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# Supersonic Phenomena

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## INTRODUCTION

IN THE past ten years considerable interest has developed among physicists and chemists in several aspects of the phenomena accompanying the production and propagation of ultra-audible sound waves. The purpose of this article is to give, insofar as they are at present understood, the explanations for these phenomena. An attempt has been made throughout to make the exposition as simple as is compatible with clarity, and to refer to experiment at every possible point. It is hoped that this may provide a convenient starting point for the understanding of experimental investigations into the subject. Copious references to a fairly complete bibliography have been given, and these may perhaps be useful to those who are already familiar with what has here been written.

The review consists of three parts. In the first of these, expressions for the propagation of plane waves of sound as a function of amplitude, pressure, density, temperature and frequency are derived. The second part gives a brief review of the various methods of measuring the velocity and absorption of sound, and the interpretation of the measurements which have been reported by different investigators. The third section reviews the effects of very intense sound waves.

Perhaps it should be stated at the outset that the terms *supersonic*, *ultrasonic*, and the ungraceful *ultra-acoustic* are here considered synonymous, and refer to sound of frequency too great to be audible. An attempt was made by some of the workers at the Loomis Laboratory to give two of them separate meanings, but since this has not become general practice there is little to be gained by laboring the point further.

## THE THEORY OF THE PROPAGATION OF PLANE SOUND WAVES

In developing expressions for the propagation of sound in media of various properties it has been considered expedient to return to first principles. This renders unnecessary references to other publications, and makes explicit any approximations later to be used as the foundation for general conclusions.

We shall consider first the velocity of sound in an isotropic homogeneous medium and retain the first order of small quantities throughout. (A numerical example will then be given to show that this is sufficiently accurate to describe contemporary experiment.) The passage of a plane sound wave through this fluid in the $x$ direction will cause it to undergo periodic local displacements resulting in periodic variations from its equilibrium pressure $P$ and density $\rho$. In particular, a slice of the medium of unit cross section and finite thickness $\tau$ will have its boundaries displaced by the amounts $\xi$ and $\xi+(\partial\xi/\partial x)\tau$, respectively. The total mass in the undisplaced slice is $\rho_0\tau$, which is equal to the mass in the displaced slice $\rho\tau[1+\partial\xi/\partial x]$, and hence, the density at $A'$ and $B'$ (see Fig. 1) is given by

$$\rho_{A'}=\frac{\rho_0}{1+\partial\xi/\partial x}$$

and $$\rho_{B'}=\frac{\rho_0}{1+\partial\xi/\partial x+(\partial^2\xi/\partial x^2)\tau}. \tag{1}$$

It will now be convenient to assume, subject to later proof, that the sound wave is transmitted adiabatically, hence

$$P/\rho^\gamma=P_0/\rho_0{}^\gamma. \tag{2}$$

If this is true the pressures on the two faces of the displaced slice will be

$$P_{A'}=(P_0/\rho_0{}^\gamma)[\rho_0(1+\partial\xi/\partial x)^{-1}]^\gamma$$

and $$P_{B'}=(P_0/\rho_0{}^\gamma)\left[\rho_0\left(1+\frac{\partial\xi}{\partial x}+\frac{\partial^2\xi}{\partial x^2}\tau\right)^{-1}\right]^\gamma.$$

In expanding $P_{B'}$ it is necessary to retain only terms in the first power of $\tau$, since this quantity may be taken arbitrarily small. This gives

$$P_{B'}=(P_0/\rho_0{}^\gamma)\left(\frac{\rho_0}{1+\partial\xi/\partial x}\right)^\gamma \times\left(1-\frac{\partial^2\xi/\partial x^2}{1+\partial\xi/\partial x}\cdot\gamma\tau\right). \tag{3}$$

The difference in pressure $P_{A'}-P_{B'}$ multiplied by unit cross section is the displacing force, and is equal to the invariant mass $\rho_0\tau$ times the acceleration $\partial^2\xi/\partial t^2$. This is, to the first order of small quantities,

$$\tau\gamma P_0\partial^2\xi/\partial x^2=\tau\rho_0\frac{\partial^2\xi}{\partial t^2}(1+\partial\xi/\partial x)^{\gamma+1},$$

or $$\frac{\partial^2\xi}{\partial t^2}\bigg/\frac{\partial^2\xi}{\partial x^2}=\frac{P_0\gamma}{\rho_0}\left(1+\frac{\partial\xi}{\partial x}\right)^{-(\gamma+1)} \tag{4}$$

and gives rigorously the equation of motion. It is perhaps worth mention in passing that several more compact derivations in current texts are not correct (cf. Lamb,[19] page 177). For very small amplitudes $\tau$ may be neglected, and the solution

$$\xi=Ae^{i\omega(t-x/V)}, \tag{5}$$

where $A$ is the amplitude of $\xi$ and $\omega$ is the frequency of a wave traveling in the $x$ direction with a phase velocity $V$ gives

$$V_0{}^2=P_0\gamma/\rho_0=(\partial P/\partial\rho)_{\text{adiab}}. \tag{6}$$

The coefficient $(\partial P/\partial\rho)_{\text{adiab}}$ is, of course, evaluated for the case $\rho=\rho_0$.

When the amplitude is finite the left-hand side of (4) does not represent a phase velocity because in this approximation $\partial\xi/\partial x$ is a periodic function of $t$ and $x$. It is negative at one time and positive at another. The meaning of (4) is that the denser portions of the wave, in which $\partial\xi/\partial x$ is negative from (1), are traveling more rapidly than the rarified portions. This is without effect on the phase velocity to the first approximation. Fay[23] has shown, in a much more detailed analysis, that although waves of finite amplitude may depart strikingly from the sinusoidal form, becoming "saw-toothed," the wave will not obliterate itself from this cause. Viscosity limits the steepness of the wave front which may be attained because of

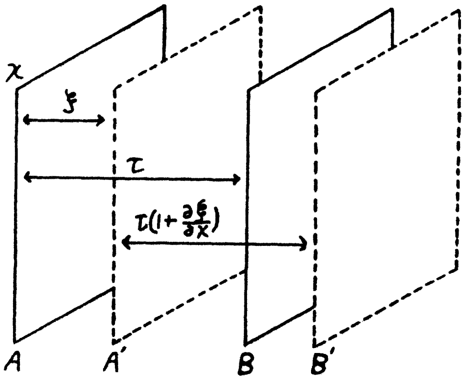

FIG. 1. Distances of the boundaries of an undisplaced slice of fluid (solid lines), and the same slice after a time $t$ displaced by a plane sound wave moving in the $x$ direction (dotted lines). In the text the slice is taken of unit cross section.

the tendency of the crests of the wave to overtake the troughs. A rapid attenuation of waves of finite amplitude does, however, result; this attenuation may be more than twenty times as great as that resulting from the viscous damping of a sinusoidal disturbance. An alteration of frequency is also entailed.[29] Audible sound, for example, which comes from a considerable distance, may have lost much of its low frequency components partly by attenuation, and partly by the passing of energy into higher frequencies. Fay's analysis shows that the effect of this on the velocity of propagation is negligible unless the intensity is sufficiently great to alter the mean density of the fluid.

It will be convenient to examine at this point the amplitudes of the waves currently used in the measurement of the velocity of sound and justify by a numerical example the use of (6) for the interpretation of experiments made with small but finite amplitudes. The ratio of the velocities of sound at zero amplitude, $V_0$, and at amplitude $A$, $V_A$, may be obtained by an expansion of (4)

$$V_0/V_A=1+\frac{\gamma(\gamma+1)}{4}(\partial\xi/\partial x)^2.$$

The second term of this expansion is omitted because it is obviously zero for a sinusoidal wave and appears also to be zero, from Fay's data, for a "saw-toothed" wave. Pielemeyer[175] gives 130 decibels as a reasonable maximum for the intensity, and supports this figure by observations made by Andrade on particle motion at resonance in a Kundt's tube. This corresponds to a value for $\partial\xi/\partial x$ of 0.004, and, for a fluid for which $\gamma=1.4$, affects the velocity of sound only about 0.001 percent. This figure is free from the troublesome objection that the amplitude at resonance cannot be obtained from the power output. It is perhaps worth mentioning, however, that 130 decibels corresponds to an acoustical output of 0.1 watt per cm$^2$. In view of the inefficiency of the conversion of electrical energy into sound because of reflection phenomena at the surface of an oscillator, and the fact that most ultrasonic generators are driven by only a few watts, this intensity appears generous for gases even at resonance. On the basis of this paragraph, (6) will be used as the fundamental acoustical equation, and effects due to amplitude will be neglected when the velocity of sound is discussed.

The assumption that the sound is transmitted adiabatically, which was made in writing (2), may now be justified by an appeal to experiment. Actually Stokes[194] and Kirchhoff[154] have shown that viscous loss and loss due to heat conduction will be negligible except near the walls of the containing vessel. Since their arguments are lengthy and of little contemporary interest it has been considered preferable to refer to measurements, which are given in Table I. The agreement with the adiabatic hypothesis for both gases and liquids is excellent, and such disharmony as remains is probably due to the difficulty in obtaining accurate measurements of the isothermal compressibility.

The next step in generalizing (6) is the introduction of the temperature. This may be done by writing $P=f(\rho, T)$ and considering $T$ as a function of $S$ and $\rho$. We then have

$$(\partial P/\partial\rho)_S=(\partial P/\partial\rho)_T+(\partial P/\partial T)_\rho(\partial T/\partial\rho)_S,$$

where $S$ is the entropy and $T$ the temperature. Similarly if the internal energy $E=f(\rho, T)$, then

$$\left(\frac{\partial T}{\partial\rho}\right)_S=\frac{(\partial E/\partial\rho)_S-(\partial E/\partial\rho)_T}{(\partial E/\partial T)_\rho}.$$

Since $(\partial E/\partial\rho)_S=MP/\rho^2$ and $(\partial E/\partial T)_\rho\equiv C$, the heat capacity for one gram molecular weight $M$ at constant volume,

$$\left(\frac{\partial P}{\partial\rho}\right)_S=\left(\frac{\partial P}{\partial\rho}\right)_T+\left(\frac{\partial P}{\partial T}\right)_\rho\cdot\frac{M}{\rho^2}\cdot\frac{P+(\partial E/\partial v)_T}{C}.$$

Finally, the so-called "thermodynamic equation of state" gives for the sum of external and internal pressures

$$P+(\partial E/\partial v)_T=T(\partial P/\partial T)_v,$$

which, on substitution in the previous equation, gives the velocity of sound in any homogeneous isotropic substance as a function of $P$, $T$, and $\rho$

$$V^2=(\partial P/\partial\rho)_T+(\partial P/\partial T)_\rho{}^2\cdot(MT/C\rho^2). \quad (7)$$

It is convenient next to consider absorption, and its effect on the velocity. This is usually effected by an analytical device borrowed from optics, which treats $V$ in (5) as a complex number. For example it may be written that $\xi = Ae^{-\beta x}e^{i\omega(t-x/c)}$ or

$$V_c = c/(1 - i\beta c/\omega), \tag{8}$$

in which $c$ has the dimensions of a velocity but is not quite equal to the phase velocity, and $\beta$ is the absorption coefficient for the amplitude expressed as a reciprocal length. This is exactly equivalent to writing (4) with a damped velocity term, but has the advantage of being considerably more easy to treat analytically. Since $\beta$ and $c$ are not functions of $x$ and $t$ it follows as before that

$$V_c^2 = (\partial^2\xi/\partial t^2)/(\partial^2\xi/\partial x^2)$$

and the effect of the absorption on the velocity is seen to be

$$\text{real part } (V_c^2)^{\frac{1}{2}} = V = c\left(\frac{1-\beta^2c^2/\omega^2}{(1+\beta^2c^2/\omega^2)^2}\right)^{\frac{1}{2}}.$$

The absorption coefficient could, of course, be obtained from the imaginary part of $V_c^2$, but it happens to be more convenient to use the imaginary part of $1/V_c^2$. The reason for this will be appreciated if the reciprocal of (8) is squared. The result is $-2i\beta/\omega c =$ imaginary part of $(1/V_c^2)$. It has been briefly mentioned above that absorption may occur because of viscosity, heat conduction, and finite amplitude of the waves; no further attention will be given to these causes. Absorption caused by failure of part of the heat capacity of a polyatomic gas to participate in the adiabatic acoustical cycle at high frequencies is of greater contemporary interest, and an expression for this, together with corresponding expressions for the velocity, will now be developed.

TABLE I. *Experimental verification of the adiabatic hypothesis.*

| SUBSTANCE | $T$* | $\gamma$** | $V_{\text{obs}}$† | $V_s$†† | $V_T$†† |
|---|---|---|---|---|---|
| Argon | 303.1 | 1.667 | 324.0 | 324.2 | 251.2 |
| Nitrogen | 273.1 | 1.400 | 337.3 | 336.7 | 284.5 |
| Benzol | 293.1 | 1.45 | 1324 | 1319 | 1095 |
| Toluol | 293.1 | 1.34 | 1328 | 1317 | 1138 |
| Carbon tetrachloride | 293.1 | 1.46 | 935 | 931 | 774 |

* $T$ is in ° Kelvin.

** $\gamma$ has been obtained for the gases from theoretical considerations, and from the ratio of the isothermal to the adiabatic compressibility $\beta_T/\beta_s$ (given in *International Critical Tables* 3, 39) for the liquids.

† $V_{\text{obs}}$ is the measured velocity of sound in $m$ sec.$^{-1}$ and has been reported in reference 179, p. 121 for argon, by several observers in *International Critical Tables* for nitrogen, and in reference 220 for the three liquids.

†† $V_s = (\gamma/\rho\beta_T)^{\frac{1}{2}}$ and $V_T = (1/\rho\beta_T)^{\frac{1}{2}}$ were calculated from data in the *International Critical Tables.*

A glance at the coefficients on the right-hand side of (7) shows that $(\partial P/\partial\rho)_T$ is simply related to the isothermal compressibility, and that $(\partial P/\partial T)_\rho$ is the ratio of the thermal coefficient of expansion and the compressibility. Both these involve adjustments of translational energy, and of the attractive and repulsive forces between molecules, but neither is concerned with the conversion of translational energy into rotational energy or vibrational energy within the molecule. From what we know of the nature of the van der Waals forces we should expect them to follow the changes in the sound wave except at very high acoustic frequencies. For the treatment of gases it is sufficient, therefore, to consider that the heat capacity is the only coefficient which fails to follow the sound wave in the range of frequencies at present experimentally available.

If the change of temperature of the translational energy of a gas due to the passage of a sound wave of frequency $\omega$ be momentarily $\Delta T$ an amount of heat will be absorbed which may be called $C_\omega\Delta T$. Thus $C_\omega$ is the heat capacity which is effective at the frequency $\omega$, and is made up of several parts. Specifically,

$$C_\omega\Delta T = (3/2)R\Delta T + E_A\sum_l l\Delta n_l + \sum_m m\Delta n_m + \cdots.$$

Here the first term on the right refers to changes of translational energy, and the subsequent terms express energy changes in a series of rotational and vibrational states corresponding to the optical frequencies $\nu_A = E_A/hN_a$ etc.; $h$ is Planck's constant and $N_a$ is Avogadro's number. The symbols $n_l$, $n_m$, etc. refer therefore to the factions of gram molecular weights in the $l$th, $m$th, etc. states, and are subject to the restrictions $\sum_l n_l = 1$, etc. Experiment shows, however, that the rotational states are excited by changes in translational energy at a rate sufficient to maintain their equilibrium distribution at all frequencies which have been studied. A simplified expression for $C_\omega\Delta T$ may therefore be written. The simplest case of all is that in which the difference between the heat capacity at very low frequencies $C_0$, and that at very high frequencies $C_\infty$, is due only to a single $0 \rightleftarrows 1$ transition; the higher states of the vibration are not excited appreciably. In this case $h\nu \gg kT$, $n_0 \gg n_1$, $n_2 \cong 0$, and

$$C_0 = C_\infty + E(\partial n_1/\partial T).$$

Since at equilibrium $\bar{n}_1 = \bar{n}_0 e^{-x}$ where $x = h\nu/kT$, and since at all times $n_0 + n_1 = 1$, it follows that

$$E(\partial n_1/\partial T) = Rx^2 e^{-x}/(1+e^{-x})^2 = C_0 - C_\infty. \quad (9a)$$

But, since $\bar{n}_2 = \bar{n}_0 e^{-2x} = 0$, this result is not physically consequent as it contains terms in $e^{-2x}$. By expanding, and discarding these we obtain the correct first approximation

$$C_0 = C_\infty + Rx^2 e^{-x}. \quad (9b)$$

To find the dependence of $C_0 - C_\infty$ on frequency it is necessary to express the rates of the transitions $0 \rightarrow 1$ and $1 \rightarrow 0$. This is most simply done by writing a reaction equation such as

$$dn_1/dt = f_{01} n_0 - f_{10} n_1, \quad (10)$$

where $f_{01}$ and $f_{10}$ are the probabilities of the $0 \rightarrow 1$ and $1 \rightarrow 0$ transitions per molecule per second, due not necessarily only to collisions, but to any cause whatever. Thus $f_{10}$ is the number of times per second that a molecule in the state 1 leaves the state 1 for the state 0. At equilibrium $dn_1/dt = 0$ and $f_{01} = e^{-x} f_{10}$. It is not necessary, if the reaction equation is stated in this way, to include a term to account for pressure fluctuations of the gas, since $n_0$ and $n_1$ are not functions of the pressure.

