

# SUPERSONIC DETECTION OF INFRA-RED RADIATION\*

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*Abstract.*—It is possible to detect a modulated infra-red beam by irradiating a supersonic field and observing the resulting changes in sound pressure amplitude at a suitably placed detector.

Two distinctly different types of coupling have been observed. The first is due to a heating of the gas under irradiation. This results in a change in wavelength of the sound so that if a detector crystal is placed at a fixed distance from a driver crystal and a standing wave set up between them, the position of the detector crystal with reference to a peak of the standing wave will shift periodically with the infra-red modulating frequency. The magnitude of the effect decreases rapidly as the modulating frequency is increased. For example, if the frequency is doubled the magnitude of the coupling is approximately halved.

The second type of coupling has been observed by irradiating a column of *CO* gas which is excited at a supersonic frequency corresponding to maximum acoustic absorption. As is well known, this frequency of maximum supersonic absorption can be shifted about by the addition of small amounts of water vapor to the *CO*. Most of the measurements reported in this paper have been taken at frequencies of 932 kilocycles per second which requires roughly 1 percent water vapor for peak absorption. In this case there is a negligible standing wave in the gas column when the separation is greater than 10 wavelengths. When the gas is irradiated under these conditions there is no appreciable decrease in the magnitude of the coupling effect as the modulating frequency is increased. This is distinctly different from the other type of coupling and it indicates that this effect is not dependent on heating the gas.

The experiments so far have been restricted to modulating frequencies less than 100 cycles per second, however it is believed that on the basis of a presently proposed explanation of this effect that there will be no large decrease in its magnitude until the modulating frequency approaches the frequency of the supersonic field.

## I. INTRODUCTION

THE investigation with which we are principally concerned at present is the detection of infrared radiation frequencies beyond the range of sensitivity of the existing photocathode type cells. In this range detectors of very rapid response are highly desirable. This characteristic of rapidity of response was one of the principal motivations for initiating the research. It is believed, on the basis of the preliminary results obtained so far with the supersonic method, that the outlook for a rapid response detector for the far infrared is indeed hopeful.

As the result of research carried out during the past year the discovery has been made that it is possible to detect a modulated infra-red beam by irradiating an appropriately chosen supersonic field and observing the

\*This paper is based on research supported by contract W33-038-ac-15293 with the A.A.F.

resulting changes in sound pressure amplitude at a suitably placed detector. Two distinctly different types of coupling between the supersonic field and the radiation have been observed. The first, due to a heating of the gas under irradiation, may be the effect first reported by Richardson.\*<sup>1</sup> This results in a change in wavelength of the sound so that if a detector crystal is placed at a fixed distance from a driver crystal and a standing wave set up between them, the position of the detector crystal with reference to a peak of the standing wave will shift periodically with the infrared modulating frequency. The magnitude of this effect decreases rapidly as the modulating frequency is increased.

The second type of coupling is observed by irradiating a column of gas which is excited supersonically at a frequency in the region of high acoustic absorption. When the gas is irradiated, subject to this condition, there is no appreciable decrease in the magnitude of the coupling effect as the modulating frequency is increased. This is distinctly different from the other type of coupling and it indicates that the effect is not dependent on heating the gas. The experiments so far have been restricted to modulating frequencies less than 100 cycles per second; however it is believed that on the basis of a proposed explanation of this effect that there will be no large decrease in its magnitude until the modulating frequency approaches the frequency of the supersonic field.

## II. EXPERIMENTAL ARRANGEMENT

For purposes of clarity and orientation the experimental apparatus will be discussed before presenting the results of the measurements. A block diagram of the equipment is shown in Fig. 1. It consists of an acoustic

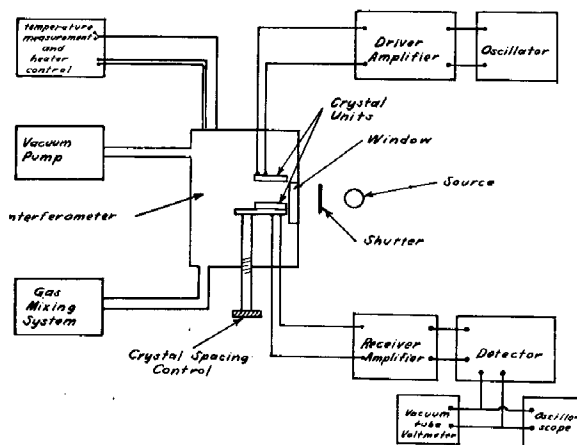


FIG. 1—Block diagram of equipment.

