408 K	483 K	578 K	648 K
Diammonium tartrate	$(NH_4)_2C_4H_4O_6$	0.05	0.10	0.39	0.80	0.86	0.95	1.14					
Lithium selenate monohydrate	$Li_2SeO_4 \cdot H_2O$	0.31	0.77	3.28	4.82	5.33	5.70	6.45					
Lithium sodium sulfate	$LiNaSO_4$	0.04	0.10	0.29	0.54	0.68	0.75	0.91					
Lithium sulfate monohydrate	$Li_2SO_4 \cdot H_2O$	0.40	1.27	4.07	6.15	6.82	7.75	9.0					
Lithium trisodium selenate hexahydrate	$LiNa_3(SeO_4)_2 \cdot 6H_2O$	0.12	0.31	0.98	1.53	1.69	1.80	2.12					
Potassium lithium sulfate	$KLiSO_4$	.....	0.23	0.83	1.36	1.50	1.61	1.78					
Dipotassium tartrate hemihydrate	$K_2C_4H_4O_6 \cdot \frac{1}{2}H_2O$	0.13	0.33	1.10	1.70	1.87	1.99	2.30					
Strontium ditartrate tetrahydrate	$Sr(HC_4H_4O_6)_2 \cdot 4H_2O$	0.013	0.04	0.15	0.21	0.23	0.24	0.27					
Tourmaline	Yellow-green	0.027	0.097	0.32	0.40	0.41	0.43	0.44	0.45	0.46	0.50	0.56	0.62
	Rose-red	0.027	0.10	0.33	0.41	0.42	0.44	0.47	0.48	0.49	0.51	0.58	0.65
	Blue-green	0.013	0.047	0.22	0.31	0.34	0.35	0.39	0.40	0.41	0.42	0.46	0.51

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* W. Ackermann, *Ann. Physik* **46**, 197 (1915).

TABLE 9f-14. FERROELECTRIC CRYSTALS

Substance	Formula	Structure at room temp.	Ferroelectric axis	Curie point, K	Max spont. polarization, coulombs/meter²	Small-signal dielectric const at room temp.			Ref.
						ϵ_a/ϵ_v	ϵ_b/ϵ_v	ϵ_c/ϵ_v	
Heavy rochelle salt	$KNaC_4H_2D_2O_6 \cdot 4D_2O$	monoc.	*a*	308 upper, 251 lower	0.37×10^{-2} at 279 K	2,300 at θ up	9.4	9.8	17, 32, 49
Lithium ammonium tartrate monohydrate	$LiNH_4C_4H_4O_6 \cdot H_2O$	orthorh.	*b*	106	0.21×10^{-2} at $T \ll \theta$	7.2	8.0	6.9	53, 58
Lithium thallium tartrate monohydrate	$LiTlC_4H_4O_6 \cdot H_2O$	orthorh.	*a*	10	0.14×10^{-2} at $T \ll \theta$	...	...	...	53
Rochelle salt	$KNaC_4H_4O_6 \cdot 4H_2O$	monocl.	*a*	297 upper, 255 lower	0.24×10^{-2} at 276 K	4,000 at θ up	10.0	9.6	17
Cesium dideuterium arsenate	CsD_2AsO_4	tetrag.	*c*	212	...	...	...	...	86
Cesium dihydrogen arsenate	CsH_2AsO_4	tetrag.	*c*	143	...	...	...	...	26, 86
Potassium dideuterium arsenate	KD_2AsO_4	tetrag.	*c*	162	...	...	...	...	86
Potassium dideuterium phosphate	KD_2PO_4	tetrag.	*c*	213	4.8×10^{-2} at $T \ll \theta$	88	88	90	4, 86
Potassium dihydrogen arsenate	KH_2AsO_4	tetrag.	*c*	97	5.0×10^{-2} at $T \ll \theta$	62	62	22	16, 86
Potassium dihydrogen phosphate	KH_2PO_4	tetrag.	*c*	123	4.95×10^{-2} at $T \ll \theta$	42	42	21	16, 86
Rubidium dideuterium arsenate	RbD_2AsO_4	tetrag.	*c*	178	...	...	...	...	86
Rubidium dideuterium phosphate	RbD_2PO_4	tetrag.	*c*	218	...	...	...	...	54