Since we wish to find the dependence on frequency of this part of the heat capacity, we must examine a case where equilibrium has not been attained, and $dn_1/dt$ is therefore not equal to zero. This means that the variables $n_1$, $f_{10}$, and $T$ will be displaced from their equilibrium values by small finite amounts $\Delta n_1$, $\Delta f_{10}$, and $\Delta T$. For example $n_1 = \bar{n}_1 + \Delta n_1$, etc. The displaced equation, in which second-order terms are disregarded, is

$$d\Delta n_1/dt = f_{10}(\bar{n}_0 \Delta e^{-x} + e^{-x} \Delta n_0 - \Delta n_1). \quad (11)$$

The time derivative may be evaluated from the statement $\Delta n_1 = \text{const}\, e^{i\omega t}$ which expresses the harmonic character of the sound wave. Furthermore $\Delta e^{-x} = e^{-x} \Delta T/T$, since $x$ is a function of temperature only. Incorporating these changes, and remembering that $\Delta n_0 = -\Delta n_1$, we obtain

$$\Delta n_1 = \frac{n_0 f_{10} x e^{-x} \Delta T}{T[i\omega + f_{10}(1+e^{-x})]}.$$

The energy change is of course $E\Delta n_1$ where $E = h\nu N_a = RTx$. Hence

$$E\Delta n_1 = \frac{n_0 f_{10} R x^2 e^{-x} \Delta T}{i\omega + f_{10}(1+e^{-x})}.$$

If we substitute from (9a), we obtain

$$E\Delta n_1 = \frac{(f_{10} + f_{01})(C_0 - C_\infty)}{i\omega + f_{10} + f_{01}}$$

which is the expression printed by Kneser[156] and several others. It has been pointed out by Rose[187] and others that this is not the consequent approximation, since it contains terms in $e^{-2x}$. In order to eliminate these $f_{01}$ must be neglected, and the result is

$$C_\omega = C_\infty + \frac{C_0 - C_\infty}{1 + i\omega\theta}. \quad (12)$$

Here the notation $\theta = 1/f_{10}$ has been introduced since it will serve as a useful abbreviation later; $\theta$ is often referred to as the "relaxation time" or better the "mean lifetime" of the state 1. When (12) is substituted into (7) we obtain

$$V_c^2 = \left(\frac{\partial P}{\partial \rho}\right)_T + \left(\frac{\partial P}{\partial T}\right)^2 \frac{MT(1 + i\omega\theta)}{C_0 + C_\infty i\omega\theta}. \quad (13)$$

Equation (13) is the fundamental statement on which is based the interpretation of acoustical dispersion in polyatomic gases. The phase velocity is obtained from the real part of the square root of (13), together with some equation of state. Far from the critical point the equation of state of an ideal gas

$$MP/\rho = RT$$

may be used, and the velocity is in this case

$$V = \left\{ \frac{RT}{M} \left( 1 + \frac{R(C_0 + C_\infty \omega^2 \theta^2)}{C_0^2 + C_\infty^2 \omega^2 \theta^2} \right) \right\}^{\frac{1}{2}},$$

whereas the absorption coefficient for the intensity, $\mu$, expressed as a reciprocal number of wave-lengths is (cf. reference 179, page 739).

$$\mu=2\beta\lambda=\frac{2\pi C_\infty\omega}{C_0 f_{10}}\left\{\frac{V_\infty^2/V_0^2-1}{(V_\infty^2/V_0^2)(C_\infty\omega/C_0 f_{10})^2+1}\right\}.$$

We must now pause briefly to comment on some aspects of the reasoning process by which (13) has been obtained, and to trace its history. Since Bourgin[134] has recently subjected this expression to a thorough critical examination, only the more superficial implications and inaccuracies of the derivation will be considered.

It should first be noted that (13) has been obtained without any assumption concerning the mechanism by which the $0\rightleftarrows 1$ transition is brought about. It is not, therefore, a collision theory inherently, although most writers obtain an identical expression by means of explicit assumptions concerning the transition probability and the pressure. Again, the statement $\theta f_{10}=1$ is true only if the number of molecules in the state 2 is less than the number which experiment can detect. With many gases, such as carbon dioxide, this is not the case, and the significance of $\theta$ must be revised in a way which will shortly be indicated. Further, the notation

$$C_\infty=3R/2+E_A\sum_l l\Delta n_l+\text{etc.}$$

is, as Bourgin remarks, convenient but physically fictional, since even states of very short lifetime lag slightly at any frequency. A numerical computation shows, however, that the dispersion due to any group of states with a common lifetime may be detected only over about two orders of magnitude of frequency if the accuracy of the velocity measurement is 0.1 percent, as in the best of contemporary work. The influence on absorption measurements is about the same. Since experiment shows that the lifetimes of the rotational states of gases are far shorter than those of most, if not all, vibrational states, the inclusion of the rotational heat capacity in $C_\infty$ is in most cases sound from the standpoint of measurement.

One further consideration underlying (13), which in no way affects the accuracy of the expression, but is often discussed by writers on dispersion, should be mentioned for the sake of completeness. This is the phase lag between the pressure and the density in a dispersive region. This comes about because in the dispersive region the lifetime of the energy-absorbing process is of the same order of magnitude as the reciprocal of the frequency, whereas the lifetime of a collision must necessarily be much less than the reciprocal of the frequency for the wave to be transmitted at all. Thus adjustments in internal energy lag behind adjustments in translational energy, the pressure impulse leads the density, and part of the energy of the wave is absorbed. This is much simpler to state analytically than it is to say in words. We write for the pressure impulse

$$\Delta P=A'\exp\left[i\varphi+i\omega(t-x/V_c)\right]$$

and allow it to lead the density impulse

$$\Delta\rho=A''\exp\left[i\omega(t-x/V_c)\right]$$

by an angle $\varphi$. Then we equate real and imaginary parts in the ratio $\Delta P/\Delta\rho$ and obtain

$$\frac{\omega^2}{c^2}-\beta^2=\frac{A''}{A'}\omega^2\cos\varphi;\quad \frac{2\beta\omega}{c}=\frac{A''}{A'}\omega^2\sin\varphi,$$

which lead to a convenient expression for the absorption coefficient

$$\mu=2\beta\lambda=2\pi\tan\varphi.$$

The type of expression which (13) represents was apparently first foreseen by Jeans.[153] It was put in articulate form by Einstein in 1920[138] in connection with the rate of dissociation of polymolecular vapors. In the case of a dissociating gas, of course, the heat capacity at very low frequencies contains the heat absorbed by the dissociation reaction. If the heat capacity is independent of frequency, the only cause for dispersion will be the lag of the dissociation reaction, and this permits the treatment of an ideal dissociating gas to be carried through very simply. Since the resulting expressions have been widely discussed in this country[169, 179] it does not appear necessary to reprint them. Herzfeld and Rice[148] gave an explanation for anomalous velocities and absorptions in nondissociating gases which was similar in intent to that of Jeans. These treatments are essentially continuous fluid theories. Immediately following this Bourgin[134] wrote a very complete theory for the propagation of sound in gases using the statistical discipline; he considered viscosity, quantization of the collision process, radiation from excited molecules, and dispersive gaseous mixtures. In 1931 Kneser renewed interest in the subject by reporting a series of measurements on carbon dioxide, and writing a theory for them based on Einstein's treatment. Kneser's exposition[156] was made more rigorous by Rutgers,[189] who followed Einstein even more closely. Meanwhile Bourgin wrote the theory of the three-state gas (a gas with the translational energy and two sets of internal energy states with separate characteristic lifetimes). Other writers have given descriptions of absorption in nondissociating gases,[144, 147, 158] absorption in a real dissociating[169] gas, and the velocity in an ideal dissociating gas in which the heat capacity and the dissociation reaction have separate characteristic lifetimes.[179] Treatments of real nondissociating gases have been given in which van der Waals' equation,[181] Sutherland's equation,[140] and Onnes's second virial coefficient[152] are used, and several versions of the three-state gas have appeared.[134, 166, 180, 187] All of these papers are based either on the thermodynamic theory developed by Einstein or the quantized kinetic theory given by Bourgin. In his last paper Bourgin has shown that the results of the two are equivalent, but that the statistical theory is the more comprehensive and logical. I agree with this, and regret that, in spite of the expenditure of considerable effort, I was unable to develop a presentation of his work sufficiently simple and compact to be included in this review.

The overwhelming majority of writers prefer to consider that the 0→1, etc. transitions are brought solely by effective collisions. Thus the transition probabilities of the $f_{l,\,l+1}$ type are set equal to the product of a molecular velocity, a target area involving the cross section of the molecules, and one or more efficiency factors. An example of such an expression is

$$f_{10} \sim N\sigma^2\left(\frac{\pi RT}{M}\right)^{\frac{1}{2}}\zeta_{10}\exp\left[-3\left(\frac{(\pi a\nu)^2M}{2kT}\right)^{\frac{1}{3}}\right], \quad (14)$$

where $N$ is the numerical density, $\sigma$ the cross section, $\zeta_{10}$ a steric efficiency factor, and the exponential factor one suggested by Landau and Teller[166] involving the molecular weight $M$ and the atomic radius $a$. This formulation of the transition probabilities is open to criticism on several grounds, which are at present best tested by experiment, and will therefore be discussed in the experimental section.

Landau and Teller have recently generalized (13) to show that all of the energy states associated with a certain mode of vibration will have the same lifetimes, and that consequently they will all fail to follow the acoustical cycle in the same frequency range. Since this argument is based on a detailed consideration of the collision process, and treats only double collisions, a new notation indicating this will be introduced. In a gas of numerical density $N$ there will be $l$ quantum states, and the number of molecules per cc in each state is $N_l$. In this case, of course,

$$\sum_l N_l = N. \quad (15a)$$

The number of vibrational quanta per cc is designated by $Z$, and is

$$Z = \sum_l lN_l. \quad (15b)$$

Instead of writing transition probabilities we shall now employ reaction rate constants of the type $k_{l,\,l+1}$. If the transitions between states are due solely to double collisions

$$f_{l,\,l+1} = k_{l,\,l+1}NK, \quad (16)$$

where $K$ is the number of collisions a molecule suffers in unit time at a numerical density of one molecule per cc. Then the general reaction equation becomes

$$dZ/dt = KN\{\sum_l k_{l,\,l+1}N_l - \sum_l k_{l,\,l-1}N_l\}, \quad (17)$$

since obviously $k_{l,\,l-1}N_l = k_{l+1,\,l}N_{l+1}$, provided the oscillator is harmonic. Eq. (17) is practically Bourgin's kinetic equation in a somewhat less general form. Landau and Teller now examine the relation between the various $k$ terms with the aid of four assumptions, all of which are extremely reasonable provided $l$ is not very large. The first of these, that the molecular vibration should be harmonic, has already been invoked. The second is that only one mode of vibration shall be concerned, and that this shall not be degenerate; this is merely to simplify the exposition, for it will soon be seen that the theory is readily generalized. The third supposes that the excitation by collisions may be described by a first-order perturbation calculation; since in cases where dispersion is observed the probability of excitation is small, this cannot be far from the truth. The fourth supposes that the interchange energy which causes the excitation of the vibration shall be a linear function of the normal coordinates of the vibration; this is essentially the case if the amplitude of the vibration is small compared to the separation of the atoms. According to these assumptions the matrix elements of the perturbation energy are proportional to the matrix elements of the coordinates of an harmonic oscillator, and all elements vanish which have a difference of more than one quantum for the beginning and end states. Thus $k_{l+m}=0$ if $l-m\neq 1$, and

$$\begin{aligned} &k_{01}:k_{12}:k_{23}:\cdots \\ &\qquad =k_{10}:k_{21}:k_{32}\cdots=1:2:3:\cdots. \end{aligned}$$

By use of this simplification, the general reaction Eq. (17) becomes

$$\begin{aligned} dZ/dt&=KN\{k_{01}\sum_{l}(l+1)N_l-k_{10}\sum_{l}lN_l\} \\ &=KN(k_{01}N-(k_{10}-k_{01})Z). \qquad (18) \end{aligned}$$

By taking partial derivatives as before, neglecting the temperature dependence of $Kk_{10}$, and discarding terms of the second order it is found that, for substitution in (13),

$$\theta=1/[KN(k_{10}-k_{01})], \qquad (19)$$

which of course reduces to the same solution as the simpler case when $h\nu\gg kT$, but differs importantly from it when $N_0\leqq N_1$.

If more than one mode of vibration must be considered either all the vibrations will leave the wave at a common frequency, as appears very often to be the case judging from experiment, or the rate of excitation of each mode of vibration will be independent of the others. The treatment of the former case is identical with the treatment of a single vibration, and in the latter case separate equations of the type of (19) may be written for each vibration. Thus the heat capacity at any frequency will be

$$C_\omega=C_\infty+C_A\left(\frac{1}{1+i\omega\theta_A}\right)+C_B\left(\frac{1}{1+i\omega\theta_B}\right)+\cdots, \qquad (20)$$

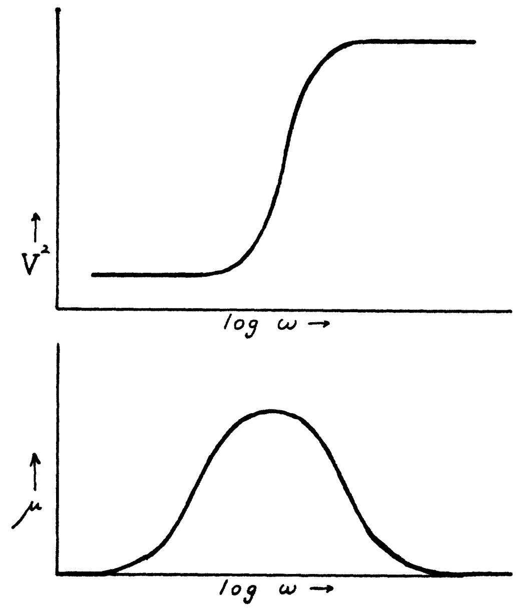

FIG. 2. The velocity and absorption in an ideal gas in the dispersive region according to Eq. (13). The point of inflection of the velocity curve is at $\omega=C_0/\theta C_\infty$, and the maximum of the absorption at $\omega=V_0C_0/\theta V_\infty C_\infty$. If double collisions are solely responsible for the transitions between states, log $\omega/N$ may be used as abscissae.

where $A$, $B$, etc. designate the various vibrations. $C_A$ is then the equilibrium heat capacity at constant volume of one vibration, $\theta_A$ its lifetime, and so on. This value of $C_\omega$ is substituted in (13) and the real and imaginary parts of the result taken, as before, to represent the velocity and the absorption. If the band-spectral analysis of the molecule has been made $C_A$ may be calculated from Planck-Einstein oscillators and the van der Waals constants; if, conversely, the vibrational frequencies are unknown they may be estimated from $C_A$, etc. which are obtained by velocity or absorption measurements.

From what has been said above it should be clear that a believer in the collision theory can find expressions sufficient to describe any measurements he may obtain, provided his experimental technique is equal to the occasion. The view expressed by Richardson and his co-workers which they have called the "resonance theory" appears to be the only rival to the collision theory. It is based on a series of measurements of the velocity of sound which do not show the relationship between velocity and frequency (or pressure) indicated in Fig. 2, but show rather an initial drop in velocity as the frequency is increased, followed by a sharp rise to a maximum, and by a subsequent fall. Since several other investigations have been made under comparable conditions without confirming these irregularities, and since it is difficult to conceive of anything which would resonate in a polyatomic molecule at 10 kc, this theory will not be discussed in this review.

Turning to liquids, it should be remarked that the appearance of dispersion because of a lag of heat capacity states of long lifetimes is not to be expected in the acoustical frequency range at present available to experimenters. There are at least two reasons for this statement. In the first place the rate of attainment of translational equilibrium in liquids is considerably greater than in gases because of the greater numerical density. This amounts to an increase in the number of "collisions," if such a term may be used, and correspondingly lowers the lifetime of the internal energy states. Secondly, the heat capacities of most liquids are large, and the absence of a small amount of vibrational energy at high frequencies would be difficult to detect. It may seem somewhat surprising that $\gamma$ in most liquids except water is much greater than unity (indeed many writers appear to share the opinion of Lamb[19] page 166, that "in liquids the difference between the isothermal and the adiabatic elasticities may be neglected"). This is due, of course, to the work which must be done against the cohesion of the liquid to produce thermal expansion. This work is $(\partial E/\partial v)_T(\partial v/\partial T)_P$ per degree centigrade, and in liquids is usually of the same order of magnitude as $C_v$, whereas for an ideal gas it is zero.