\*See end of article for numbered references.

Interferometer with piezoelectric crystals as the source and detector of the supersonic field, a driver oscillator and amplifier, and receiver amplifier and detector with associated indicating instruments. Also included is a gas mixing system, a vacuum pump and temperature measurement and results control apparatus. Now returning to the interferometer, the upper crystal unit is the source of the sound and the lower unit is the detector of the acoustic field. The detector crystal can be moved with respect to the source crystal by means of the crystal spacing control. In the present interferometer the crystal spacing can be varied from about  $\frac{1}{8}$  inch to several inches. As indicated in the figure the interferometer is fitted with off-centering attachments to enable the crystals to be placed in close proximity to the window through which the infrared beam enters the interferometer. This arrangement is desirable when a gas is used which is highly absorbing for the radiation bands which are utilized to obtain the coupling effect. The driver and receiver crystal units each consist of a single X-cut quartz crystal vibrating in thickness mode. Most of the measurements to date have been taken at a frequency of 932 kilocycles per second which requires a crystal thickness of 0.180 inches. The material of the window through which the infrared radiation passes to enter the interior of the interferometer is potassium bromide. This crystal transmits wave lengths out to 25 microns efficiently. The modulator of the radiation beam is a mechanically operated shutter. Its frequency can be varied continuously from a low value of 5 cycles per second to about 100 cycles per second. This range of shutter speeds is rather limited but it has been adequate for our preliminary studies. We have under construction a shutter which will reach 2,000 to 3,000 cycles per second. It should be noted that a mechanical shutter operating in air in general produces a spectrum of noise which includes as one of its principal components sound of the same frequency as the modulation frequency of the infrared beam. This sound can pass through the window of the interferometer and modulate the supersonic wave thus partially masking the radiation coupling. Consequently, some care must be taken in the design of the shutter to eliminate this interference.

The source of radiation is simply a heated body. Its temperature can be varied from room temperature to red heat.

Under the present experimental setup the temperature of the interferometer can be held within  $0.1^{\circ}\text{C}$  variation, at any temperature from room temperature to  $100^{\circ}\text{C}$  by means of the heater control circuit.

The apparatus can be evacuated by means of a mechanical pump as indicated in the diagram. An evacuation is necessary even if the gas is continuously flowing through the chamber in order to eliminate any material absorbed on the walls. A bake out under vacuum may even be desirable. The magnitude and character of the observed effects are very dependent on the presence of small amounts of certain gases such as water vapor. This will be more fully discussed when we come to the experimental measurements.

In order to obtain accurately known gas compositions in the chamber an

external mixing system is used. For obtaining some combinations this apparatus consists of a series of interconnected containers of known volume. For other compositions the continuous flow method is very convenient. As an example, a  $CO_2$  water vapor combination is readily obtained by passing tank  $CO_2$  through a drying system and then through a series of bubblers containing water held at a temperature such that the magnitude of its vapor pressure is that needed to obtain the desired composition.

A brief description of the electronic components will now be given. As the driving unit for the source crystal, there is first, an oscillator which is stable with respect to frequency and amplitude. The frequency stability is necessary because the crystal units are operated on resonance. Thus due to the sharp characteristic of the quartz units any frequency drift which does not take place very slowly will manifest itself as a change in the amplitude of the input voltage into the receiver and will be indistinguishable from a change in level due to the radiation coupling. Concerning amplitude variation, it is immediately apparent that such changes would similarly result in undesirable interference. The output of the oscillator is fed into the amplifier which excites the driver crystal unit. This amplifier has a variable output voltage up to 50 volts.