Rubidium dihydrogen arsenate	RbH_2AsO_4	tetrag.	*c*	111	...	...	...	...	50, 86
Rubidium dihydrogen phosphate	RbH_2PO_4	tetrag.	*c*	146	5.6×10^{-2} at $T \ll \theta$	35	35	22	50, 86
Guanidine aluminum sulfate hexahydrate	$C(NH_2)_3Al(SO_4)_2 \cdot 6H_2O$	trigonal	*c*	none	0.35×10^{-2} at 296 K	5	5	6	34, 35
Guanidine chromium sulfate hexahydrate	$C(NH_2)_3Cr(SO_4)_2 \cdot 6H_2O$	trigonal	*c*	none	0.37×10^{-2} at 296 K	5	5	6	34, 35
Guanidine gallium sulfate hexahydrate	$C(NH_2)_3Ga(SO_4)_2 \cdot 6H_2O$	trigonal	*c*	none	0.37×10^{-2} at 296 K	5	5	6	34, 35
Guanidine vanadium sulfate hexahydrate	$C(NH_2)_3V(SO_4)_2 \cdot 6H_2O$	trigonal	*c*	none	0.38×10^{-2} at 296 K	...	...	...	77
Guanidine aluminum selenate hexahydrate	$C(NH_2)_3Al(SeO_4)_2$	trigonal	*c*	none	0.45×10^{-2} at 296 K	5	5	6	34, 35
Guanidine chromium selenate hexahydrate	$C(NH_2)_3Cr(SeO_4)_2 \cdot 6H_2O$	trigonal	*c*	none	0.47×10^{-2} at 296 K	5	5	6	34, 35
Guanidine gallium selenate hexahydrate	$C(NH_2)_3Ga(SeO_4)_2 \cdot 6H_2O$	trigonal	*c*	none	0.47×10^{-2} at 296 K	5	5	6	34, 35
Deuteroguanidine aluminum sulfate hexahydrate	$C(ND_2)_3Al(SO_4)_2 \cdot 6D_2O$	trigonal	*c*	none	0.35×10^{-2} at 296 K	5	5	6	34, 35
Methyl ammonium aluminum alum	$(CH_3NH_3)Al(SO_4)_2 \cdot 12H_2O$	cubic	cubic 111	176	1.0×10^{-2} at 166 K	9	9	9	64
Methyl ammonium chromium alum	$(CH_3NH_3)Cr(SO_4)_2 \cdot 12H_2O$	cubic	cubic 111	161	1.0×10^{-2} at 162 K	...	...	...	74
Methyl ammonium gallium alum	$(CH_3NH_3)Ga(SO_4)_2 \cdot 12H_2O$	cubic	cubic 111	171	...	...	...	...	74
Methyl ammonium indium alum	$(CH_3NH_3)In(SO_4)_2 \cdot 12H_2O$	cubic	cubic 111	164	1.2×10^{-2} at 162 K	...	...	...	74
Methyl ammonium iron alum	$(CH_3NH_3)Fe(SO_4)_2 \cdot 12H_2O$	cubic	cubic 111	169	1.3×10^{-2} at 167 K	...	...	...	74
Methyl ammonium vanadium alum	$(CH_3NH_3)V(SO_4)_2 \cdot 12H_2O$	cubic	cubic 111	157	0.9×10^{-2} at 155 K	...	...	...	74
Methyl ammonium aluminum (selenate) alum	$(CH_3NH_3)Al(SeO_4)_2 \cdot 12H_2O$	cubic	cubic 111	216	1.2×10^{-1} at 214 K	...	...	...	74
Deuterated methyl ammonium aluminum alum	$(CH_3ND_3)Al(SO_4)_2 \cdot 12D_2O$	cubic	cubic 111	177	1.0×10^{-1} at 175 K	...	...	...	74
Ammonium indium alum	$NH_4In(SO_4)_2 \cdot 12H_2O$	cubic	cubic 111	127	1.2×10^{-1} at 125 K	...	...	...	74
Ammonium iron alum	$NH_4Fe(SO_4)_2 \cdot 12H_2O$	cubic	cubic 111	88	0.4×10^{-1} at 86 K	...	...	...	74
Ammonium vanadium alum	$NH_4V(SO_4)_2 \cdot 12H_2O$	cubic	cubic 111	110	1.0×10^{-1} at 114 K	...	...	...	74