It is not dangerous to predict, however, that the investigation of dispersion in liquids will eventually become a fertile field for measurement when sufficiently high frequencies have been attained, and the theory of the liquid state is in more satisfactory condition. Besides dispersion caused by heat capacity lag, dispersion caused by the lag of a dissociation reaction with a high heat of dissociation could be detected. Indeed it appears that such a case has been reported during the preparation of this review.[245] The theory for this may easily be written with (13) as a start. Again, the phenomena in very viscous liquids should provide an interesting study. In this case the density, compressibility, and thermal expansion are all functions of time, and a radically different attack is necessary.[221]

There is little to be said concerning solids. Two papers have appeared dealing with the theory of the absorption of sound at high temperatures in solids,[231, 232] but most of the attention devoted to solids has been confined to transverse vibrations, with which we are not here concerned. In some crystals, when the free rotation of certain groups sets in below the melting temperature, measurements of the dispersion of sound should provide information concerning the rate at which energy is supplied to these groups by the vibrating molecules of the lattice.

## EXPERIMENTAL METHODS AND RESULTS FOR THE VELOCITY AND ABSORPTION OF SOUND

In this section an attempt will be made to serve a double purpose. The text will be made complete enough so that the casual reader need not turn to the end of the paper to consult the large number of references which must perforce be included, and the references will be given in a way which it is hoped will facilitate the bibliographical labor of a closer student of the subject.

The most popular instrument for the measurement of the velocity and absorption of sound is the sonic interferometer originally devised by Pierce.[115] This consists of an oscillator driven by a valve tube circuit and a movable reflector attached to a micrometer screw. As the reflector is approached to or withdrawn from the surface of the oscillator the plate current of the driving circuit undergoes periodic changes which are easily measurable with a microammeter. If the oscillator were giving off plane waves, the distance between two points of maximum reaction would be one-half the wave-length; very often this is practically the case. If the change of plate current were a linear function of the intensity of sound at a point of maximum reaction, the absorption coefficient could be obtained directly from the decrement of the electrical reaction; this is seldom if ever the case. Thus the interpretation of interferometric data is simpler for the velocity[96, 102, 105, 118] than for the absorption.[79, 82, 95, 117] For the determination of the fundamental constants of dispersive fluids there is, however, little to choose, since the information is obtained from the velocity as the difference between two large numbers, whereas the absorption is concerned with the position and magnitude of the maximum of a function which virtually vanishes on either side (cf. Fig. 2). A large number of modifications of the original interferometer have been described. Double[87] and even triple[129] oscillators have been employed in sending-receiving systems. Instruments suitable for wide temperature[61, 116] and pressure[125] ranges have been devised. In addition several papers dealing with the theory of interferometry have appeared.[62, 82, 90, 95]

The sources of sound in interferometers are usually either piezoelectric or magnetostriction oscillators, which change periodically in dimensions with the frequency of an applied electromagnetic field. Single quartz crystals, cut in a variety of ways, are usually employed as piezoelectric sources because of their mechanical strength and lack of chemical reactivity; they are suitable for frequencies between 50 and 50,000 kc. The general characteristics of the piezoelectric effect[80, 103, 104] have been investigated, the modes of vibration of quartz plates studied,[78] and the characteristics of the wave field they generate described.[100, 119] In addition their acoustical energy yield,[65] their suitability as frequency standards,[75, 115] and the alteration of their frequencies with changing environment have been studied.[81, 112] Magnetostriction oscillators have been successfully employed between 1 and 500 kc,[114, 179] and probably would be practical to 1000 kc. A general study of the magnetostrictive effect has been made,[72] a revised piece of apparatus for the study of the velocity recently described,[109] and some of the effects of the waves reported.[110]

Three difficulties have caused confusion in the interpretation of interferometric measurements. In the first place, the wave given off by the oscillator is usually by no means plane.[82, 119] The face of the oscillator usually does not vibrate back and forth as a whole like a piston, but various portions of the surface vibrate in different ways.[78] Thus the point of maximum reaction is a compromise between the points of maximum reaction of the various components of the wave and, particularly near the surface of the oscillator, irregular spacing which may differ from the half-wave-length by several percent is usually found. This has been discussed by Grossmann[82] and by Grabau[143] from different points of view; Eucken and Becker have devised a useful procedure for compensating for these irregularities.[140] In addition, when measurements are made in a confined space reflections of the various components of the wave from the walls may occur and cause very complicated patterns indeed. The second difficulty arises from larger variations in the frequency of the oscillator due to changes of temperature and pressure than are to be expected from dimensional changes. Thus, to cite an extreme example from my own experience, the change from 250 to 500 mm pressure of acetic acid vapor caused a change in frequency of 3 percent in a massive nickel tube, and this change could be reproduced. Cases are on record where relatively small changes of pressure have caused crystals to stop oscillating.[196] The explanation which suggests itself for this is that chemical adsorption takes place on the crystal and its mount, adding its effect to any direct damping of the crystal which the change of pressure may entail. The third difficulty in the interpretation of interferometric measurements occurs in evaluating the absorption coefficient from the decrement of the plate current as the reflector is withdrawn from the oscillator. This situation has been subjected to detailed analysis, especially by Hubbard,[95] and is now sufficiently understood to yield reliable absorption coefficients. Much of the early work on the subject, however, treats the electrical and acoustical decrements as if they were identical, and therefore requires revision.*

Two other considerations enter when the velocity or the absorption is measured in small tubes. The Helmholtz-Kirchhoff tube correction[88, 89, 101] has been tested and found good over a wide range of conditions, and may be employed with plane waves with some confidence.[77, 98, 108] When the length of the tube is great compared to its diameter, however, care must be taken to

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* *Note added in proof.* A series of studies by S. K. Kulkarni Jatkar has recently appeared in J. Indian Inst. Sci. **21A**, 245, 455, 477 (1938) and **22A**, 1 (1939). These deal comprehensively with the aberrations of sonic interferometers, and should be helpful to anyone who intends to undertake interferometric measurements.

avoid the phenomenon of radial resonance which was discovered by Boyle and Field,[215] has been treated theoretically by Field,[218] and has been the subject of considerable experiment.[97, 219] This occurs because the walls of the tube are not infinitely rigid, and is far greater in effect with liquids than with gases.

The following procedure is recommended for measuring the velocity in dispersive gases. The apparatus should permit complete evacuation and, if possible, degassing in order to eliminate traces of adsorbed impurities. Moisture is especially troublesome if it is not thoroughly pumped off; not only does it make the composition of the gas an undetermined function of time and temperature, but, because of the phenomenon of "trace catalysis" which will be discussed below, it may, even if present in minute quantity, shift the dispersive region to higher frequencies. The apparatus should be calibrated by measurements on some standard gas or mixture of gases which are known not to be dispersive over the entire range of pressure, temperature, and frequency to be employed. The calibration will give information concerning the reproducibility of the wave pattern, any irregularities which it may contain, and the comparability of the various measurements. The frequency and the length are easily measurable to 0.1 percent or better, but experience shows that the accuracy of the velocity measurements may be far inferior to this. If irregularities in the wave pattern appear which are reproducible and not greater than 1 percent it is reasonably safe to treat them as apparatus corrections, and compensate for them in the same way that a tube correction is applied. This is permissible, however, only if the velocity in the dispersive gas is much the same as that in the gas used for calibration (i.e., if the acoustical geometry remains the same). The frequency of the oscillator should be measured at the beginning and end of each determination, and the result discarded if any variation is found. Finally, the degree of purity of the gas studied should be accurately known and frequently verified. When these precautions are taken it makes little difference if the values resulting from measurement are as much as 1 percent in error, for (7) and (13) combine to give, for an ideal gas,

$$\theta=\frac{C_0}{C_\infty\omega}\left\{\frac{{V_\omega}^2-{V_0}^2}{{V_\infty}^2-{V_\omega}^2}\right\}^{\frac{1}{2}}. \tag{21}$$

Systematic errors in the measured quantities $V_0$, $V_\omega$, and $V_\infty$, almost eliminate each other, and thus leave the determination of the fundamental quantities $\theta$ and $C_\infty$ unaffected.

A modification of the interferometric technique has been devised by Richardson, who explores the standing-wave field with a hot wire.[177] This appears to be a promising approach to the determination of the absorption coefficients of gases.[127] A thermopile may be used in much the same way.[84, 85]

The reverberation technique developed by Knudsen[162] has proved very effective for the determination of the absorption coefficients of gases. This method utilizes a source of sound, such as a magnetostriction oscillator, a large gas-tight chamber, a crystal microphone or some other device for measuring the intensity of sound, and suitable amplification and recording devices. A burst of sound is introduced into the chamber, and its decay measured from the decrease in amplitude with time of the microphone. This apparatus has proved especially valuable in the audible range, where the physical dimensions of an interferometer become prohibitively large, but it may also be used at higher frequencies.[163]

The most important rival of the interferometric method of determining the velocity is the recently perfected optical technique. Before this is discussed, however, it will be well to mention a few miscellaneous matters pertinent to the subject. For example, both pneumatic jets[86] and condenser microphones[120] have been suggested as sources of sound, although neither appears to have been used in velocity determinations. Velocity determinations have been made in gases by the distribution of coagulated smoke,[111, 113] and by the introduction of a film of liquid on the wall of the vessel which, with suitable illumination, gives bright lines at the antinodes.[74] In liquids, velocity determinations have been made from the distribution of charcoal powder in a standing-wave system,[123, 262] and from the interference of capillary waves on the surface of the liquid.[76] Modifications of the Rayleigh disk have been devised to measure the absorption in

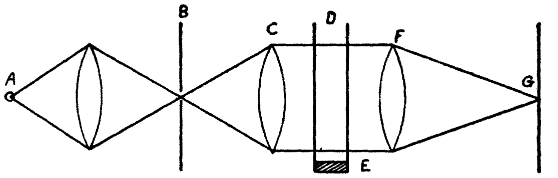

FIG. 3. Apparatus for demonstrating the diffraction of light by ultrasonic waves according to Debye-Sears-Lucas-Biquard. *A* is a lamp and lens, *B* a slit normal to the paper, *C* a lens to make the light parallel, *D* a trough containing liquid, *E* a piezoelectric oscillator, and *F* another lens which focuses the light on a screen at *G*, where the diffraction lines appear.

gases,[131, 171] and in liquids,[73, 205] and it has been pointed out that the interpretation of the results with this instrument requires correction.[99] Finally, two modifications of methods for determining the absorption coefficient which do not fall readily into any of the classifications here adopted have been described.[70, 71]

The optical methods which have recently been developed for measuring velocities and absorptions, particularly in liquids, are outgrowths of a discovery announced independently and almost simultaneously by Debye and Sears[42] and by Lucas and Biquard.[50] These writers, realizing that the periodic condensation and rarifaction in a sound wave progressing through a liquid would act as an optical diffraction grating, suggested the illumination of the liquid normal to the direction of propagation of the sound wave with parallel light from a slit source, as illustrated in Fig. 3. The emergent light, when focused on a screen by another lens, consists of one or more sets of diffraction lines evenly spaced about the primary image. The spacing of the lines is related to the grating constant as in the case of an optical transmission grating, and hence is a simple function of the wave-length of sound. The elementary theory of the effect was written by Debye,[42] and has been greatly extended by Brouillin,[39] Lucas,[49] and by Raman and Nath[52, 53, 55, 56, 58] as well as by a host of others.[35, 37, 40, 41, 44, 45, 47, 57, 60] Such matters as the change in frequency of the diffracted light,[30, 43, 48, 230] the shifting in intensity of various orders of diffraction by changing acoustical intensity,[38, 46] and several others have been investigated both theoretically and experimentally. Since it would almost double the length of this review to include a description of these developments, the reader is requested to consult a special section of the bibliography where they are listed.

The Debye-Sears-Lucas-Biquard method has stimulated a number of experimenters to produce variations,[37, 107, 200, 206] some of which have led to important and even dramatic results. For example, Töpler's "*Schlieren-Methode,*" which is obviously closely related, permits the direct visualization and photographing of the waves.[34, 126, 229] Again, in place of the second lens and screen in Fig. 4, Hiedemann and Hoesch use simply a microscope and comparator, and thus observe standing waves as a series of bright lines and dark bands, whose separation may be observed with great accuracy.[92, 227, 229] As Hiedemann points out, the standing-wave system is comparable to a series of glass rods mounted parallel to each other and separated by their diameters; thus the breadth of the lines is finite, practically all of the light falling within 1/15 of the spacing of the lines. Hiedemann and others have also done away with the necessity for standing waves by the use of stroboscopic light sources, such as a Kerr cell or another acoustic grating, which illuminates the system with the same frequency as the sound wave itself.[64, 229] This permits direct observation of any irregularities in the wave field, and facilitates the observation of the diffraction, reflection, refraction, and interference of sound waves.[122] It also yields values for the velocity of sound in liquids which are accurate to 0.02 percent if suitable precautions to avoid heating the liquid by power loss near the crystal are taken.[33] It is possible also to distinguish the transverse from the longitudinal vibrations in transparent solids, and to secure accurate measurements of their elastic constants.[63, 91, 227] It has been known for some time that the distribution of energy in the sound field produced by a vibrating quartz plate is very uneven; there are "rays" of great intensity, and regions where almost no sound is perceptible. The optical methods make these visible.[93, 225]

Turning now from methods to results, it will be convenient first to consider the so-called "zero-frequency" velocities and absorptions. It should be mentioned in passing that the zero-frequency properties may, as in the noble gases, persist to very high frequencies indeed, or, as in oxygen and carbon dioxide, be replaced by other properties well within the audible range.

Gases and vapors give confirmation of the band-spectral analysis in the low frequency range if the expression

$$C = C' + \int_{\infty}^{v} T(\partial^2 P/\partial T^2)dv,$$

which corrects for the van der Waals forces, is used in computing the velocity. Here $C'$ is, of course, the heat capacity at infinite dilution which is provided by the spectroscopic data. It is often more profitable to find $C'$ by extrapolation, and compute the second virial coefficient from the velocity of sound.[150, 165] The accuracy of acoustical measurements is sufficient to compete successfully with other methods for the determination of the heat capacity, but one serious difficulty arises. With some gases a part of the heat capacity disappears at very low frequencies, and the observer can never be sure that the value which he obtains at ultrasonic frequencies does not lack such a term. Acoustical measurements are also about as accurate as any for the determination of $P$, $v$, $T$ data. The measurement of the low frequency absorption coefficient of gases has yielded little of interest.

Liquids present quite a different picture. Since the heat capacity of most polyatomic liquids can not be evaluated theoretically, the velocity of sound yields, in conjunction with the density and the isothermal compressibility, an empirical constant $\gamma$ which awaits interpretation on a molecular-kinetic basis. Measurements on a large number of organic liquids and liquid mixtures have been reported;[220, 236, 239, 243, 246, 249, 251] of special interest are the results of Parthasarathy, which he has correlated with the chemical constitution of the liquid.[239] It is not necessary to use large volumes of liquid; Bär, indeed, was able to determine the velocity in heavy water by using only 1 cc. Measurements on liquid oxygen[116, 233] and hydrogen have been reported. Several investigations dealing with the velocity[201, 217, 237, 247] and absorption[238] in electrolyte solutions have shown that the concentration-compressibility function depends on the valence of the dissolved ions. Theoretical[223, 224] and experimental[241, 242] investigations into the properties of colloidal systems show that, to a first approximation, the velocity is independent of the presence of a disperse phase, and that to a second approximation the velocity is independent of the degree of dispersion of the disperse phase.