Consider now the detector. Under the present experimental arrangement the magnitude of the voltage generated by the pickup crystal is usually in the range 0.01 to 1 volt. This voltage is fed into an r-f amplifier. When the gas in the interferometer only slightly damps the sound wave the r-f voltage on the pickup crystal is of the same order as the driver voltage. Under these circumstances the driver voltage is set at a low value. However when the gas greatly attenuates the sound wave the voltage at the detector crystal may be only a few hundredths of a volt for 50 volts on the source crystal when the maximum spacing is used in the experiments. The output of the receiver amplifier is fed into a detector which has a flat characteristic down to 5 cycles per second. A vacuum tube voltmeter and an oscilloscope are used as indicating instruments. The oscilloscope is of principal use in observations on the shape of the modulation envelope. The present arrangement is capable of detecting a percentage modulation of the carrier down to 0.05 percent.

Before proceeding to the measurements it might be desirable to examine a more detailed diagram of the acoustic interferometer. This is shown in Fig. 2. As indicated previously the crystal units are shown placed close to the window through which the modulated infrared beam passes. The lower unit is the detector. Its position relative to the generator crystal can be varied through a wide range by means of the spacing control. This consists of a long rod which is moved vertically without rotation by means of the arrangements indicated at the bottom of the diagram. The displacement of this rod is read by means of a micrometer screw mounted to the side. A Wilson seal is built into the alignment support of the movable rod to make this part of the system vacuum tight.

A second window opposite to the one through which the radiation enters is shown on the right hand side of the diagram. With a photocell mounted

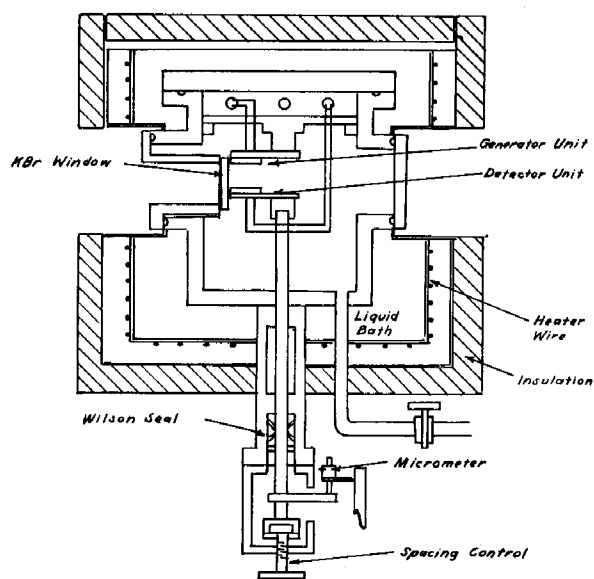


FIG. 2.—Detailed diagram of acoustic interferometer.

outside the window and a source of radiation in the visible range the intensity pattern of the radiation as a function of time can be determined. It is desirable to have this to compare with the modulation amplitude of the infrared supersonic coupling effect. As indicated in the diagram the interior chamber is surrounded by a liquid bath for accurate temperature regulation. Heat is supplied by passing current through nichrome windings placed on the jacket containing the bath. The whole interferometer with the exception of the windows is covered with a layer of heat insulation.

### III. EXPERIMENTAL RESULTS AND PROPOSED MECHANISM

Having indicated in some detail the experimental arrangement, we are now prepared to discuss the measurements. With an air, water vapor mixture in the interferometer at room temperature and with a supersonic frequency of 932 kilocycles per second, one obtains a good standing wave between the crystal units for all separation distances. This is due to the low dampening coefficient of air under these conditions and to the small divergence of the sound beam. The crystals are one inch square and the wave length of the sound is about 0.3 mm so that the source is roughly 80 wavelengths in diameter.