Deuterated ammonium iron alum	$ND_4Fe(SO_4)_2 \cdot 12D_2O$	cubic	cubic 111	88	0.4×10^{-1} at 86 K	...	...	...	74
Urea chromium alum	$(CONH_2NH_3)Cr(SO_4)_2 \cdot 12H_2O$	cubic	...	160	0.1×10^{-1} $T \ll \theta$	...	...	...	64
Ammonium bisulfate	$(NH_4)HSO_4$	monocl.	*c*	upper 270 lower 154	0.8×10^{-1} at 200 K	...	...	16	71
Ammonium sodium sulfate dihydrate	$NH_4NaSO_4 \cdot 2H_2O$								

Ammonium lithium sulfate	NH_4LiSO_4								
Ammonium sulfate	$(NH_4)_2SO_4$	orthorh.	*c*	224	$0.25–0.45 \times 10^{-2}$ at 215 K	10	9	9	37, 55, 62
Ammonium fluoberyllate	$(NH_4)_2BeF_4$	orthorh.	*b*	176	0.19×10^{-1} at 163 K	9	10	9	37, 55, 62
Deuteroammonium sulfate	$(ND_4)_2SO_4$	orthorh.	*c*	224	0.45×10^{-1} at 215 K	10	9	9	37
Deuteroammonium fluoberyllate	$(ND_4)BeF_4$	orthorh.	*b*	179	0.19×10^{-1} at 163 K	9	10	9	37
Diammonium dicadmium sulfate	$(NH_4)_2Cd_2(SO_4)_3$	cubic	cubic 111	89	0.3×10^{-2} at 83 K	9	9	....	45
Lithium trihydrogen selenite	$LiH_3(SeO_3)_2$	monocl.	*c*	none	15×10^{-2} at R.T.	29	13	30	72
Rubidium bisulfate	$RbHSO_4$	monocl.	*c*	258	0.65×10^{-1} at 178 K	7	8	10	73
Sodium trideuterium selenite	$NaD_3(SeO_3)_2$	monocl.	*a*	271	....	∼100	....	....	7
Sodium trihydrogen selenite	$NaH_3(SeO_3)_2$	monocl.	*a*	194	1.2×10^{-2} at *0*	∼100	....	....	7, 72
Deuterotriglycine sulfate	$(ND_3CH_2COOD)_3SO_4$	monocl.	*b*	333	....	....	....	....	
Diglycine manganous chloride dihydrate	$(NH_2CH_2COOH)_2\cdot MnCl_2\cdot 2H_2O$	monocl.	*b*	328	1.3×10^{-2} at 300 K	6.6	8.1	7.4	68
Diglycine nitrate	$(NH_2CH_2COOH)_2\cdot HNO_3$	monocl.	monocl. (101)	196	0.6×10^{-2} at 196 K	....	14	....	69
Glycine silver nitrate	$NH_2CH_2COOH\cdot AgNO_3$	monocl.	*b*	218	0.55×10^{-2} at 78 K	....	....	....	67
Triglycine fluoberyllate	$(CH_2NH_2COOH)_3H_2BeF_4$	monocl.	*b*	343	3.2×10^{-2} at R.T.	9	15	4	36
Triglycine selenate	$(CH_2NH_2COOH)_3H_2SeO_4$	monocl.	*b*	295-300	....	....	....	....	21, 36, 56
Triglycine sulfate	$(CH_2NH_2COOH)_3H_2SO_4$	monocl.	*b*	321	2.2×10^{-2} at R.T.	9	50	4	36, 56
Antimony sulfur bromide	SbSBr	orthorh.	*c*	93	....	....	....	....	60
Antimony sulfur iodide	SbSI	orthorh.	*c*	294	$\sim 25 \times 10^{-2}$ at 273 K	25	25	5×10^4	23
Bismuth sulfur bromide	BiSBr	orthorh.	*c*	103	....	....	....	....	60
Bismuth sulfur iodide	BiSI	orthorh.	*c*	113	....	....	....	....	60
Hydrogen bromide	HBr	....	....	89.7	0.4×10^{-2} at 78 K	....	....	....	38
Hydrogen chloride	HCl	....	....	98.4	1.2×10^{-2} at 90 K	....	....	....	38
Germanium telluride	GeTe	trig.	....	670	....	....	....	....	63
Ammonium monochloracetate	$(CH_2ClCOO)NH_4$	monocl.	*b*	∼123	$\sim 0.1 \times 10^{-1}$ at 78 K	....	5	....	66