The question of the absorption and dispersion of sound in liquids offers much greater interest. Several observers starting apparently with Biquard,[212] have found that the absorption coefficients of many polyatomic liquids are more than a hundred-fold as great as is to be expected from considerations of viscosity and the like;[205, 216, 238] Bär confirms this, and adds the welcome proof that the effect is not due to excessive amplitude or, indeed, to any apparatus effect, by finding a normal coefficient for mercury.[204] Lucas has made an extensive theoretical investigation into possible causes for this phenomenon, and has shown that fluctuations in density are not enough to account for it. He is inclined to the belief that, as is so often assumed in modern physics and physical chemistry, the liquids made up of polyatomic molecules have a sub-microscopic structure.[234] If this were true it would account for the dispersion recently found by Hiedemann and his associates[228] in several liquids. Other observers have failed to detect dispersion,[214, 240, 248] or have reported a decrease in velocity with increasing frequency;[244, 245] this is doubtless due to the inferiority of their methods of determining the velocity compared to that of Hiedemann. It seems to me that the case for cybotactic groups is strong but not conclusive; doubtless the same investigators who have carried it so far will decide it within the next two or three years. The anomalous temperature coefficients of the absorption in many liquids[207, 244] should contribute valuable evidence when the case is complete. It is not necessary to go so far afield to account for the dispersion[245] and absorption[208] which have been recently reported in acetic acid; a reaction with a heat of dissociation of some 14 Calories per mole is involved, and dispersion may occur from exactly the cause foreseen by Einstein.[138]

Several methods for the determination of the velocity in solid plates,[69, 102, 202, 209, 213, 320] rods,[124] and sheet materials[250] have been described. Although many measurements have been reported, apparently the only important generalization which has emerged is that deduced by Boyle and his students for the reflection coefficient, $R$, between two contiguous media in which the velocity of sound is, respectively, $V_1$ and $V_2$, and the thickness of the second is $\tau$

$$R=\frac{(\rho_1V_1/\rho_2V_2-\rho_2V_2/\rho_1V_1)^2}{4\ \mathrm{cotg}^2\ (2\kappa\tau/\lambda_2)+(\rho_1V_1/\rho_2V_2+\rho_2V_2/\rho_1V_1)^2}.$$

This has been extensively confirmed by experiment,[213] and, although theoretically true for media of infinite extent only, has proved correct for relatively small plates.

The reviewer is faced with a disheartening task in discussing the measurements which have been reported concerning the dispersion of sound in gases. Although the evidence is overwhelmingly in favor of the collision theory, the details of the picture vary from laboratory to laboratory. This is in part due to difficulties in interpreting interferometric data, but in far greater part to the failure of many investigators to provide adequate means for securing information concerning the chemical composition of the gas they are studying. It is only by the assumption that unreported traces of impurities have displaced the dispersive region that one can reconcile the statements that the properties of nitrous oxide are identical with carbon dioxide[157, 177] and that there is no resemblance in their behavior.[199] For this reason no attempt will here be made to fix the numerical value of the relaxation time for any gas. A list of gases will be given which have been studied, either alone or as the principal constituent of a mixture, with references to the various papers in which the measurements may be found. The words "dispersive" or "not dispersive" will be affixed if the evidence seems to point clearly in either direction. A general discussion, in which numerical values are sparingly used, will follow.

Acetic acid, inconclusive, 195.
Aerosols, dispersive, 135, 164.
Air, dispersive, 108, 114, 143, 151, 162, 171, 178, 185, 197.
Ammonia, dispersive, 193.
Carbon dioxide, dispersive, 90, 95, 114, 131, 132, 137, 140, 142, 144, 149, 150, 156, 157, 170, 174, 176, 177, 178, 181, 183, 186, 198, 199.
Carbon disulfide, dispersive, 181.
Carbon monoxide, dispersive, 152, 191.
Chlorine, dispersive, 140.
Ethylene, dispersive, 181, 182.
Ethylene dichloride, 133.
Helium, not dispersive, 149, 152.
Hydrogen, not dispersive, 131, 136, 146, 149, 152, 160, 163, 181, 188, 197, 198.
Nitrogen, not dispersive, 149, 150, 162, 172.
Nitrogen tetroxide, dispersive, 145, 155, 161, 179, 196.
Nitrous oxide, dispersive, 131, 141, 142, 157, 173, 177, 199.
Oxygen, dispersive, 139, 147, 152, 159, 163, 165, 172, 174, 192.
Sulfur dioxide, dispersive, 144, 173, 177, 181, 199.

The general conclusions which result from a study of these papers are as follows:

(1) Dispersion and absorption of sound are to be expected in any polyatomic gas in which an appreciable amount of vibrational energy is excited, at pressures, temperatures, and frequencies which are at present experimentally available. The reason for this is primarily the inevitable inefficiency of the conversion of translational energy into a quantum of vibrational energy by collision. Very elementary and qualitative consideration of the process of collision shows that most of the force of the impact will be consumed by the repulsive forces of the colliding molecules, and that only a small fraction of it is available for the alteration of the vibrational energy.[187] A more detailed analysis by quantum mechanical methods confirms this.[166] A steric factor is also to be expected, since the structure of most molecules is such that the direction of the impact will be important in effecting excitation by collision. Experiment has found relaxation times for excited states, at room temperature and atmospheric pressure, ranging from $\theta=10^{-8}$ sec. in sulfur dioxide to $\theta=10^{-2}$ sec. in oxygen.

(2) The effect of pressure variations is in accord with the kinetic theory of heat; an increase of pressure increases the number of collisions, and displaces the dispersive region to higher frequencies. Very thorough measurements on carbon dioxide by several investigators[140, 149, 150, 181] concur with but one dissenting voice[177] that the excitation of the transverse vibration of this gas is effected by double collisions in the sense demanded by (14) above. Double collisions appear to be the usual mechanism by which vibrational energy is excited, although in a few cases, such as the excitation of oxygen by water vapor,[159] triple collisions appear to be a possibility. The collision theory

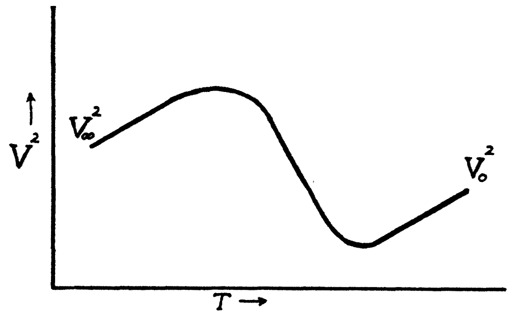

FIG. 4. The dependence of the velocity on temperature at constant pressure and frequency as found experimentally in several gases. The falling off of the velocity from $V_\infty$ occurs because the transitions between states are more frequent and the collision lifetimes diminish as the temperature rises. At high temperatures the dispersive region has been traversed, and the velocity becomes $V_0$.

has received impressive support from the study of the dependence of the dispersion on pressure. Indeed, no case has yet been reported where the effect of radiation has been detected, although with molecules having a large dipole moment and vibrational states of long relaxation times this is to be expected.

Incidentally, much confusion may be avoided in reporting the results of pressure studies if the old-fashioned custom of "reducing the velocity to 0°C" is abandoned. In the first place, velocities in the dispersive region are dependent on rates which are unspecified functions of temperature, and treating the velocity as if it were a function only of the square root of the absolute temperature neglects this completely. In the second place, the equation of state of an ideal gas is a poor approximation for a real gas, even over relatively small pressure intervals. For example, in carbon dioxide the zero frequency velocity at infinite dilution is, at 30°C, 271.2 $\text{m}\cdot\text{sec.}^{-1}$ from band spectra. At 1700 mm pressure the apparent increase in molecular weight caused by the van der Waals forces has reduced $V$ to 269.8 $\text{m}\cdot\text{sec.}^{-1}$. A glance at (13) shows that a corresponding reduction in velocity will appear at all frequencies if the pressure is high. Hence an isotherm should never be plotted with $V^2$ and $\log \omega/P$ as its coordinates, bue either $V^2$ and $\log \omega/N$ should be used, or $V^2$ should be idealized by correcting for van der Waals forces, and plotted[181] against $\log \omega/P$.

(3) The effect of increasing the temperature is to increase the transition probability, which produces an isobar of the type illustrated by Fig. 4. Since increasing the temperature at constant pressure decreases the number of collisions in proportion to $T^{\frac{1}{2}}$, according to the collision theory a function of this type necessarily indicates a decrease of the collision lifetime of the state causing the dispersive region. Such behavior was first noted in carbon dioxide, carbon disulfide, and ethylene,[181] and has since been reported for carbon dioxide and several other gases.[140, 142, 152, 199] The measurements which Penman[173] published, and which he considered to refute the collision theory, have been repeated by Warner,[199] and shown to be without sufficient accuracy to warrant any conclusions.

Although they do not agree in detail, measurements indicate that the increase in the $0 \rightarrow 1$ transition probability is exponential with temperature, and that the exponent involved is larger than that dictated by the Boltzmann factor corresponding to the particular state involved. Landau and Teller[166] point out that only molecules of high translational energy will be able to effect its conversion into vibrational energy, and that the process, when it occurs, will take place classically; they suggest the exponential factor which terminates (14). This would increase the transition probability in carbon dioxide at 100°C by a factor of about 2 in a 30° temperature interval. A rough analysis of Warner's results, which, although he has preferred to publish them without interpretation, appear to be the most complete available, shows that the probability is about doubled by raising the temperature 15°. In view of the difficulty of reading with accuracy the graphs which Warner has published, this is not considered a serious disagreement.

It may perhaps be unnecessary to point out, in passing, that if, for some reason not at present clear, a molecule which is in an excited state has an advantage over a molecule which is in the zero state in bringing about the conversion of translational into vibrational energy, an exponential temperature dependence of $\theta$ resembling a chemical activation energy will appear. In (14) it is implicitly assumed that a $0-1$ collision and a $0-0$ collision are equally effective in causing the $0 \rightarrow 1$ transition. If the $0-1$ collision is markedly more effective, (14) will be multiplied by $\exp -[h\nu/kT]$, and the temperature coefficient of the lifetime will be greater. Although this possibility seems remote, it is urgently necessary that more determinations of the effect of temperature be made if the full significance of dispersion measurements is to be understood.

(4) As a result of the researches of Knudsen[162] with the reverberation method, which have been amply confirmed by others,[172, 192] it has been found that very small traces of foreign gases may have an enormous effect on the efficiency of the collision process, and consequently on the location of the dispersive region. The effect of the presence of these traces is always to shift the dispersive region to higher frequencies; any other result would necessitate a revision of the collision theory. Kneser and Knudsen interpret this result[159] as meaning that a collision of a molecule of the dispersive gas with a molecule of the "trace catalyst" is more effective in exciting the vibrational energy of the dispersive gas than is a collision with one of its own species. Measurements on mixtures by a large number of investigators bear out this interpretation, but there is no general agreement why this is true. One school of thought regards the excitation of vibrational energy as a preliminary to chemical reaction, and seeks correlation between collision efficiency and the probability of a reaction involving the destruction of one or both of the colliding molecules.[140, 170] Eucken, who has championed this view, even distinguishes between "chemical" and "physical" methods of excitation.[141] In order to test the general validity of this interpretation the efficiencies of hydrogen and of deuterium in exciting ethylene were compared,[182] and hydrogen found eight times as effective per collision. In this case the reaction probabilities of the two isotopes are practically identical, and the only decided difference lies in the moments of inertia, and consequent magnitudes of the rotational quanta. On this basis water and ammonia, which have small moments of inertia, should be effective trace catalysts, and appear to be so for a number of gases.[140, 142, 159, 162, 186] It is clear, however, that the magnitude of the moment of inertia cannot supply an explanation for many cases; for example Knudsen reports that ethyl alcohol is the most effective catalyst for oxygen of the many he has investigated. If, as is currently believed, there is no free rotation about the carbon-carbon bond in ethanol, the moment of inertia of this molecule must be very large, and its rotational quanta correspondingly ineffective. Nor does the suggestion that the magnitude of the dipole moment influences the transition probability[170] prove especially helpful. It seems necessary, therefore, tentatively to assume that the energy in several degrees of freedom in the ethanol molecule transfers itself simultaneously to the oxygen molecule during a collision. If this were the case, the torsional quanta of ethanol, which must be very large, might participate in the exchange. Processes of this nature are not unknown in chemical reaction kinetics.

To summarize: the efficiency of the conversion of translational energy into vibrational energy by the collision of a molecule of one species with one of another is highly specific, and no one property of the molecules is sufficient to define it. Further study will be necessary before the facts which are at present known may be fully explained.

(5) No information has been obtained concerning the rates of adjustment of the rotational energy or of the van der Waals forces, since both appear to follow the acoustical cycle to the highest frequencies yet employed. The report that rotational dispersion could be found in hydrogen[181] has been refuted.[160, 182, 188, 198]

(6) In many gases several sets of energy states are adjusted with a common frequency, with the result that they show only one dispersive region which is common to all of them. Examples of such behavior are carbon dioxide, carbon disulfide, ethylene,[181] and nitrous oxide.[142] In this case (20) combined with (13) gives, for an ideal gas where $\theta_A=\theta_B=$etc.

$$V=\left\{\frac{RT}{M}\left(1+\frac{R(C_\infty+C_A+C_B+\cdots+C_\infty\omega^2\theta^2)}{(C_\infty+C_A+C_B+\cdots)^2+C_\infty{}^2\omega^2\theta^2}\right)\right\}^{\frac{1}{2}},$$

where $\theta$ represents the lifetime of the most rapidly adjusted set of states from the standpoint of conversion of translational into vibrational energy. It is unlikely that the rates of adjustment of the several states are identical in these cases; more probably they fall out together because of rapid redistribution of energy within the molecule. It is remarkable that the symmetrical linear vibration of carbon dioxide should have an independent rate which is some two orders of magnitude less than that of the transverse vibration, since the first excited state of the linear vibration perturbs the second state of the transverse vibration.[139, 181, 198]

(7) In cases where there is doubt whether the molecule is colinear the value of the high frequency velocity provides conclusive proof. For example Reid's measurements on carbon dioxide prove it to be linear, although in this case the proof was unnecessary.[181]

(8) Chemical reaction rates may be determined by the acoustical method, but only gases with low heat capacities and high reaction heats are suitable at present.[195] Indeed, nitrogen tetroxide is the only success to date,[161, 180] and this gas not only has a low heat capacity, but is exceptionally easy to purify.

## The Effect of Sound Waves of Large Amplitude

Sound waves of great intensity may be obtained in the audible range from submarine signaling oscillators which give, under the most favorable conditions, acoustical outputs of about 500 watts.[274] Sound waves in the audible and ultrasonic ranges may also be obtained by the pneumatic method,[86] but this is suitable for gases only. Magnetostriction oscillators[114] made of nickel or chromium steel have been employed both at audible and ultrasonic frequencies; these are somewhat less efficient than the submarine oscillators. Commonly, however, the source is a piezoelectric crystal, usually quartz, driven in an insulating liquid. The liquid is necessary to prevent shattering of the crystal at large amplitudes, and is usually xylol or transil oil. Under transil oil the shattering point of crystal quartz is reached with an output of the order of 3 watts per cm$^2$ if the crystal is 5 cm in diameter; the shattering point may be reached with an electrical input of the order of 200 watts. A safe output is perhaps a fifth of this.[298, 345] Whatever the source of sound or its frequency, the physical, chemical, and biological effects are usually much the same.

Although most observations with high amplitude waves are concerned with liquids, the coagulation of smokes and other aerosols is an exception. Hiedemann and his co-workers[265–270, 297] have shown both theoretically and experimentally that there is an optimum particle size for coagulation at any frequency. Other aspects of the process, including the absorption of sound by aerosols,[135, 164] have been investigated.[253] The formation of mists by a thin film of liquid in contact with a solid surface, which several observers have reported,[101, 265, 339] should also be mentioned. Mist formation is evidently due largely to the transverse waves in the solid; in accordance with this a liquid is more easily "atomized" the lower its viscosity.

The presence of intense sound waves in liquids gives rise to several phenomena which all observers report. The surface of the liquid on which the waves impinge becomes disturbed, and at high intensities is actually broken up into drops which may be thrown several feet. It is not entirely clear how much this is due to actual radiation pressure and how much it may be due to secondary electrical and mechanical pumping actions entailed by the generation of sound. Again, the liquid heats slowly, evidently due to viscous absorption of sound. In measuring the heating due to absorption it is essential to eliminate dielectric power loss which, in early investigations, sometimes contributed nine-tenths of the heating effect.[318] The intensity of the waves may be measured either by modifications of the Rayleigh disk,[65, 69, 73, 205, 342] or by total absorption in a solid such as pitch.[319] It has recently been observed that waves of relatively small amplitude are visible in liquids,[312] and several demonstrations of their existence suitable for large gatherings have been described.[68, 94, 262]

By far the most important consequence of the passage of intense sound waves through liquids is cavitation,[261, 263, 298] or the formation of bubbles of gas or vapor. This sets in at intensities of about 0.03 watt per cm$^2$ in the ultrasonic range.[264] Its importance lies in the fact that almost all of the phenomena described below disappear if easily visible cavitation is suppressed, either by degassing the liquid, or by applying to it a large hydrostatic pressure.[295, 299, 302, 332, 343] Cavitation has been shown to exist in a degassed liquid very near its boiling temperature,[315] but only one observer has reported it in pure water at room temperature,[340] and he finds not easily visible bubbles, but opalescence. Since the gas bubbles formed by cavitation do not redissolve, but rise jerkily to the surface, the most obvious result is degassing of the liquid. This is a gradual process, however; unless the liquid is radiated many hours the volume of gas liberated per unit time appears independent of time.[315, 341] The degassing of metal melts has been reported to have valuable technical application.[1]

One of the most spectacular concomitants of cavitation is the faint luminescence of liquids which was first discovered in water.[287, 348] Chambers has found the intensity of light to be proportional to the product of the dipole moment of the liquid and its viscosity.[277] Several observers report that the luminescence originates at the liquid-gas interface of the cavitated bubble.[277, 285, 301] This is a very fundamental observation, since it shows that enough energy is produced locally to give visible light of $6\times 10^{14}$ per sec. frequency. Clearly sound waves of frequency less than $10^6$ per sec., such as are employed, cannot cause this by any primary process.