The upper half of Fig. 3 shows the observed modulation voltage, indicated on the vacuum tube volt meter at the output of the detector, as a function of shutter frequency for a particular water vapor content. The percentage modulation of the carrier frequency at 10 cycles per second

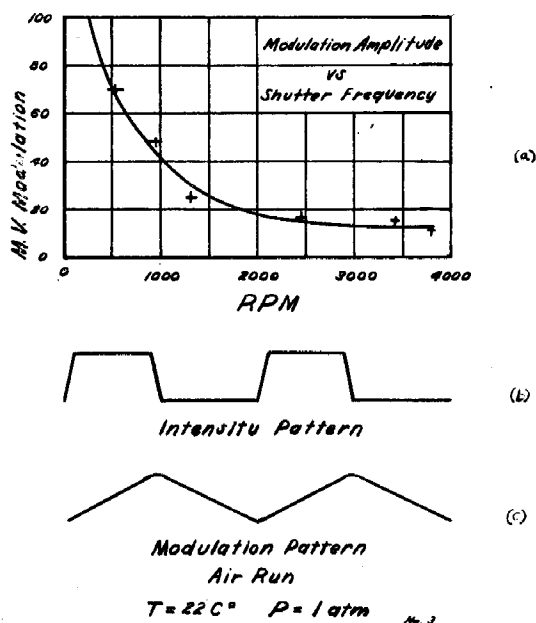


FIG. 3—(a) Observed modulation voltage as a function of shutter frequency. (b) Intensity pattern of the radiation which modulates the supersonic field. (Lower illustration). (c) The observed modulation pattern due to the coupling.

shutter speed is roughly 5 percent for this particular run. Five percent modulation corresponds to about 70 millivolts on the graph. The percent modulation obtained is a function of the infrared intensity and crystal spacing. The actual millivolt reading at the detector is a function of the vibration amplitude of the source crystal, in addition to the factors just mentioned. The quite rapid decrease of the modulation amplitude with shutter speed should be noted. The decay is about one half for each doubling of the frequency.

The lower half of Fig. 3 compares the intensity pattern of the radiation which modulates the supersonic field and the observed modulation pattern due to the coupling as indicated on the oscilloscope at the output of the detector. The envelope of the modulation voltage has a characteristic triangular shape. Figure 4 compares the coupling effect in air for two different water vapor concentrations the first a high concentration and the second a very low concentration. From these curves it is clear that the magnitude of the effect is strongly dependent on the water content of the air.

It seems desirable to point out at this point that there is another important thing to consider when making observations. It is that the magnitude of the coupling effect depends quite markedly on the position of the receiver crystal with respect to a standing wave peak so that care must be

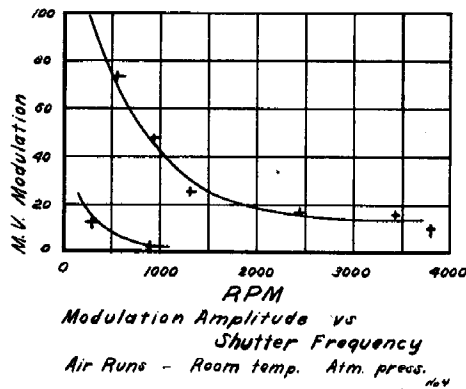


FIG. 4—The coupling effect in air for two different water vapor concentrations.

exercised to place this crystal in the same relative position to get comparable results.

The observed phenomena of the type just described can be readily correlated by the following mechanism. It is suggested that the effect is principally due to a periodic heating of the gas column by the incident radiation. Referring again to Fig. 3, a comparison of the intensity pattern of the radiation with the modulation pattern shows that on the basis of a heating effect one of the slopes of the modulation amplitude graph corresponds to a period of illumination of the gas, the other to a period of non-illumination. This is clear from the following argument. Suppose for the purpose of discussion that the pickup crystal is placed on the forward side of a standing wave peak and that the radiation is incident on the gas column. Then the internal modes of the molecules are absorbing energy. Some is reemitted but the rest is transferred to the translational degrees of freedom of the molecules by collision processes. This results in an overall heating of the gas. The corresponding temperature rise takes place at a constant time rate for constant intensity of radiation if the temperature difference does not become too great. It is to be noted that the sharp trapezoidal pattern shown on the slide assures a constant intensity over most of the period of illumination. The rising temperature of the gas column results in a changing velocity of sound and a corresponding shift in the wave length. For small changes the shift in wavelength is proportional to the change in the temperature. The change of the wavelength of sound causes the number of wavelengths between the driver crystal and the detector crystal to vary with the time. This variation results in a shifting position of the detector relative to a standing wave peak as a function of the time. This manifests itself as a modulation of the amplitude of the supersonic signal at the receiver crystal. A detailed calculation shows that the magnitude of the modulation can vary greatly as a function of the relative position of the detector crystal with respect to a peak of the standing wave.