Ammonium hydrogen dimonochloroacetate	$(CH_2ClCOO)_2H\cdot NH_4$	monocl.	102 axis	128	0.18×10^{-2} at 78 K	∼5 along ferroelectric axis			40
Boracite	$Mg_3B_7O_{13}Cl$	....	....	265	small	....	....	....	46
Nickel-iodine boracite	$Ni_3B_7O_{13}I$	cubic	....	64	small	....	∼14	....	2
Colmanite	$CaB_3O_4(OH)_3\cdot H_2O$	monocl.	*b*	271	0.5×10^{-2} at 235 K	....	∼20	....	30
Dicalcium strontium propionate	$Ca_2Sr(CH_3CH_2COO)_6$	tetrag.	*c*	282	0.3×10^{-2} at 228 K	....	....	....	57
Lithium hydrazinium sulfate	$Li(N_2H_5)SO_4$	orthorh.	*c*	none	0.3×10^{-2} at 300 K	....	....	14	70
Potassium ferrocyanide trihydrate	$K_4Fe(CN)_6\cdot 3H_2O$	monocl.	(010) plane	251	1.4×10^{-2} at 193 K	....	....	....	95, 96
Potassium rutenocyanide trihydrate	$K_4Ru(CN)_6\cdot 3H_2O$	monocl.	(010) plane	259	1.4×10^{-2} at 210 K	....	....	....	96
Potassium osmocyanide trihydrate	$K_4Os(CN)_6\cdot 3H_2O$	monocl.	(010) plane	271	3.5×10^{-2} at 227 K	....	....	....	96
Potassium manganocyanide trihydrate	$K_4Mn(CN)_6\cdot 3H_2O$	monocl.	(010) plane	233	....	....	....	....	96
Tetramethyl ammonium trichloromercurate	$((CH_3)_4N)\cdot HgCl_3$	monocl.	....	none	1.2×10^{-2} at R.T.	50 along ferroelectric axis			22, 24
Tetramethyl ammonium tribromomercurate	$((CH_3)_4N)\cdot HgBr_3$	monocl.	....	none	1×10^{-2} at R.T.	....	∼10	....	24, 22
Tetramethyl ammonium triiodomercurate	$((CH_3)_4N)\cdot HgI_3$	monocl.	....	none	1.7×10^{-2} at R.T.	....	∼10	....	24
Tetramethyl phosphonium tribromomercurate	$((CH_3)_4P)\cdot HgBr_3$	monocl.	....	none	3×10^{-2} at R.T.	....	∼10	....	24
Thiourea	$(NH_2)_2SC$	orthorh.	*b*	169	2.5×10^{-2} at 169 K	3	32	3	29, 85
Trisarcosine calcium chloride	$(CH_3NHCH_2COOH)_3CaCl_2$	orthorh.	*b*	127	0.27×10^{-2} at 78 K	....	5	....	48
Aluminum metaniobate (ceramics)	$AlNb_3O_9$	....	....	493	....	....	∼170	....	18
Barium metaniobate (ceramics)	$BaNb_2O_6$	....	....	∼343	....	....	∼130	....	18
Barium titanate	$BaTiO_3$	tetrag.	*c*	393	26×10^{-2} at 296 K	∼5,000	∼5,000	∼160	59, 81, 94
Bismuth titanate	$Bi_4Ti_3O_{12}$	orthorh.	*c*	916-948	3.5×10^{-2} at R.T.	....	....	112	75, 90
Cadmium niobate (ceramics)	$Cd_2Nb_2O_7$	cubic	....	188	6×10^{-2} at 93 K (111)	....	∼310	....	19, 44, 81
Lead metaniobate	$Pb(NbO_3)_2$	orthorh.	*a* + *b*	843	....	200	200	600	25, 31

TABLE 9f-14. FERROELECTRIC CRYSTALS (*Continued*)

Substance	Formula	Structure at room temp.	Ferroelectric axis	Curie point, K	Max spont. polarization, coulombs/meter²	Small-signal dielectric const at room temp.			Ref.