The acceleration of chemical reactions by intense sound has also been shown to be due to cavitation.[285, 331] The great majority of reactions involved are oxidations such as the conversion of iodine ions into iodine molecules,[255, 302] but effects on hydrolysis[315] and on the inversion of cane sugar[336] have also been reported. There is some evidence that depolymerization results in certain liquids.[342] Several explanations have been advanced for the acceleration of chemical reactions, but none of them can here be accepted with any enthusiasm. The first[315] attributed the acceleration to a direct temperature effect: since the maximum values of $+\Delta T$ and $-\Delta T$ are practically equal, the net effect of the wave is to accelerate the reaction in proportion to its activation energy; in other words, since the rise and fall of temperature are linear and the dependence of the reaction rate on temperature is exponential an acceleration must result. This explanation was founded on a very exaggerated estimate of the amplitude of the waves, and may be refuted unequivocally by a thermodynamic argument. If we take $3\times 10^7$ ergs per cm$^2$ per sec. as the maximum power output of a quartz crystal, the pressure amplitude obtained from Rayleigh's expression is (reference 18, Vol. II, page 16)

$$I=P^2/2\rho V.$$

For water $\rho\cong 1$, $V\cong 1.5\times 10^5$ cm per sec., and $P$ is in this case therefore $2.6\times 10^6$ dynes per cm$^2$. The resulting adiabatic temperature change from the relation first given by Joule

$$(\partial T/\partial P)_S=(T/C_P)(\partial v/\partial T)_P$$

is less than 0.01°C, and therefore too small to influence appreciably any known reaction.

Three secondary results of cavitation might be accelerating agents. One of these is the large pressure which Rayleigh has shown to accompany the collapse of bubbles.[258] It might be argued that pressure surges from this cause are sufficiently great to cause the adiabatic temperature changes required. This explanation is improbable for several reasons. In the first place, easily visible cavitation disappears at a fairly sharp point with increasing hydrostatic pressure, and beyond this point no acceleration of reactions occurs. This is an indication that the formation of bubbles which contain gas, and which do not collapse readily, is the cause of the acceleration. Again, many reactions are accelerated only when certain dissolved gases are cavitated, and are unaffected by the cavitation of others. Finally, sonic cavitation is in general almost noiseless, whereas the bubble collapse which produces high pressures is accompanied by a rattling sound. A more attractive explanation has been suggested by Marinesco,[306] who has ingeniously measured the surface temperatures of bubbles by determining whether explosives detonate when immersed in liquids which do not wet them. He finds that explosives with detonation temperatures below 230°C detonate, whereas those with higher detonation temperatures do not. The consistency of his results make it appear unlikely that resonance phenomena are present, and indicates that small regions of very high temperature exist in the liquid because of the presence of cavitated bubbles. An alternative suggestion results from the computations of Smith,[334] which show that enormous pressures are built up in the neighborhood of bubbles which are vibrating at their resonance frequencies. This will occur when the frequency of the sound wave is equal to a frequency determined by the diameter, surface tension, and gas pressure of the bubble. A sharp dependence on the acoustic frequency is of course entailed, after the manner of all resonance phenomena, and the explanation fails in the audible range because the dimensions of the resonant bubble become impossibly large. All three of these explanations provide regions in the liquid where the temperature is far higher than the average, and consequently they are perhaps sufficient to account for the acceleration of reactions which are already in progress. None can account, however, for luminescence, nor for the formation of hydrogen peroxide from oxygen and water which appears to be the basis for the acceleration of most oxidation reactions.

It appears necessary, therefore, to postulate a ballo-electrical (*Wasserfallelektricität*) mechanism in order to obtain sufficient energy. Just as the spraying of a liquid in air produces charged drops, the spraying of holes in a liquid, which is cavitation, must produce charged bubbles. In search of this effect, Mr. Hobart and I in the Loomis Laboratory investigated the electrical potentials in a liquid which was forced into strong cavitation by driving it through a constriction in a wide tube with high hydrostatic pressure. We found considerable random variations in potential in the region which was visibly cavitating, and none in other parts of the liquid which were flowing equally rapidly. It appears possible, therefore, that over distances comparable to molecular dimensions electrical potentials of the order of magnitude necessary to produce chemical reaction may be generated by cavitation. Apparently the first to appreciate this was Föttinger. (See reference 258, footnote.) A somewhat similar mechanism was suggested by Beuthe,[255] who considered the origin of the charge frictional, and by Levšin and Kževkin in connection with luminescence.[301]

An important member of the group of phenomena produced by cavitation is the formation of colloidal systems, more especially the emulsification of one liquid in another.[283, 304, 336, 345] This, in distinction to the acceleration of oxidation reactions, is usually independent of the identity of the cavitating gas. The emulsification of various liquids, including mercury,[345] in water has been reported by many observers, and studied in detail. Heavy liquid metals such as mercury and gallium do not appear to require cavitation in order to be emulsified,[257, 314, 316] but other emulsifications are greatly facilitated if it occurs.[258, 259, 295, 323] The emulsions produced are often more stable than those produced by colloid mills or similar devices. There appears to be a small group of technical products, ranging from cosmetics to photographic plates, which can be produced in better quality by supersonic emulsification than in any other way.[279, 282] Colloidal metals have been produced by subjecting the cathode to sonic vibration during electrolysis,[281] and by analogous procedures.[280, 326] Many inorganic and organic sols[324] and gels[290] are peptized by supersonic waves without the presence of peptizing agents. On the other hand, coagulation will result if the particle size bears a certain relationship to the acoustical wavelength;[271, 311, 338] the analogy to the coagulation of aerosols naturally presents itself. Naturally flow orientation of unsymmetrical particles occurs at small intensities; this may readily be demonstrated with aged vanadium pentoxide sols between crossed Nicol prisms.[271] Naturally also thixotropic gels are liquefied by the motion and local heating of the medium.[289]

Several other physical and physico-chemical effects which have been described[315] should briefly be mentioned. Explosives are detonated not only in liquids, as mentioned above, but also on vibrating glass surfaces in air. Sound waves will alter sensitive metastable systems such as, for example, the yellow to red enantiatropic change in mercuric iodide at room temperature. Superheated liquids break into almost explosive ebullition on radiation with intense sound.[315]

Undercooled liquids and supersaturated solutions are forced to crystallize by intense sound, but only under restricted conditions.[321] Since there have been conflicting reports about this,[341, 345] the matter will be discussed a little more fully. It has long been known that many liquids, such as benzophenone, remain undercooled indefinitely at room temperature if they have been preheated high above their melting temperature, but recrystallize readily if melted and preheated only a few degrees. When the preheating has been high no amount of shaking produces crystallization; when it has been low shaking produces the immediate appearance of crystals. The presence of certain adsorbing substances, such as carbon or clean glass, requires that the preheating shall be far higher than if they are absent. Often dust, which has been included by accident and is of unknown composition, serves as the adsorbent; many liquids will not crystallize at any temperature if they have been passed through sufficiently fine filters and sealed in flamed glass tubes. The role of supersonic waves is exactly equivalent to shaking: when the liquid may be caused to crystallize in a sealed glass tube by shaking, supersonic waves will also cause it to crystallize, but if it has been sufficiently preheated neither will have any effect. Another aspect of the influence of supersonic waves on crystallization is the decrease in grain size of metals on acoustical treatment of the crystallizing melt.[328, 333] This is to be expected with all crystallizing substances, since the sonic agitation shears off small particles of the growing crystals, and these particles act in turn as nuclei.

The sonic irradiation of metals which are in the passive state is sometimes to increase the passivity and sometimes to relieve it; similarly, metals which are cathodically polarized during electrolysis are depolarized by sound if the current density is low.[327] Some polarized electrodes are microphonic.[309] The quality of some electrolytic deposits is improved by sonic radiation during electrolysis.[347] The fogging of photographic plates in a standing-wave field has been reported by Marinesco,[305, 307] who attributes it to sonic activation of molecules; the balloelectrical hypothesis accounts for this. Finally, it has been shown that the electrical conductivity is increased and the electrical breakdown voltage diminished in a standing-wave field.[308]

Numerous biological observations have been made since the beginning of supersonic history.[254, 346] Blood is laked,[272, 295] small animals are killed,[256, 299] and organisms such as paramoecia, algae, and many bacteria are destroyed.[273, 292, 293, 296, 329, 344] These effects appear to depend largely on cavitation. The reduction of curd tension in milk has been studied,[274] and many dairies use sonic treatment in the preparation of infant's milk. The influence of cavitation on the activity, stability, and degree of dispersion of several proteins,[275, 284] including some pepsins,[278] has been studied. Chambers appeared to have made an especially valuable discovery when he demonstrated the sonic extraction of some labile bacterial constituents;[276] he found later, however, that the method was not of as general value as was to be hoped.[322, 325] Several therapeutic suggestions for the use of supersonic waves have been made,[286, 288] but none seems to have yielded results of general value.

## Bibliography*

The reader is entitled to know how a bibliography has been compiled, and just how comprehensive he may expect it to be. In collecting these papers I have gone through the section marked "Acoustics" in *Science Abstracts A* from January 1934 to April 1938, recording all pertinent work, but omitting references to explosions, signaling, and theoretical treatments of the modes of vibration of rods, disks, and the like. For earlier work I have leaned heavily on Grossmann's *Ultraakustik* (*Handbuch der Experimentalphysik*, Vol. 17 (1934), p. 463), which has been compiled with exceptional scholarship and understanding. I am well aware that the result is incomplete, since I should have missed my own last two papers by following this procedure. Since many of the titles convey little or no information (for example my own "The Chemical Effects of High Frequency Sound Waves. I. A Preliminary Survey"), I have tried to indicate in a few words what seem to me the important points of the paper. The separation into categories is often somewhat arbitrary since many of the papers belong in several categories at once, but it is hoped that the reader may find it useful. The instrumental section is less complete than the others.

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* *Note added on going to press.* This bibliography was completed early in June 1938, and is being sent to the printer in January 1939. In the intervening months several important papers, dealing especially with the dispersion of sound in liquids, have appeared both in Germany and in India. I regret that it is not practical to include them here, and assure their authors, several of whom have sent me reprints, that they are not being wilfully ignored.

### Reviews

1. L. Bergmann, *Ultrasound and its Employment in Science and Technology* (V.D.I. Verlag, G. m.b.H. Berlin, 1937).
2. L. Bergmann, Zeits. f. tech. Physik **17**, 512 (1936). Supersonic waves in scientific research.
3. L. Bergmann, Naturwiss. **25**, 113 (1937). A comprehensive review, particularly of technological applications.
4. P. Biquard, Revue d'acoustique **1**, 93 (1932); **2**, 288 (1933); **3**, 104 (1934).
5. R. W. Boyle, Sci. Prog. **23**, 75 (1928).
6. C. Florisson, Bull. Soc. Belg. Élect. **52**, 165, 263, 339 (1936). Chiefly concerned with depth-sounding.
7. E. Grossmann, Article on Ultrasonics, *Handbuch der Experimentalphysik* (Wien and Harms, Leipzig, 1934), Vol. 17. An excellent comprehensive survey, containing many references to earlier work which is not included above.
8. E. Hiedemann, Ergb. der exact. Naturwiss. **14**, 201 (1935); Stahl und Eisen **56**, 600 (1936); V.D.I. **80**, 581 (1936); and Chem. Weekband **34**, 390 (1937). The last of these reviews is especially recommended, as it gives a full and simple account of the work on rendering visible ultrasonic waves, and the coagulation of smokes to which the author and his collaborators have so greatly contributed.
9. J. C. Hubbard, J. Acous. Soc. Am. **4**, 99 (1933). A brief survey.
10. M. Kluge, A.T.M. **3**, T61, May (1934). The velocity of sound.
11. H. O. Kneser, Ann. d. Physik **16**, 337 (1933); Zeits. f. tech. Physik **16**, 213 (1935). The absorption of sound in gases.
12. R. Lucas and P. Biquard, Revue d'acoustique **3**, 198 (1934). The diffraction of light by sound waves reviewed.
13. W. Mayberry, Electronics **10**, 7 (1937). Chiefly the effects of large amplitude waves.
14. W. T. Richards, J. App. Phys. **9**, 298 (1938). What the French call "vulgarization."
15. E. G. Richardson, Phys. Soc. Reports, 1934–38.
16. W. Rodewald, Zeits. f. tech. Physik **15**, 192 (1934).
17. R. W. Wood, Book, in preparation.

### Three books often referred to

18. Lord Rayleigh, *The Theory of Sound* (London, 1894–96).
19. H. Lamb, *The Dynamical Theory of Sound* (Arnold, London, 1931).
20. J. B. Crandall, *The Theory of Vibrating Systems and Sound* (D. Van Nostrand and Co., New York, 1926).

### Papers on the theory of wave propagation

21. H. Batemann, Proc. Nat. Acad. Sci. **22**, 607 (1936). Progressive waves of finite amplitude, and steady motions of an elastic fluid.
22. L. Brillouin, Revue d'acoustique **5**, 99 (1936). Radiation pressure and "tension."
23. R. D. Fay, J. Acous. Soc. Am. **3**, 223 (1931). Plane sound waves of finite amplitude.
24. E. F. Ghiron, Alta Frequenza **4**, 530 (1935). Distortion in the propagation of large amplitude waves.
25. E. J. Irons, Revue d'acoustique **2**, 211 (1933). Particle motions in semi-stationary waves described.
26. B. P. Konstantinow and I. M. Bronstein, Physik. Zeits. Sowjetunion **9**, 630 (1936). Applications of the continuity equation in acoustics.
27. R. B. Lindsay, C. R. Lewis and R. D. Albright, J. Acous. Soc. Am. **5**, 202 (1934). Acoustic filtration in nonhomogeneous media.
28. T. Sakurai, Proc. Phys. Math. Soc. Japan **19**, 297 (1937). The propagation of waves.
29. A. L. Thuras, R. T. Jenkins and H. T. O'Neil, J. Acous. Soc. Am. **6**, 173 (1935). Extraneous frequencies generated in air carrying intense sound waves.

### The theory of the diffraction of light by sound, and experiments dealing with this theory

30. L. Ali, Helv. Phys. Acta **9**, 63 (1936). Döppler effect. Also Helv. Phys. Acta **8**, 502 (1935).
31. H. R. Asbach, C. Bachem and E. Hiedemann, Zeits. f. Physik **88**, 395 (1934). Stationary and progressive waves made visible by stroboscopic and other methods. Photographs.
32. H. R. Asbach, E. Hiedemann and K. H. Hoesch, Naturwiss. **22**, 465 (1934). Visible waves in solids, notably quartz plates.
33. C. Bachem, Zeits. f. Physik **87**, 738 (1934). Temperature elevation near vibrating quartz due to dielectric loss is found by stroboscopic examination of progressive waves.
34. C. Bachem, E. Hiedemann and H. R. Asbach, Zeits. f. Physik **87**, 734 (1934). "*Schlieren-Methode*" observations.
35. R. Bär, Helv. Phys. Acta **6**, 570 (1933); **8**, 591 (1935); **9**, 265 (1936); **9**, 367 (1936); **10**, 130 (1937). A comprehensive investigation into the theory and experiment of this field. Both the Raman and Nath and the Brillouin theories are discussed.
36. R. Bär and E. Meyer, Helv. Phys. Acta **6**, 242 (1933); Physik. Zeits. **34**, 393 (1933). A method of making visible the diffraction of light by sound.
37. H. E. R. Becker, Hochfreq. und Elektroakus. **48**, 89 (1936). A modification of the Debye-Sears method.
38. H. E. R. Becker, Ann. d. Physik **25**, 373 (1936). A theory and experiments confirming it for obtaining the intensity of sound from the intensity of diffracted light.
39. L. Brillouin, *The Diffraction of Light by Ultrasound* (Hermann & Cie., Paris 1933). A comprehensive theoretical treatment.
40. P. H. van Cittert, Physica **4**, 590 (1937). Theoretical, supporting Raman and Nath.
41. E. David, Physik. Zeits. **38**, 587 (1937). Intensity of light scattered investigated theoretically.