The rapid drop-off of the magnitude of the modulation level with shutter

frequency is readily seen to be consistent with this picture since the temperature change should be directly proportional to the time of illumination. Thus the modulation level should be proportional to the reciprocal of the shutter frequency.

The dependence of the effect on the water content is easily understood when one recalls that water vapor has a number of strongly absorbing bands in the near infrared region of the spectrum.

Before discussing the radiation coupling effect in the gas composition,  $\text{CO}_2$  water vapor, it might be first desirable to make a few preliminary remarks concerning anomalous acoustic absorption in  $\text{CO}_2$ -water vapor mixtures. If the sound velocity and absorption coefficient per wavelength for such mixtures are determined as a function of the sound frequency, one finds that there is a frequency range over which the velocity shifts continuously from a value characteristic of low frequency to a value characteristic of high frequency. In this range the acoustic absorption coefficient rises to a peak value and then falls. The position of this frequency range in the acoustic spectrum is dependent upon, the pressure, temperature, and gas composition. These effects in the  $\text{CO}_2$ -water vapor system have been studied quite extensively both experimentally and theoretically and numerous papers have appeared in the literature.<sup>2, 3, 4</sup> The theory shows that the effect is due to the finite time required for the flow of energy to take place between the external degrees of freedom and the internal degrees of freedom of a molecule. For example, when the temperature of the gas is raised by a sudden compression in the distribution of energy in the internal modes of the molecules is not immediately the equilibrium distribution corresponding to the higher temperature. The time required for equilibrium to be closely approached may be of the same order as the period of a sound wave passing through the gas. It is in the frequency range where the time for approach to equilibrium is of the same order as the period of the sound wave that high absorption takes place. One can say roughly that the internal energy acquired from the external degrees of freedom during an increase in temperature of a quantity of gas flows back into the external degrees of freedom out of phase with the sound wave, i.e. during a rarefaction or temperature minimum. The energy flow raises the level of minimum temperature and thus reduces the amplitude of the temperature variations below what they would be if the energy flow could closely follow the changes. A highly damped sound wave is the result.

Figure 5 shows several curves abstracted from the literature.<sup>2</sup> These curves illustrate the effect of composition of the gas on the absorption coefficient per wavelength. The upper graph in the figure shows the variation of the absorption coefficient as a function of the percent water vapor present in the mixture for frequencies 285 and 615 kilocycles per second. These curves are plotted for room temperature and one atmosphere pressure. It should be noted that the peak absorption occurs at a lower water content when the frequency is lower but that the value of the absorption coefficient at the peak is practically the same in both cases. The lower graph shows the frequency of maximum acoustic absorption plotted as a function



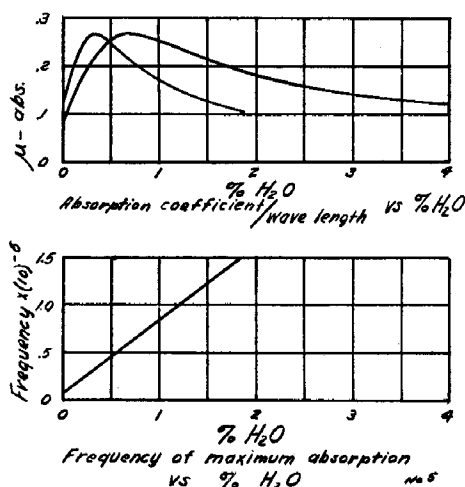


FIG. 5—The variation of the absorption coefficient as a function of the percent water vapor present in the mixture for frequencies of 285 and 615 kilocycles per second.