						ϵ_a/ϵ_v	ϵ_b/ϵ_v	ϵ_c/ϵ_v	
Lead metatantalate (ceramics)	$Pb(TaO_3)_2$	orthorh.	......	423	......	......	~1,200	......	25
				513	......	......	~300	......	42
Lead titanate (ceramics)	$PbTiO_3$	tetrag.	*c*	763	......	......	~50	......	80
Lithium niobate	$LiNbO_3$	trigonal	*c*	1468	71×10^{-2} at R.T.	84	84	30	1, 51, 97
Lithium tantalate	$LiTaO_3$	trigonal	*c*	891-938	50×10^{-2} at R.T.	51	51	45	1, 51, 76, 97
Manganese metatantalate (ceramics)	$MnTaO_3$	......	......	......	......	......	~750	......	18
Potassium iodate	KIO_3	trigonal	*c*	485	0.3×10^{-2} at R.T.	......	......	20	33
Potassium niobate	$KNbO_3$	orthorh.	*c*	691	26×10^{-2} at 691 K	......	......	~500	81, 89
Potassium nitrate	KNO_3	orthorh.	*c*	397	8.0×10^{-2} at 393 K	5	5	5	79
Potassium tantalate	$KTaO_3$	cubic	*c*	13	......	......	......	~500	39
Rare-earth manganates	$ErMnO_3$	hexag.	*c*	......	......	......	......	......	6
	$HoMnO_3$	hexag.	*c*	......	......	......	......	......	6
	$LuMnO_3$	hexag.	*c*	......	......	......	......	......	6
	$TmMnO_3$	hexag.	*c*	......	......	......	......	......	6
	$YbMnO_3$	hexag.	*c*	973-998	$4\text{-}5 \times 10^{-2}$ at R.T.	......	......	~20	9, 41
Yttrium manganate	$YMnO_3$	hexag.	*c*	933	$4\text{-}5 \times 10^{-2}$ at R.T.	......	......	~20	9, 41
Rare-earth molybdates	$Eu_2(MoO_4)_3$	orthorh.	*c*	434	0.14×10^{-2} at R.T.	......	......	9.5	13
	$Gd_2(MoO_4)_3$	orthorh.	*c*	432	0.17×10^{-2} at R.T.	......	......	10	13
	$Sm_2(MoO_4)_3$	orthorh.	*c*	463	0.24×10^{-2} at R.T.	......	......	12	13
	$Tb_2(MoO_4)_3$	orthorh.	*c*	430	0.18×10^{-2} at R.T.	......	......	11	13
Sodium niobate	$NaNbO_3$	orthorh.	*c*	<64	......	76	76	~670	20
Sodium nitrate	$NaNO_2$	orthorh.	*b*	437	8.6×10^{-2} at R.T.	7.5	8	5	61
Tungsten trioxide	WO_3	monocl.	......	......	probably ferroelectric				52
Mixed niobates									
(ceramic)	Ba_2BiNbO_6	rhomb.	......	633	......	......	......	......	93
	$Sr_{0.75}Ba_{0.25}Nb_2O_6$	tetrag.	*c*	333	14×10^{-2} at R.T.	......	......	3,400	5, 47, 97
	$Sr_{0.5}Ba_{0.5}Nb_2O_6$	tetrag.	*c*	403	......	......	......	450	5, 47
	$Sr_{0.25}Ba_{0.75}Nb_2O_6$	tetrag.	*c*	472	25×10^{-2} at R.T.	......	......	118	5, 47, 97
	$Pb_{0.4}Ba_{0.3}Sr_{0.3}Nb_2O_6$	tetrag.	*c*	415	......	......	......	......	78
	$PbO{=}2.5Nb_2O_5$	orthorh.	......	908	......	......	......	300	78
(ceramic)	$Ba_3CuNb_2O_9$	tetrag.	*c*	653	......	......	~50	......	93
(ceramic)	$BaBi_2Nb_2O_9$	orthorh.	......	473	......	......	~280	......	87
(ceramic)	$PbBi_2Nb_2O_9$	orthorh.	......	833	......	......	~170	......	82, 87
(ceramic)	$SrBi_2Nb_2O_9$	orthorh.	......	713	......	......	~190	......	87
(ceramic)	$Sr_3CuNb_2O_9$	tetrag.	*c*	663	......	......	......	......	93
(ceramic)	$PbSc_{\frac{1}{4}}Cr_{\frac{1}{4}}Nb_{\frac{1}{2}}O_3$	......	......	330	......	......	~1,270	......	88
(ceramic)	$PbFe_{\frac{1}{2}}Nb_{\frac{1}{2}}O_3$	rhomb.	......	393	......	......	~1,200	......	14
	$PbMg_{\frac{1}{3}}Nb_{\frac{2}{3}}O_3$	cubic	*c*	265	24×10^{-2} at 77 K	......	~10,000	......	8, 12