42. P. Debye and F. W. Sears, Proc. Nat. Acad. Sci. **18**, 409 (1932). Also P. Debye, Physik. Zeits. **33**, 849 (1932). The experimental set-up and general theory which bears the names of these investigators.

43. P. Debye, H. Sack, and F. Coulon, Comptes rendus **198**, 922 (1934). Alteration of the frequency of the diffracted light.

44. R. C. Extermann, Helv. Phys. Acta **10**, 185 (1937); Nature **138**, 616 (1936); and with G. Wannier, Helv. Phys. Acta **9**, 520 (1936). An extension of the theory.

45. E. Hiedmann and E. Schreuer, Zeits. f. Physik **99**, 363 (1936). Agrees with the Raman and Nath theory.

46. J. Hrdlička, M. A. Valouch and L. Zachoval, Comptes rendus **203**, 768 (1936). The intensity in various orders of the Debye-Sears effect at two million cycles.

47. W. Korff, Physik. Zeits. **37**, 708 (1936). A photometric investigation of the intensity relations which leads to the support of a modified Brillouin theory.

48. F. Levi, Helv. Phys Acta **9**, 234 (1936). Changes in frequency of the diffracted light.

49. R. Lucas, Comptes rendus **195**, 1066 (1932); **199**, 1107 (1934); **202**, 1165 (1936). A complete theory, with comparisons with other theories.

50. R. Lucas and P. Biquard, Comptes rendus **194**, 2132 (1932), J. de phys. et rad. **3**, 464 (1932). The independent and simultaneous discovery of the method described by Debye and Sears.

51. H. Mueller, Phys. Rev. **52**, 223 (1937). Experiments with polarized light diffracted in solids support Raman and Nath.

52. N. S. N. Nath, Proc. Ind. Acad. Sci. **4A**, 222, 262 (1936). A comparison of the Raman and Nath theory with experiment.

53. O. Nomoto, Proc. Phys. Math. Soc. Japan **18**, 402 (1936); **19**, 255 (1937). Extensive comparison of the Raman and Nath theory with experiment. Photographs.

54. S. Parthasarathy, Current Sci. **4**, 243 (1936). Finds no polarization of diffracted light.

55. S. Parthasarathy, Proc. Ind. Acad. Sci. **3A**, 442, 594 (1936). Experimental tests of the Raman and Nath theory.

56. C. V. Raman and N. S. N. Nath, Proc. Ind. Acad. Sci. **2A**, 406 (1935); **3A**, 75, 119, 459 (1936). A general theory of the phenomenon.

57. S. M. Rytow, Physik. Zeits. Sowjetunion **8**, 626 (1935). Theory of the transition from a 2-dimensional grid to a 3-dimensional lattice, with experiments which prove it.

58. S. M. Rytow, Comptes rendus de l'Acad. des Sciences U.S.S.R. **3**, 151 (1936). Examines the validity of the Raman and Nath theory under various conditions. Also *ibid.* **2**, 229 (1936).

59. M. Sansoni, Nuovo Cimento **12**, 35 (1935). Reviews Brillouin's theory and the experiments of Lucas and Biquard.

60. G. Wannier and R. C. Extermann, Helv. Phys. Acta **9**, 337 (1936). The theory of Raman and Nath gives comparatively exact results only when the thickness of the liquid layer is less than 3.5 cm.

### Instruments and methods

61. H. L. Andrews, Rev. Sci. Inst. **6**, 167 (1935). An acoustic interferometer with a wide temperature range.

62. H. Backhaus, Ann. d. Physik **5**, 1 (1930). Positions of equal amplitude and phase in a spherical wave form.

63. R. Bär, Helv. Phys. Acta **9**, 617 (1936). Optical methods for showing the vibrations of quartz plates.

64. R. Bär, Helv. Phys. Acta **9**, 678 (1936); **10**, 4, 311 (1937). Various methods, mostly stroboscopic, for the visualization of ultrasonic waves in liquids.

65. E. Baumgardt, Comptes rendus **204**, 757 (1937). The supersonic yield of quartz from the radiation pressure.

66. H. E. R. Becker, Ann. d. Physik **25**, 359 (1936); **26**, 645 (1936). An investigation of the hypothesis that a vibrating quartz plate "pulls away" from the liquid in which it is immersed; negative results up to 0.3 atmos. pressure amplitude.

67. H. E. R. Becker, W. Hanle, and O. Maercks, Physik. Zeits. **37**, 414 (1936). The modulation of light with an oscillating quartz crystal.

68. L. Bergmann and H. J. Goehlich, Physik. Zeits. **38**, 9 (1937). A demonstration of supersonic waves based on their direct visibility which is suitable for a large gathering.

69. W. Bez-Bardili, Zeits. f. Physik **96**, 761 (1935). A total reflectometer for the measurement of the velocity of sound and the elastic constants of solids.

70. E. and H. Biancani and A. Dognon, Comptes rendus **197**, 1070 (1933). Intensity measurements from the absorption of sound in liquids.

71. P. Biquard, Comptes rendus **193**, 226 (1931); **196**, 257 (1933). Methods for measurement of the absorption of sound in liquids. Also *ibid.* **197**, 309 (1933).

72. K. C. Black, Proc. Am. Acad. Sci. **53**, 49 (1928). A dynamic study of magnetostriction.

73. R. W. Boyle, Sci. Prog. **23**, 75 (1928). Torsion intensity meter.

74. O. Brandt and H. Freund, Zeits. f. Physik **95**, 415 (1935) and Zeits. f. d. Unterr. **48**, 259 (1935). A revival of the method of Divorak (Pogg. Ann. **153**, 102 (1874)) which makes sound waves in gases visible by the illumination of a thin layer of liquid on the walls of the containing vessel. Bright lines are seen at the antinodes.

75. W. Cady, Proc. Soc. Radio Eng. **10**, 83 (1922); Rev. Sci. Inst. **10**, 475 (1925). A discussion of piezoelectric resonators, particularly as frequency standards.

76. J. P. Cauce, Comptes rendus **206**, 504 (1938). The velocity of sound by a capillary interference method.

77. R. E. Cornish and E. D. Eastman, Phys. Rev. **33**, 90 (1929). The tube correction in velocity determinations.

78. D. W. Dye, Proc. Roy. Soc. **A138**, 1 (1932). The modes of vibration of quartz plates.

79. F. E. Fox, Phys. Rev. **52**, 973 (1937). The absorption coefficient of liquids by interferometry.

80. E. Giebe and A. Scheibe, Ann. d. Physik **9**, 93 (1931), Zeits. f. Physik **46**, 607 (1927). The piezoelectric effect.

81. E. Grossman and M. Wein, Physik. Zeits. **32**, 377 (1931). On the influence of the mount on the frequency of a vibrating crystal.

82. Grossman, Physik. Zeits. **32**, 222 (1931); **35**, 83 (1934); Ann. d. Physik **13**, 688 (1932); J. Acous. Soc. Am. **6**, 106 (1934). An analysis of the properties of waves sent off by crystal oscillators which permits greater accuracy in the determination of the velocity and absorption of sound by interferometric methods.

83. J. Greutzmacher, Zeits. f. Physik **96**, 342 (1935). The use of a concave quartz oscillator increases the energy density. See also Zeits. f. tech. Physik **17**, 166 (1936).

84. L. Harris, Phys. Rev. **45**, 635 (1934). Measurement of temperature in sound wave fields. See also companion paper by E. A. Johnson, Phys. Rev. **45**, 641 (1934).

85. L. Harris and E. A. Johnson, Rev. Sci. Inst. **5**, 153 (1934). Specially sputtered thermocouples measure the adiabatic temperature change of a 5000-cycle wave.

86. J. Hartmann, Phys. Rev. **20**, 719 (1922); Phil. Mag. **11**, 926 (1931); J. de phys. et rad. **7**, 49 (1936). The production of supersonic waves by pneumatic jets.

87. F. W. Hehlgans, Ann. d. Physik **86**, 587 (1928). One quartz plate employed as a sender and another as a receiver in an interferometric apparatus.

88. H. von Helmholtz, Gesam. Wiss. Abh. Leipzig **1**, 383 (1882). Tube correction formula.

89. P. S. H. Henry, Proc. Phys. Soc. **33**, 341 (1931). A comprehensive discussion of the tube correction.

90. W. D. Hershberger, J. Acous. Soc. Am. **3**, 263 (1931); **4**, 273 (1933), Physics **2**, 269 (1932). The theory and practice of sonic interferometry.

91. E. Hiedemann, Zeits. f. Physik **96**, 273 (1935); Nature **136**, 273 (1935). The precision determination of the elastic constants of transparent bodies.

92. E. Hiedemann and K. H. Hoesch, Naturwiss. **22**, 577 (1935); **23**, 415 (1935); Zeits. f. Physik **102**, 253 (1936). Numerous methods for making supersonic waves visible.

93. E. Hiedemann and K. Osterhammel, Zeits. f. Physik **107**, 273 (1937). Optical investigation of the directional characteristics of waves.

94. E. Hiedemann and N. Seifen, Zeits. f. Physik **91**, 413 (1934). A lecture demonstration.

95. J. C. Hubbard, Phys. Rev. **36**, 1688 (1931); **38**, 1011 (1931); **41**, 523 (1932); **46**, 525 (1934). The determination of absorption coefficients by the acoustic resonator interferometer.

96. J. C. Hubbard and A. L. Loomis, Phil. Mag. **5**, 1177 (1928). An interferometer for liquids.

97. W. H. Hulswit, Jr., J. Acous. Soc. Am. **9**, 224 (1938). Radial resonance dispersion.

98. G. W. C. Kaye and G. G. Sherratt, Proc. Roy. Soc. **A141**, 123 (1933). Supports the classical tube correction formula.

99. L. V. King, Proc. Roy. Soc. **A147**, 212 (1934); **A153**, 1 (1935). Corrections for the Rayleigh disk.

100. L. V. King, Can. J. Research **11**, 135, 484 (1934). The acoustic radiation field of a piezoelectric oscillator.

101. G. Kirchhoff, Pogg. Ann. **134**, 177 (1868). The classical tube correction.

102. E. Klein and W. D. Hershberger, Phys. Rev. **36**, 1262 (1930); **37**, 760 (1931). A sonic interferometer for liquids.

103. M. von Laue, Zeits. f. Physik **34**, 347 (1925). A discussion of the piezoelectric effect.

104. P. Langevin, Fr. Pat. 505903 (1918), Brit. Pat. 145691 (1921); Rev. gén. Electr. **23**, 626 (1928). The first piezoelectric sound generator.

105. A. L. Loomis and J. C. Hubbard, J. Opt. Soc. Am. **17**, 295 (1928). A sonic interferometer for liquids.

106. O. Maerks, Physik. Zeits. **37**, 562 (1936). The employment of sound diffraction as a light relay.

107. D. Nomoto, Proc. Phys. Math. Soc. Jap. **18**, 402 (1936). Visible sound waves. Also *ibid.* **19**, 337 (1937). Illustrated.

108. G. A. Norton, Phys. Rev. **44**, 951 (1934); J. Acous. Soc. Am. **7**, 16 (1935). The velocity of sound in small tubes checks the classical tube correction formula.

109. A. Noyes, Jr. and G. W. Pierce, J. Acous. Soc. Am. **9**, 205 (1938). Several pieces of apparatus of modern design, intended primarily for velocity determinations.

110. E. P. Ostrovskij, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **14**, 491 (1937). Experiments with magnetostriction oscillators.

111. R. C. Parker, Proc. Phys. Soc. **49**, 95 (1937). The smoke method for the measurement of ultrasonic velocities.

112. S. Parthasarathy, Proc. Ind. Acad. Sci. **A3**, 544 (1936). Resonance properties of a quartz oscillator immersed in various liquids.

113. E. B. Pearson, Proc. Phys. Soc. **47**, 136 (1935). The velocity of sound from coagulated smoke particles. Dispersion in oxygen and nitrogen reported, but this is denied by Parker, reference 111.

114. G. W. Pierce, Proc. Am. Acad. Sci. **63**, 1 (1928); J. Acous. Soc. Am. **9**, 185 (1938). The first paper on magnetostriction oscillators, and an improved apparatus.

115. G. W. Pierce, Proc. Am. Acad. Sci. **60**, 271 (1925). The first sonic interferometer.

116. A. Pitt and W. J. Jackson, Can. J. Research **12**, 686 (1935). A low temperature Pierce interferometer, with measurements on oxygen and hydrogen.

117. A. L. Quirk and G. D. Rock, Rev. Sci. Inst. **6**, 6 (1935). An interferometer designed for absorption measurements in liquids.

118. C. D. Reid, Phys. Rev. **35**, 814 (1930); **37**, 1147 (1931). Interferometry technique.

119. S. N. Rževkin, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **16**, 267 (1937). Stroboscopic examination of a wave field produced by a quartz crystal.
120. G. Sacerdote, Alta Frequenza **2**, 516 (1933). A condenser-microphone source of sound.
121. C. Sălceanu, Comptes rendus **205**, 1219 (1937); and with C. Istray, Comptes rendus **206**, 329, 502 (1938). The resonance of liquids in tubes.
122. E. Schreuer and K. Osterhammel, Zeits. f. Physik **107**, 44, 560 (1937). Some interference phenomena.
123. H. Straubel, Physik. Zeits. **32**, 379 (1931). Making waves visible with suspended powder. Cf. Boyle and collaborators, reference 262.
124. J. I. Surgart, Rev. Sci. Inst. **7**, 252 (1936). A method for measuring the velocity of sound in short rods.
125. J. C. Swanson, Rev. Sci. Inst. **4**, 603 (1933). An interferometer for liquids at high pressures.
126. E. P. Tawil, Comptes rendus **191**, 92 (1930). The first description of visible waves using the "*Schlieren-Methode.*"
127. O. Tugman, Rev. Sci. Inst. **7**, 287 (1936). The velocity of sound in gases by the hot wire method.
128. L. A. Tumermann and V. Symanovskij, Comptes rendus de l'Acad des Sciences, U.S.S.R. **15**, 323 (1937). A fluorometer based on the Debye-Sears effect.
129. H. L. Yeagley, Rev. Sci. Inst. **6**, 148 (1935). A triple-quartz-plate generating and receiving system.
130. J. Zühlke, Ann. d. Physik **21**, 667 (1935). An objective method of measuring the wave-length.

### The velocity and absorption of sound in gases

131. T. P. Abello, Proc. Nat. Acad. Sci. **13**, 699 (1927), Phys. Rev. **31**, 1083 (1928). Absorption measurements in hydrogen and carbon dioxide.
132. G. F. Barnes, J. Acous. Soc. Am. **3**, 579 (1932). The determination of $\gamma$ in several gaseous mixtures at 658.2 kc.
133. W. H. Billhartz, Jr. and F. L. Bishop, Jr., J. Acous. Soc. Am. **7**, 225 (1936). The velocity in ethelyene dichloride, no dispersion.
134. D. G. Bourgin, Nature **122**, 133 (1928); Phil. Mag. **7**, 821 (1929), Phys. Rev. **34**, 521 (1929); **42**, 721 (1932); **50**, 355 (1936); J. Acous. Soc. Am. **4**, 108 (1932); **5**, 57 (1934). A comprehensive statistical theory embracing every aspect of the dispersion of sound in gases and gaseous mixtures. Required reading.
135. O. Brandt, Kolloid Zeits. **81**, 2 (1937). The frequency dependence of sound absorption in aerosols.
136. R. E. Cornish and E. D. Eastman, J. Am. Chem. Soc. **50**, 627 (1928). The velocity in hydrogen at audible frequencies.
137. R. W. Curtis, Phys. Rev. **46**, 811 (1934). Absorption and reflection coefficients in air and carbon dioxide.
138. A. Einstein, Sitz. Berl. Akad. 380 (1920). A theory for the determination of the rate of dissociation of a partially dissociated gas.
139. A. Eucken, O. Mücke and R. Becker, Naturwiss. **20**, 85 (1932); Zeits. f. physik. Chemie **18B**, 167 (1932). Oxygen absorption found in the audible range.
140. A. Eucken and R. Becker, Zeits. f. physik. Chemie **20B**, 467 (1933); **27B**, 219 (1934). The first two of an outstanding series of experimental studies entitled "The excitation of intramolecular vibrations by collisions." These two deal with carbon dioxide and chlorine and mixtures with helium, water and the like. The second contains valuable comments on the technique of interferometry.
141. A. Eucken and H. Jaacks, Zeits. f. physik. Chemie **30B**, 85 (1935). Nitrous oxide in mixtures with several gases. Indications are found that chemical and physical modes of excitation may be distinguished.
142. A. Eucken and E. Nümann, Zeits. f. physik. Chemie **36B**, 163 (1937). Carbon dioxide and nitrous oxide carried to 400°C, and several mixtures.
143. M. Grabau, J. Acous. Soc. Am. **5**, 1 (1934). The velocity in air.
144. E. Grossman, Ann. d. Physik **13**, 681 (1932); Physik. Zeits. **33**, 202 (1932). Absorption measurements in gases which confirm Kneser's early work on carbon dioxide and nitrous oxide, and indicate dispersion in sulfur dioxide.
145. E. Grüneisen and E. Goens, Ann. d. Physik **72**, 193 (1923). The velocity in nitrogen tetroxide at audible frequencies. No observable dispersion.
146. E. Grüneisen and E. Merkel, Ann. d. Physik **66**, 344 (1921). The velocity in hydrogen.
147. P. S. H. Henry, Nature **129**, 200 (1932); Proc. Camb. Phil. Soc. **28**, 249 (1932). Points out that oxygen must have an absorption region in the audible range, and gives a derivation of the absorption coefficient which supplements Kneser's derivation for the velocity.
148. K. Herzfeld and F. O. Rice, Phys. Rev. **31**, 691 (1928). The first theoretical explanation for the dispersion of sound in nonreactive gases.
149. A. H. Hodge, J. Chem. Phys. **5**, 974 (1937). The velocity in hydrogen, helium, carbon dioxide, and nitrogen up to 100 atmos.
150. J. C. Hubbard and A. H. Hodge, J. Chem. Phys. **5**, 978 (1937). $\gamma$ for several gases as a function of pressure.
151. C. Ishii, Inst. Phys. Chem. Research Tokyo, No. **500**, 201 (1935). Confirms Knudsen on the velocity in dry and humid air.
152. A. van Itterbeek and P. Mariëns, Physica **4**, 207, 609 (1937). An extended study of the velocity and absorption at ordinary and at low temperatures in oxygen, hydrogen, nitrogen, and carbon monoxide. The pressure dependence of the dispersion has also been studied, and found abnormal for oxygen above 13°C. In general the absorption coefficients are somewhat larger than those to be expected from current theory.
153. Sir James Jeans, *Dynamical Theory of Gases* (Cambridge University Press, 1904 edition). The first indication that dispersion due to heat capacity could be expected.