of water vapor content. It is a straight line within the limits of experimental error for the range of water vapor values shown. In our experiments on the radiation coupling the water vapor content was varied from low values, through the region of maximum absorption which occurs at 1.1 percent for 932 kilocycles per second to values well above the range of maximum absorption. One final statement might be in order before discussing our measurements, there seems to be some feeling in the literature that the so called deformation mode of the  $CO_2$  molecule is the one responsible for the observed anomalous effect.

Considering now the measurements, the water vapor contents used so far have all been such that there is no appreciable standing wave in the  $CO_2$ ,  $H_2O$  mixture when the spacing between the units is greater than about fifteen wavelengths. At maximum absorption the energy of the sound wave is decreased by a factor of 16 in ten wavelengths. Our experiments show that the infrared coupling effect in  $CO_2$ —water vapor combinations exhibits markedly different characteristics depending on the  $H_2O$  concentrations. For high concentrations, say greater than 3 percent, the modulation pattern appearing on the oscilloscope is similar to that for air, that is, triangular in form. It also exhibits the rapid decay with increasing shutter frequency. Clearly then, the previous mechanism suggested for air will apply in this case. However, the magnitude of the modulation amplitude for the same change in wavelength will be smaller for the  $CO_2$ ,  $H_2O$  mixture as compared with air for equal supersonic carrier levels at the detector crystal because the operating position of the detector crystal for the air case can be chosen to take advantage of the steep slope of a standing wave in the supersonically excited gas. In the  $CO_2$ ,  $H_2O$  case the slope at any operating position is that of the envelope of the damped traveling wave.

When the  $H_2O$  content is near that required for maximum acoustic absorption, the modulation pattern as indicated on the oscilloscope assumes the same shape as the intensity pattern of the radiation. The upper half of Fig. 6 shows a comparison of these patterns. The first is the graph of the intensity of radiation as a function of time. The second and third are the graphs of the modulation amplitude as a function of time. The second curve is for a water vapor content well above that needed for maximum acoustic absorption and it has a characteristic triangular shape. The third curve is for a water content near maximum absorption. This curve has the same shape as the intensity pattern. By appropriate choice of water vapor content intermediate shapes can also be obtained.

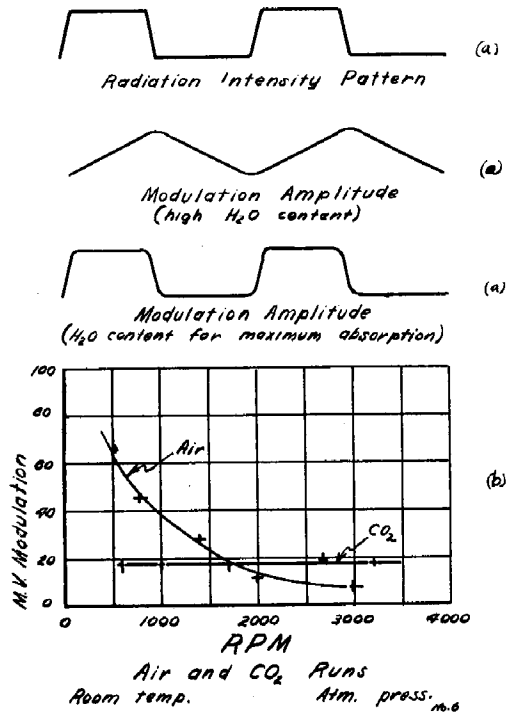


FIG. 6—(a) Comparison of modulation amplitude variation with time for high  $H_2O$  content of the  $CO_2$ - $H_2O$  mixture and a given radiation intensity pattern with that for an  $H_2O$  content which yields maximum absorption. (b) Comparison of modulation amplitude for an air run with that for a  $CO_2$  run for which the gas composition was approximately that required for maximum acoustic absorption.