	$PbNi_{1/3}Nb_{2/3}O_3$	cubic	c	148	...	...	~1,600	...	8
	$K_3Li_2Nb_5O_{15}$	tetrag.	c	693	25×10^{-2} at R.T.	300	...	100	97, 11, 92
	$NaSr_2Nb_5O_{15}$	orthorh.	c	543	...	...	...	2,000	92
	$Na_3Li_2Nb_5O_{15}$	orthorh.	c	>1073	...	...	...	100	92
	$K_2NaLi_2Nb_5O_{15}$	tetrag.	c	...	...	...	...	500	92
	$KSr_2Nb_5O_{15}$	tetrag.	c	429	8×10^{-2} at R.T.	1,200	1,200	1,000	28, 97
	$KBa_2Nb_5O_{15}$	tetrag.	c	650–665	...	...	...	...	28, 15
	$KPb_2Nb_5O_{15}$	tetrag.	c	651	...	...	...	...	28
	$NaBa_2Nb_5O_{15}$	orthorh.	c	833–858	40×10^{-1} at R.T.	242	242	51	27, 28, 78, 97
	$NaPb_2Nb_5O_{15}$	tetrag.	c	779	...	...	...	...	28
	$RbSr_2Nb_5O_{15}$	tetrag.	c	412	...	...	...	...	28
	$RbPb_2Nb_5O_{15}$	tetrag.	c	714	...	...	...	...	28
	$K_3Li_2Ta_{2.5}Nb_{2.5}O_{15}$	tetrag.	c	303	...	...	...	30,000	11
Mixed tantalate									
(ceramic)	Ba_2BiTaO_6	rhomb.	...	673	...	...	...	...	93
(ceramic)	$Ba_3CuTa_2O_9$	tetrag.	c	743	...	...	...	...	93
(ceramic)	$Sr_3CuTa_2O_9$	tetrag.	c	1523	...	...	...	...	93
(ceramic)	$BaBi_2Ta_2O_9$	orthorh.	...	383	...	...	~400	...	87
(ceramic)	$PbBi_2Ta_2O_9$	orthorh.	...	703	...	...	~180	...	87
(ceramic)	$SrBi_2Ta_2O_9$	orthorh.	...	608	5.8×10^{-2} at R.T.	...	~180	...	87
(ceramic)	$PbFe_{1/2}Ta_{1/2}O_3$	...	...	243	...	...	...	...	83
Mixed titanates									
	$BiK(TiO_3)_2$	tetrag.	c	643	...	...	...	500	14, 43
	$BiNa(TiO_3)_2$	tetrag.	c	593	8×10^{-2} at 389 K	...	...	700	14, 43
(ceramic)	$BaBi_4Ti_4O_{15}$	orthorh.	...	668	...	...	~150	...	87
(ceramic)	$PbBi_4Ti_4O_{15}$	orthorh.	...	843	...	...	~220	...	87
(ceramic)	$SrBi_4Ti_4O_{15}$	orthorh.	...	803	...	...	~190	...	87
(ceramic)	$Na_{0.5}Bi_{4.5}Ti_4O_{15}$	orthorh.	...	928	...	...	~200	...	87
(ceramic)	$K_{0.5}Bi_{4.5}Ti_4O_{15}$	orthorh.	...	823	...	...	~140	...	87
	$Ba_2Bi_4Ti_5O_{18}$	tetrag.	c	602	2×10^{-2} at R.T.	...	...	400	3
(ceramic)	$Pb_2Bi_4Ti_5O_{18}$	...	...	583	6×10^{-2} at 508 K	...	~400	...	87
(ceramic)	$Sr_2Bi_4Ti_5O_{18}$	...	...	558	3.5×10^{-2} at 528 K	...	~280	...	87
Mixed tungstates									
(ceramic)	Ba_2CuWO_6	tetrag.	c	1473	...	...	...	...	93
(ceramic)	Sr_2CuWO_6	tetrag.	c	1193	...	...	...	...	93
(ceramic)	$Ba_3Bi_2WO_9$	rhombo.	...	723	...	...	...	...	93
(ceramic)	$PbSc_{2/3}W_{1/3}O_3$	...	...	261	...	...	~2,000	...	93
(ceramic)	$PbLi_{1/3}Nb_{1/3}W_{1/3}O_3$	...	...	233	...	...	...	...	93
(ceramic)	$PbLi_{1/4}Fe_{1/4}W_{1/2}O_3$	...	...	203	...	...	...	...	93
(ceramic)	$PbLi_{1/4}Yb_{1/4}W_{1/2}O_3$	...	...	243	...	...	~400	...	93
(ceramic)	$PbYb_{1/2}Ti_{1/4}W_{1/4}O_3$	...	...	323	...	...	...	...	93
(ceramic)	$PbFe_{2/3}W_{1/3}O_3$	...	...	178	...	...	~2,000	...	84
	$PbCo_{1/2}W_{1/2}O_3$	rhombo.	...	77	...	...	~250	...	10

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TABLE 9f-15. ANTIFERROELECTRIC CRYSTALS

Substance	Formula	Structure at room temperature	Transition temperature, K	Small-signal dielectric const. at room temperature			Ref.