154. G. Kirchhoff, Pogg. Ann. **134**, 177 (1868). Heat conduction as a cause of dispersion.

155. G. B. Kistiakowsky and W. T. Richards, J. Am. Chem. Soc. **52**, 4661 (1930). An unsuccessful attempt to measure the dispersion in nitrogen tetroxide.

156. H. O. Kneser, Ann. d. Physik **11**, 761, 777 (1931). The dispersion theory of Einstein applied to non-dissociating gases, and some measurements on carbon dioxide.

157. H. O. Kneser and J. Zühlke, Zeits. f. Physik **77**, 649 (1932). Nitrous oxide and carbon dioxide have almost the same relaxation times.

158. H. O. Kneser, Ann. d. Physik **16**, 347 (1933). The results of several experimenters calculated for relaxation times. Deals especially with absorption.

159. H. O. Kneser, J. Acous. Soc. Am. **5**, 122 (1933). The interpretation of Knudsen's results. Further discussion in Physik. Zeits. **35**, 983 (1934), and with V. O. Knudsen, Ann. d. Physik **21**, 682 (1935).

160. H. O. Kneser and M. H. Wallmann, Naturwiss. **30**, 510 (1934). The dispersion in hydrogen reported by Richards and Reid does not exist.

161. H. O. Kneser and O. Gauler, Physik. Zeits. **37**, 677 (1936). Sound propagation in partly dissociated gases.

162. V. O. Knudsen, J. Acous. Soc. Am. **3**, 126 (1931); **5**, 112 (1933); **6**, 199 (1935). An account of the reverberation technique for the measurement of absorption coefficients, and the absorption in nitrogen, oxygen, and air of various degrees of humidity. The last paper summarizes the remarkable "trace catalysis" phenomena.

163. V. O. Knudsen and L. Obert, J. Acous. Soc. Am. **7**, 249 (1936). The reverberation method extended to 34 kc.

164. T. J. Laidler and E. G. Richardson, J. Acous. Soc Am. **9**, 217 (1938). The absorption of sound in smokes.

165. J. A. van Lammeren, Physica **2**, 833 (1935). The second virial coefficient and the specific heat of oxygen from velocity measurements.

166. L. Landau and E. Teller, Physik. Zeits. Sowjetunion **10**, 34 (1936). Discussed in the text.

167. R. Lawlor, J. Acous. Soc. Am. **5**, 172 (1934). Propagation in mixtures.

168. P. Lebedeev, Ann. d. Physik **35**, 171 (1911). A modification of the classical formula for absorption due to heat conduction.

169. D. G. C. Luck, Phys. Rev. **40**, 440 (1932). Van der Waals forces corrected for in the Einstein treatment. Absorption in dissociating gases.

170. I. M. Matter, Physik. Zeits. Sowjetunion **12**, 233 (1937). Carbon dioxide, both pure and in mixtures, measured. The conclusion is reached that both the dipole moment and the possibility of chemical reaction are of importance in determining the probability of energy transfer.

171. N. Nekelepajew, Ann. d. Physik **35**, 175 (1911). Absorption measurements with a torsion pendulum.

172. H. Oberst, Zeits. f. tech. Physik **17**, 580 (1936). Confirms Knudsen.

173. H. L. Penman, Proc. Phys. Soc. **47**, 543 (1935). The effect of temperature.

174. W. H. Pielemeyer, Phys. Rev. **34**, 1184 (1929); **35**, 1417 (1930); **36**, 1005, 1667 (1930); **38**, 1236 (1931); **41**, 833 (1932). Measurements of absorption and velocity, mainly in carbon dioxide and oxygen.

175. W. H. Pielemeyer, J. Acous. Soc. Am. **7**, 37 (1935). The effect of intensity on velocity.

176. E. J. Pumper, Physik. Zeits. Sowjetunion **8**, 300 (1935). The change in velocity of carbon dioxide and oxygen between 1 and 0.02 atmos. at 44 kc.

177. W. Railston and E. G. Richardson, Proc. Phys. Soc. **47**, 533 (1935). The hot wire method, and the theory of resonators.

178. D. L. Rich and W. H. Pielemeyer, Phys. Rev. **25**, 117 (1925). Absorption in air and carbon dioxide.

179. W. T. Richards and J. A. Reid, J. Chem. Phys. **1**, 114, 737 (1932/33). Also J. Am. Chem. Soc. **54**, 3014 (1932). Dispersion in nitrogen tetroxide.

180. W. T. Richards, J. Chem. Phys. **1**, 863 (1933). The paper of Landau and Teller makes it unnecessary to read this monstrosity.

181. W. T. Richards and J. A. Reid, J. Chem. Phys. **2**, 193, 206 (1934); Nature, **130** 739 (1932). The effect of temperature and pressure on the dispersion of several gases and mixtures.

182. W. T. Richards, J. Chem. Phys. **4**, 561 (1936). A comparison between the efficiency of hydrogen-ethylene and deuterium-ethylene collisions.

183. E. G. Richardson, Proc. Roy. Soc. **A146**, 56 (1934). Hot wire technique, and a critical examination of the collision theory.

184. Y. Rocard, Revue d'acoustique **3**, 47 (1934). A comparison of the absorption due to heat conduction, viscosity, and vibrational energy. The classical causes of absorption are summarized in J. de phys. et rad. **1**, 426 (1930).

185. Y. Rocard, Comptes rendus **198**, 802 (1934). Absorption in air.

186. H. H. Rogers, Phys. Rev. **41**, 369 (1932); **45**, 208 (1934). Moisture as a "trace catalyst" for carbon dioxide.

187. M. E. Rose, J. Chem. Phys. **2**, 260 (1934). The three state gas.

188. A. S. Roy and M. E. Rose, Proc. Roy. Soc. **A149**, 511 (1935). The absence of dispersion in hydrogen.

189. A. J. Rutgers, Ann. d. Physik **16**, 350 (1933). The correct development of the dispersion theory following the method of Einstein.

190. H. L. Saxton, J. Chem. Phys. **6**, 30 (1938). A development of the dispersion theory for the two state gas which includes the effect of viscosity. Closely resembles the work of Bourgin.

191. G. G. Sherratt and E. Griffiths, Proc. Roy. Soc. **A147**, 292 (1934). The high temperature heat capacity of carbon monoxide agrees with band spectroscopic data, but at lower temperatures there is dispersion.

192. L. S. Sinness and W. E. Roseveare, J. Chem. Phys. **4**, 426 (1936). Confirms Knudsen's work on oxygen.

193. O. Steil, Zeits. f. physik. Chemie **31B**, 343 (1936). Dispersion in ammonia which is attributed to the steriochemistry of nitrogen.

194. G. G. Stokes, Trans. Camb. Phil. Soc. **8**, 297 (1845); Phil. Mag. **1**, 305 (1851). Viscosity and heat conduction losses.

195. C. O. Strother and W. T. Richards, J. Chem. Phys. **4**, 566 (1936).

196. C. E. Teeter, J. Am. Chem. Soc. **54**, 4111 (1932); J. Chem. Phys. **1**, 251 (1933). Absorption in nitrogen tetroxide.

197. F. A. Walch, Proc. Phys. Soc. **48**, 899 (1936). Velocity in air.

198. M. H. Wallmann, Ann. d. Physik **21**, 671 (1934). Confirms Richards and Reid on dispersive properties of carbon dioxide. Finds, however, no dispersion in hydrogen.

199. G. W. Warner, J. Acous. Soc. Am. **9**, 30 (1937). Discussed in text.

### The velocity and absorption of sound in liquids and solids

200. C. Bachem and E. Hiedemann, Zeits. f. Physik **89**, 502 (1934); **91**, 413 (1934); **94**, 68 (1935). The optical measurement of velocities.

201. C. Bachem, Zeits. f. Physik **101**, 541 (1936). The compressibility of electrolyte solutions.

202. R. Bär and A. Walti, Helv. Phys. Acta **7**, 658 (1934). The determination of Poisson's ratio.

203. R. Bär, Helv. Phys. Acta **8**, 500 (1935). The velocity in heavy water.

204. R. Bär, Helv. Phys. Acta **10**, 332 (1937). The absorption in liquids made up of multi-atomic molecules is greater than expected (Biquard), but is normal in mercury.

205. E. Baumgardt, Comptes rendus **199**, 1383 (1934); **202**, 203 (1936); **204**, 416 (1937). An optical method and a modified Rayleigh disk used to measure the absorption in liquids. Benzol shows 100 times the theoretical absorption.

206. P. Bažulin, Physik. Zeits. Sowjetunion **8**, 354 (1935). Absorption in liquids by an optical method.

207. P. Bažulin, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **3**, 285 (1936). Abnormalities in the absorption of acetic acid.

208. P. Bažulin, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **14**, 273 (1937). The temperature coefficient of absorption by liquids.

209. R. Bechmann, Zeits. f. Physik **91**, 670 (1934). The velocity in anisotropic media: a quartz plate used as an example.

210. L. Bergmann, Physik. Zeits. **34**, 761 (1933). Velocity measurements in liquids. A discussion concerning methods for solids appears in V. D. I. **81**, 878 (1937).

211. W. Bez-Bardili, Physik. Zeits. **36**, 20 (1935). Refraction of supersonic waves.

212. P. Biquard, Comptes rendus **188**, 1230 (1929); **202**, 117 (1936); Ann. d. Physique **6**, 195 (1936). Opacity of liquids much greater than classical considerations can explain.

213. R. W. Boyle and G. B. Taylor, Trans. Roy. Soc. Can. **19**, 177 (1925); and J. P. Lehmann, Trans. Roy. Soc. Can. **21**, 115 (1927); and W. F. Rawlinson, Trans. Roy. Soc. Can. **22**, 55 (1928); and D. K. Froman, Report Canadian Res. Council, June 1927; and Froman, Can. J. Research **1**, 405 (1929), and D. O. Sproule, Can. J. Research **2**, 3 (1930); **5**, 601 (1931); and Lehmann, Can. J. Research **3**, 491 (1930). An extensive theoretical and experimental study of the passage of sound through contiguous media. A general relation concerning the reflection coefficient is derived, and numerous coefficients are determined.

214. R. W. Boyle and G. B. Taylor, Trans. Roy. Soc. Can. **21**, 79 (1927). No dispersion found in water and castor oil between 47 and 528 kc.

215. R. W. Boyle, D. K. Froman and G. S. Field, Can. J. Research **6**, 102 (1932). Experimental determination of radial resonance dispersion.

216. J. Claeys, J. Errera and H. Sack, Comptes rendus **202**, 1493 (1936). Confirms Biquard that absorption in liquids is much greater than that calculated from classical considerations.

217. H. Falkenhagen and C. Bachem, Nature **135**, 830 (1935); Zeits. f. Elektrochem. **41**, 570 (1935). The compressibility of electrolyte solutions.

218. G. S. Field, Nature **128**, 117 (1931); Can. J. Research **5**, 131 (1931). The theory of radial resonance.

219. G. S. Field and R. W. Boyle, Can. J. Research **6**, 192 (1932). Experiments on radial resonance.

220. E. B. Freyer, J. C. Hubbard, and D. H. Andrews, J. Am. Chem. Soc. **51**, 759 (1929). The velocity in numerous organic liquids.

221. A. Gemant, Physics **6**, 363 (1935). Compressional waves in media with a complex viscosity.

222. E. Grossmann and E. Hiedemann, Zeits. f. Physik **95**, 383 (1935). The demonstration of diffraction with surface ripples.

223. J. J. Hermans, Phil. Mag. **25**, 426 (1938). A potential difference of 0.01 volt is to be expected when colloid particles lag behind their double layers at high acoustic frequencies.

224. K. F. Herzfeld, Phil. Mag. **9**, 741 (1930). The theory of the propagation of sound through colloidal systems.

225. E. Hiedemann and H. R. Asbach, Physik. Zeits. **34**, 734 (1933); **35**, 26 (1934); Zeits. f. Physik **87**, 442 (1934). An optical investigation of the characteristics of supersonic fields in liquids, and the transmission by walls of various thicknesses.

226. E. Hiedemann, C. Bachem, and H. R. Asbach, Nature **133**, 176 (1934). Measurement of the velocity by direct visualization of the waves.

227. E. Hiedemann, K. H. Hoesch, and H. R. Asbach, Zeits. f. Physik **90**, 322 (1934); and K. H. Hoesch, Zeits. f. Physik **96**, 268 (1935); **98**, 141 (1935). Methods of making visible waves in transparent bodies. It is possible to distinguish between the longitudinal and transverse waves in glass.

228. E. Hiedemann, N. Seifen, and E. Schreuer, Naturwiss. **24**, 681 (1936). Concerning the dispersion of sound in liquids.

229. E. Hiedemann and K. H. Hoesch, Zeits. f. Physik **104**, 197 (1937). Another optical method for photographing waves compared with that of Bär and the "*Schlieren-Methode*."

230. E. Hiedemann and Schreuer, Zeits. f. Physik **107**, 463 (1937). Periodicities in images of waves due to Döppler and modulation effects.

231. A. S. Kompaneietz, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **14**, 267 (1937). Absorption by crystals at high temperatures; theoretical.

232. L. Landau and G. Rumer, Physik. Zeits. Sowjetunion **11**, 18 (1937). Absorption in solids due to interaction of quanta of sound and of heat energy.

233. H. W. Liepmann, Helv. Phys. Acta **9**, 507 (1936). The velocity in liquid oxygen.

234. R. Lucas, Comptes rendus **201**, 1172 (1935); **203**, 459 (1936); **203**, 611 (1936); J. de phys. et rad. **8**, 41 (1937). The cause for the "sonic turbidity" of liquids is considered to be subcrystalline orientation. Density fluctuations are too small to account for it.

235. N. N. Malov and S. N. Rschevkin, Zeits. f. Hochfrequen. **40**, 134 (1932). Transmission by various materials.

236. L. Mandelstam and M. Leontovič, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **3**, 111 (1936). Absorption in liquids and related optical phenomena.

237. S. Oka, Proc. Phys. Math. Soc., Japan **15**, 413 (1933). The propagation of supersonic waves through electrolytes.

238. H. Oyama, E. E. Jap. J. **55**, 985 (1935). Absorption in various liquids and electrolyte solutions.

239. S. Parthasarathy, Proc. Ind. Acad. Sci. **2A**, 497 (1935); **3A**, 285, 297, 482, 519 (1936); **4A**, 59 (1936). The velocity in a large number of liquids and liquid mixtures. Attempts are made to correlate this with chemical structure. Reviewed in Current Sci. **6**, 322 (1938).

240. S. Parthasarathy, Proc. Ind. Acad. Sci. **4A**, 222 (1936). Dispersion in organic liquids.

241. A. Passynski, Acta Physiochemica **3**, 779 (1936). The velocity in colloidal systems.

242. C. R. Randall, Nat. Bur. Stand. J. Research **8**, 79 (1932). The velocity in colloidal systems compared to Herzfeld's theory.