Another distinguishing characteristic of the radiation coupling effect for  $CO_2$ ,  $H_2O$  mixtures of such composition to yield maximum acoustic absorption is that the modulation amplitude remains practically constant with increasing shutter frequency. This is very strikingly illustrated on the lower half of Fig. 6. A comparison of the modulation amplitude for an

air run and a  $CO_2$  run is made. The gas composition in the  $CO_2$  run was near that required for maximum acoustic absorption. The amplitude of the modulation for the low shutter frequencies for the  $CO_2$  is smaller than that for air but it remains constant with shutter frequency and the amplitude for air decreases in proportion to the reciprocal of the frequency.

Before suggesting a possible mechanism for this second type of coupling effect it seems desirable to point out that it can not be due primarily to heating. This conclusion is based on the following argument. A heating of the gas, that is a change in temperature, would continue at a constant rate under constant intensity of illumination and would not yield the flat topped characteristic indicated by the third curve. This would be true if the temperature change were not too great. However, if the temperature rise were great enough so that the energy loss per second balanced out the energy gain per second—that is, if an equilibrium temperature were approached—the modulation amplitude characteristic would level off but it would not show the rapid change in slope indicated by the third curve on the slide. Hence a simple heating effect is not the main cause of the observations.

The observed effects can be correlated on the basis of the following argument. The experimental conditions have been arranged to obtain high acoustic absorption due to energy transfer to and from the internal modes of the  $CO_2$  molecules. The rate of this transfer is dependent on the number of collisions and on the transition probability parameters of the collision processes occurring in the gas. When the gas is irradiated with infrared, the number of molecules in the various excited states is immediately changed; in particular, the number in states associated with the high acoustic absorption. Now assuming that the number of collisions per second is unchanged which holds if the radiation is applied quickly enough so that not much heating takes place, then it is possible to obtain a change in the acoustic absorption coefficient due to a difference in the values of the transition parameters of excited molecules as compared with the unexcited molecules. In other words the number of molecules per unit volume which have a particular value for transition parameter is changed. This is manifested by a change in the absorption coefficient. This proposed mechanism explains both the observed shape of the modulation pattern and the observed constant amplitude as a function of frequency. The form of the pattern is explained by the assumption that the heating is small and by the fact that the adjustment of the number of internally excited molecules to a changing intensity of the radiation field is very rapid. The constant modulation amplitude as a function of shutter frequency is also explained by this rapid adjustment of internal modes. It follows from this argument that the modulation amplitude should not appreciably decrease until the shutter frequency approaches the frequency of the supersonic wave. As a further check on the above argument it was observed that when a layer of  $CO_2$  gas about 1 cm thick was interposed between the source of radiation and the excited gas the coupling was decreased by a factor of three. This layer of gas is sufficient to greatly attenuate the 15-micron band, the one

felt to be responsible for the acoustic absorption. It should be noted that on the basis of the proposed mechanism a small velocity change will accompany the absorption change.

#### IV. CONCLUSION

In conclusion it may be stated that two distinctly different types of coupling between infrared radiation and a supersonically excited gas have been observed. The magnitude of the first type of coupling, essentially due to a heating of the gas decreases rapidly with increase in the modulation frequency of the radiation beam. The second type of effect, associated with a gas excited in a supersonic frequency range of high acoustic absorption, is apparently caused by changes in the collision transition probability parameters of molecules under excitation due to radiation as compared with molecules not subjected to radiation. This second type of effect is perhaps the more interesting for it may make possible the development of very rapid response detectors for the far infrared. The feasibility of this can only be decided by determinations of the sensitivity of various gas compositions. There are such a large number of possible combinations that a detailed study of the mechanism of the effect is necessary to develop criteria of choice.

From a fundamental point of view it now appears possible to determine directly which modes of the molecules are responsible for the acoustic absorption.

#### ACKNOWLEDGEMENT

Mr. T. A. Newkirk and Mr. Ernst Maier assisted very materially in this investigation.

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