				ϵ_a/ϵ_v	ϵ_b/ϵ_v	ϵ_c/ϵ_v	
Ammonium chromium sulfate	$NH_4Cr(SO_4)_2 \cdot 12H_2O$	....	82	...	.....	.....	22
Ammonium dihydrogen arsenate	$NH_4H_2AsO_4$	tetrag.	216	75	75	12	5,
Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	tetrag.	148	56	56	15, 5	5, 30
Ammonium paraperiodate	$(NH_4)_2H_3IO_6$	trigonal	251	143	143	180	2, 6
Barium bismuth molybdate (ceramic)	$Ba_3Bi_2MoO_9$	monocl.	773	...	.....	.....	29
Barium · bismuth vanadate (ceramic)	Ba_2BiVO_6	monocl.	593	...	~25	.....	29
Barium hafnate (ceramic)	$BaHfO_3$	cubic	488	...	~90	.....	19
Cesium trihydrogen selenite	$CsH_3(SeO_3)_2$	triclinic	145	80	60	30	14
Copper formate tetrahydrate	$Cu(HCOO)_2 \cdot 4H_2O$	monocl.	234	20	400	.....	21
Deuteroammonium dideuterium arsenate	$ND_4D_2AsO_4$	orthorh.	304	...	.....	.....	9
Deuteroammonium dideuterium phosphate	$ND_4D_2PO_4$	tetragonal	243	73	73	22, 5	15, 18
Deuteroammonium paraperiodate	$(ND_4)_2D_3IO_6$	trigonal	266	...	.....	.....	1
Deuterosilver paraperiodate	$Ag_2D_3IO_5$	trigonal	279	...	.....	.....	11
Lead cadmium niobium tungsten oxide (ceramic)	$PbCd_{\frac{4}{9}}Nb_{\frac{2}{9}}W_{\frac{1}{3}}O_3$	....	768	...	~200	.....	28, 29
Lead cobalt tungstate	Pb_2CoWO_6	rhomb.	305	...	.....	~250	4
Lead hafnate (ceramic)	$PbHfO_3$	tetragonal	488	...	~90	.....	24
Lead magnesium tungstate (ceramic)	Pb_2MgWO_6	....	311	...	~140	.....	27
Lead manganese tungsten oxide (ceramic)	Pb_2MnWO_6	....	423	...	~150	.....	29
Lead metaniobate	$PbTa_2O_6$	....	343	...	~860	.....	7
Lead nickel tungsten oxide (ceramic)	Pb_2NiWO_6	cubic	290	...	~50	.....	20
Lead silicate (ceramic)	Pb_4SiO_6	....	428	...	~23	.....	13
Lead vanadite (ceramic)	$Pb_3V_2O_5$	....	373	...	~30	.....	12
Lead zirconate (ceramic)	$PbZrO_3$	orthorh.	506	...	~80	.....	25, 26
Silver paraperiodate (powder)	$Ag_2H_3IO_6$	trigonal	227	...	~57	.....	2, 10, 11
Sodium niobate	$NaNbO_3$	orthorh.	911	76	76	670	8, 16
Sodium tantalate	$NaTaO_3$	orthorh.	....	...	.....	.....	16
Sodium trideuterium selenite	$NaD_3(SeO_3)_2$	monocl.	271	100	.....	.....	3
Tungsten trioxide	WO_3	triclinic	1013	...	.....	.....	17, 23

References for Table 9f-15

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