243. W. Schaafs, Zeits. f. Physik **105**, 658 (1937). The velocity in solutions and solutes.

244. C. Sörensen, Ann. d. Physik **27**, 70 (1936). The temperature coefficient of the absorption in water is normal, and that in benzol anomolous. Also *ibid.* **26**, 121 (1936) concerning dispersion.

245. B. J. Špakovskij, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **18**, 169 (1938). Most liquids show no dispersion, but acetic acid, shows an increase in velocity of 1 percent at 2000 and 3000 kc.

246. J. C. Swanson, J. Chem. Phys. **2**, 689 (1934). The velocity in nine organic liquids at 200 kc between 1 and 300 atmos.

247. A. Szalay, Physik. Zeits. **35**, 639 (1934). The compressibility of dilute electrolyte solutions.

248. B. Špakovskij, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **3**, 588 (1934). Dispersion in liquids.

249. E. B. Wilson and W. T. Richards, J. Phys. Chem. **36**, 1268 (1932). The velocity in several liquid mixtures.

250. A. B. Wood and F. D. Smith, Proc. Phys. Soc. **47**, 149 (1935). Velocities in sheet materials.

251. R. Wyss, Helv. Phys. Acta **7**, 406 (1934). The velocity and absorption in benzol and carbon tetrachloride. Also *ibid.* **10**, 237 (1937), where a comparison is given between the electrical and optical methods of determining the velocity.

252. V. Zolina, Acta Physiochemica **4**, 85 (1936). Elastic vibrations in anisotropic liquids show flow orientation.

### Effects of sound waves of large amplitude

253. N. daC. Andrade, Trans. Faraday Soc. **32**, 1111 (1936). Coagulation of smoke.

254. T. P. Beckwith and A. R. Olson, Proc. Soc. Exp. Biol. and Med. **29**, 362 (1931/32). Physiological.

255. H. Beuthe, Zeits. f. physik. Chemie **163A**, 161 (1933). Supports the observation that hydrogen peroxide accelerates chemical reactions, and suggests that it is formed by frictional electricity.

256. E. and H. Biancani and A. Dognon, C. R. **197**, 1693 (1933). Since the blood does not heat much when subjected to sound waves, it is suggested that perhaps heating of the brain produces the lethal effect.

257. C. Bondy and K. Söllner, Trans. Faraday Soc. **31**, 843 (1935). The influence of gases on mercury emulsions.

258. C. Bondy and K. Söllner, Trans. Faraday Soc. **31**, 837 (1935). Emulsification is considered due to the collapse of bubbles.

259. C. Bondy and K. Söllner, Trans. Faraday Soc. **32**, 556 (1936). Emulsification described.

260. R. W. Boyle, S. C. Morgan, and J. F. Lehmann, Trans. Roy. Soc. Can. **17**, 141 (1923). Stethoscopic examination of a supersonic wave field.

261. R. W. Boyle and J. F. Lehmann, Rep. Can. Res. Counc. May, 1923. Examination of some of the characteristics of the Langevin oscillator. Cavitation described.

262. R. W. Boyle, J. F. Lehmann, and C. D. Reid, Trans. Roy. Soc. Can. **19**, 167 (1925). Vizualization of wave patterns in liquids by suspended dust, and radiation pressure measurements.

263. R. W. Boyle and G. B. Taylor, Phys. Rev. **27**, 518 (1926). More about cavitation.

264. R. W. Boyle, G. B. Taylor, and D. K. Froman Trans. Roy. Soc. Can. **23**, 187 (1929). About 0.03 watts per sq. cm will produce cavitation in naphtha at 42 kc.

265. O. Brandt and H. Freund, Zeits. f. Physik **92**, 385 (1934). The wavelets and mist in a Kundt's tube are described, and the coagulation of mists is reported.

266. O. Brandt and H. Freund, Zeits. f. Physik **94**, 348 (1935). Aggregation of aerosols.

267. O. Brandt and E. Hiedemann, Trans. Faraday Soc. **32**, 1101 (1936). Same subject.

268. O. Brandt and E. Hiedemann, Kolloid Zeits. **75**, 129 (1936). 5 to 50 kc found especially favorable for the coagulation of aerosols.

269. O. Brandt, Kolloid Zeits. **76**, 272 (1936). The behavior of paraffine fogs, which have been chosen because of the roundness of their particles, is extensively reported.

270. O. Brandt, H. Freund, and E. Hiedemann, Kolloid Zeits. **77**, 103 (1936); Zeits. f. Physik **104**, 511 (1937). A very extensive theoretical and experimental study of the motion of particles in a sound field, including a demonstration that there is an optimum radius at any one frequency.

271. F. J. Burger and K. Söllner, Trans. Faraday Soc. **32**, 1598 (1936). Solidification of concentrated gypsum, kaolin, etc. suspensions, and orientation of $V_2O_5$ sols at small intensities of sound.

272. L. A. Chambers, J. Morph. and Physiol. **52**, 155 (1931). Some histological effects of ultrasonic waves.

273. L. A. Chambers and N. Gaines, J. Cell. and Comp. Physiol. **1**, 451 (1932). Shows milk sterilization, bacterial destruction, and the killing of frogs due to cavitation.

274 L. A. Chambers, J. of Dairy Sci. **19**, 29 (1936). Conditions affecting the reduction of curd tension in milk by audible sound.

275. L. A. Chambers and E. W. Flosdorf, J. Biol. Chem. **114**, 75 (1936). Denaturation of proteins by intense sound.

276. L. A. Chambers and E. W. Flosdorf, Proc. Soc. Exp. Biol. and Med. **34**, 631 (1936). Sonic extraction of labile bacterial constituents.

277. L. A. Chambers, J. Chem. Phys. **5**, 290 (1937). Emission of visible light from cavitated liquids.

278. L. A. Chambers, J. Biol. Chem. **117**, 639 (1937). Influence of cavitation on activity, stability, and degree of dispersion of several pepsins.

279. B. Claus, Zeits. f. tech. Physik **15**, 74 (1934). Homogeniety and sensitivity of photographic emulsions increased by supersonic radiation.

280. B. Claus, Zeits. f. tech. Physik **16**, 202 (1935). A supersonic pulverizer.

281. B. Claus, Zeits. f. tech. Physik **16**, 80 (1935). A method for obtaining metals in a finely divided state by exposing cathode to intense sound waves.

282. H. W. Dangers, Zeits. f. Physik **97**, 34 (1935). A procedure for obtaining photographic emulsions of high sensitivity using ultrasonic waves as the emulsifier.

283. W. Daniewski, Acta Physica Polonica **2**, 45 (1933). Petroleum-water emulsions.

284. E. W. Flosdorf and L. A. Chambers, J. of Immun. **28**, 297 (1935). An immunological study of the effects of intense sound vibrations on egg albumin.

285. E. W. Flosdorf, Chambers, and W. M. Malisoff, J. Am. Chem. Soc. **58**, 1069 (1936). The acceleration of oxidation reactions by intense audible sound.

286. H. Frenzel, K. Hinsberg, and H. Schultes, Zeits. f. d. Ges. Experim. Med. **89**, 246 (1933) and Zeits. f. Hals-, Nasen-, und Ohrenheilkunde **34**, 245 (1933). Theraputic suggestions.

287. J. Frenzel and H. Schultes, Zeits. f. physik. Chemie **27B**, 421 (1934). Luminescence in water as a result of cavitation induced by supersonic waves.

288. H. Freundlich, K. Söllner, and F. Rogowski, Klin. Wochenschr. **11**, 1512 (1932). A therapeutic suggestion.

289. H. Freundlich, F. Rogowski, and K. Söllner, Zeits. f. physik. Chemie **160A**, 469 (1932) and Kolloid-Beihefte **37**, 223 (1933). Softening of thixotropic gels, and local heating phenomena.

290. H. Freundlich and K. Söllner, Trans. Faraday Soc. **32**, 966 (1936). Peptization of gels due to cavitation.

291. J. Hartmann and P. von Mathes, Phil. Mag. **22**, 883 (1936). Modes of vibration of a soap film at 12 kc.

292. E. N. Harvey, E. B. Harvey, and A. L. Loomis, Biol. Bull. **55**, 459 (1928). Some biological effects of supersonic waves, particularly describing the mechanics of cell destruction.

293. E. N. Harvey and A. L. Loomis, Nature **121**, 622 (1928); J. Bacteriol. **17**, 373 (1929). Action on luminous bacteria.

294. E. N. Harvey, Am. J. Physiol. **91**, 284 (1929). The behavior of heart muscle and other irritable tissue.

295. E. N. Harvey, Biol. Bull. **59**, 306 (1930). Blood laking, emulsification, and cavitation.

296. E. N. Harvey and A. L. Loomis, J. Gen. Physiol. **15**, 2 (1931). Photographs of the destruction of rapidly centrifuged cells by sound waves.

297. E. Hiedemann, Kolloid Zeits. **77**, 168 (1936). Action of vibrations on aerosols.

298. F. L. Hopwood, Nature **128**, 748 (1931), **138**, 1059 (1936), also J. Sci. Inst. **6**, 34 (1929) and Proc. Roy. Soc. **26**, 339 (1931). Various effects of intense radiation.

299. C. H. Johnson, J. Physiol. **67**, 356 (1929). The critical pressure for preventing cavitation, and its relation to the lethal effect of sound.

300. A. Kuntze, Ann. d. Physik **26**, 349 (1936). Modulated supersonic waves.

301. V. L. Levšin and S. N. Kževkin, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **16**, 399 (1937). Reports luminescence in several liquids, and gives a ballo-electrical explanation for its appearance.

302. S. C. Liu and H. Wu, J. Am. Chem. Soc. **56**, 1005 (1934). Cavitation shown to be essential for the acceleration of several oxidation reactions.

303. H. Ludloff, Zeits. f. tech. Physik **17**, 518 (1936). Suggests the determination of the elastic constants of solid bodies from the surface waves set up by supersonic vibrations.

304. N. Marinesco, Comptes rendus **194**, 1824 (1932); **196**, 346 (1933). Emulsification, and the effect of sound on gels.

305. N. Marinesco and M. Reggiani, Comptes rendus **200**, 548 (1935), also **196**, 858 (1933). The action of sound on photographic plates.

306. N. Marinesco, Comptes rendus **201**, 1187 (1935). From the deflagration of explosives in liquids which do not wet them, it is found that the temperature of bubbles is 230°C with 10 kv input at 1000 kc.

307. N. Marinesco, Comptes rendus **202**, 757 (1936). The blackening of photographic plates by supersonic radiation.

308. W. Meyer, Zeits. f. Physik **102**, 279 (1936). The electrical conductivity is increased, and the breakdown voltage diminished in several liquids by a standing wave field.

309. L. Nikitin, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **4**, 309 (1934). Electrochemically polarized electrodes are microphonic for audible sound.

310. H. Oyama, Report Radio Research, Japan **4**, 41 (1934). Generation and application of intense sound waves of frequencies up to 42 megacycles.

311. R. C. Parker, Trans. Faraday Soc. **32**, 1115 (1936). Experiments on coagulation.

312. S. Parthasarathy and N. S. N. Nath, Ind. Acad. Sci. Proc. **4A**, 555 (1936). The visibility of supersonic waves in liquids.

313. P. R. Pisharoty, Ind. Acad. Soc. Proc. **4A**, 27 (1936). Discusses amplitude changes along the path of visible waves.

314. M. Reggiani, Comptes rendus **200**, 123 (1935). The stability of mercury sols prepared with various emulsifying agents.

315. W. T. Richards and A. L. Loomis, J. Am. Chem. Soc. **49**, 3086 (1927). The detonation of explosives, the acceleration of chemical reactions, and the degassing of liquids.

316. W. T. Richards, J. Am. Chem. Soc. **51**, 1724 (1929). Emulsification in gas-free liquids.

317. W. T. Richards, Proc. Nat. Acad. Sci. **15**, 310 (1929). An intensity gauge which has been superseded by more accurate devices.

318. W. T. Richards and A. L. Loomis, Proc. Nat. Acad. Sci. **15**, 587 (1929). The heating of liquids in high frequency electric fields.

319. W. T. Richards, Proc. Nat. Acad. Sci. **17**, 611 (1931). A method for determining the intensity of sound by total absorption in a very viscous material.

320. W. T. Richards, Science **76**, 36 (1932). A suggestion for determining the velocity of sound in solids.

321. W. T. Richards, J. Am. Chem. Soc. **54**, 479 (1932). A theory for the persistence and development of crystal nuclei above the melting temperature which includes a discussion of the effect of sound waves on metastable liquids.

322. T. M. Rivers, J. E. Smadel and L. A. Chambers, J. Exper. Med. **65**, 677 (1937). Inactivation of elementary bodies of vaccinia by sonic vibration.

323. F. Rogowski and K. Söllner, Zeits. f. physik. Chemie **166A**, 428 (1933). The importance of the gas phase in emulsification.

324. N. Sata and S. Watanabe, Part I Kolloid Zeits. **73**, 50 (1935); Part II **78**, 277 (1937); Part III by Sata alone **81**, 182 (1937); Part IV Sata and Y. Niwase **81**, 294 (1937). Peptization of ferric oxide, charcoal, and mercuric sulfide under various conditions.

325. H. W. Scherp and L. A. Chambers, Proc. Soc. Exp. Biol. Med. **35**, 495 (1936). Influenza and poliomyelitis viruses not importantly changed.

326. E. Schmidt and B. Claus, Kolloid-Beihefte **45**, 41 (1936). Sol and emulsion formation, particularly with metals.

327. G. Schmid and L. Ehret, Zeits. Elektro. **43**, 408 (1937). Metallic passivity sometimes favored and sometimes hindered by supersonic waves. Also **43**, 597 (1937). At low current densities the cathode is depolarized.

328. G. Schmid and L. Ehret, Zeits. Elektro. **43**, 869 (1937). Fine grain produced by radiation of solidifying metal melts.

329. F. O. Schmitt, A. R. Olsen, and C. H. Johnson, Proc. Exp. Biol. Med. **25**, 718 (1927/28). Effects on protoplasm.

330. F. O. Schmitt, Protoplasma **7**, 332 (1929). Manipulation.

331. F. O. Schmitt, C. H. Johnson and A. R. Olson, J. Am. Chem. Soc. **51**, 370 (1929). The acceleration of several chemical reactions of the oxidation type by hydrogen peroxide formed by cavitation.

332. F. O. Schmitt and B. Uhlenmeyer, Proc. Exp. Biol. Med. **27**, 629 (1929/30). Several effects of cavitation.

333. H. J. Seemann, Metallwirt. **15**, 1067 (1936). Research on metals.

334. F. D. Smith, Phil. Mag. **19**, 1147 (1935). The destructive effect of bubbles liberated by cavitation.

335. S. J. Sokoloff, Physik. Zeits. **36**, 142 (1935). A method for detecting the homogeneity of metal blocks.

336. S. J. Sokoloff, Tech. Phys. U.S.S.R. **3**, 176 (1936). Colloidal dispersions and coagulations. discussed, and the acceleration of several reactions reported, especially the inversion of cane sugar.

337. S. J. Sokoloff, Acta Physiochemica **3**, 939 (1936). The acceleration of the solidification of metals.

338. K. Söllner and C. Bondy, Trans. Faraday Soc. **32**, 616 (1936). A study of the mechanism of coagulation.

339. K. Söllner, Trans. Faraday Soc. **32**, 1532 (1936). The formation of fogs.

340. K. Söllner, Trans. Faraday Soc. **32**, 1537 (1936). Visible cavitation in degassed liquids.

341. C. Sörensen, Ann. d. Physik **26**, 121 (1936). Absorption, velocity, and degassing effects in liquids.

342. A. Szalay, Physik. Zeits. **35**, 293 (1934), and Zeits. f. physik. Chemie **A164**, 234 (1933). The depolymerizing action of supersonic waves, including measurements on the intensity of the radiation. See also Nature **131**, 278 (1933).

343. G. B. Taylor and D. O. Sproule, Trans. Roy. Soc. Can. **23**, 91 (1929). Some observations on cavitation.

344. O. B. Williams and N. Gains, J. Infect. Dis. **47**, 485 (1930). The disintergration of sonically killed bacteria.

345. R. W. Wood and A. L. Loomis, Phil. Mag. **6**, 418 (1927). The physical and biological effects discussed for the first time.

346. H. Wu and S. Liu, Proc. Soc. Exp. Biol. Med. **28**, 782 (1930/31). Some physiological effects.

347. W. T. Young and H. Kersten, J. Chem. Phys. **4**, 426 (1936). Some effects on electrochemical deposits.

348. P. V. Zimakov, Comptes rendus de l'Acad. des Sciences, U.S.S.R. **3**, 450 (1934). Cavitation causes the emission of light by aqueous solutions.