an Article from **SCIENTIFIC AMERICAN**

MAY, 1957 VOL. 196, NO. 5.

The Shortest Radio Waves

At the border between infrared and radio waves lie electromagnetic ripples measured in millimeters. They are now made in the laboratory, where they are used to study the properties of atoms and molecules

by Walter Gordy

In 1800 the English astronomer Sir William Herschel, holding an ordinary thermometer behind a prism which spread out the sun's light into its spectrum, moved the thermometer into the darkness beyond the red end of the spectrum and to his amazement found that the thermometer registered hotter radiation there than anywhere within the visible span. This act—it is almost too simple to call an experiment—must be regarded, symbolically at least, as one of the most significant ever performed in a laboratory. It opened the door to the great and possibly limitless sea of radiation which lies beyond the reach of the eyes of man. One year later Johann Wilhelm Ritter in Germany discovered invisible radiation on the other side of the rainbow colors—the ultraviolet. Before the close of the century, radio waves had been discovered beyond Herschel's infrared, X-rays beyond Ritter's ultraviolet. Today man has detected and explored the whole vast range of radiation from miles-long radio waves to the billionth-of-an-inch gamma rays [*see chart on page 52*].

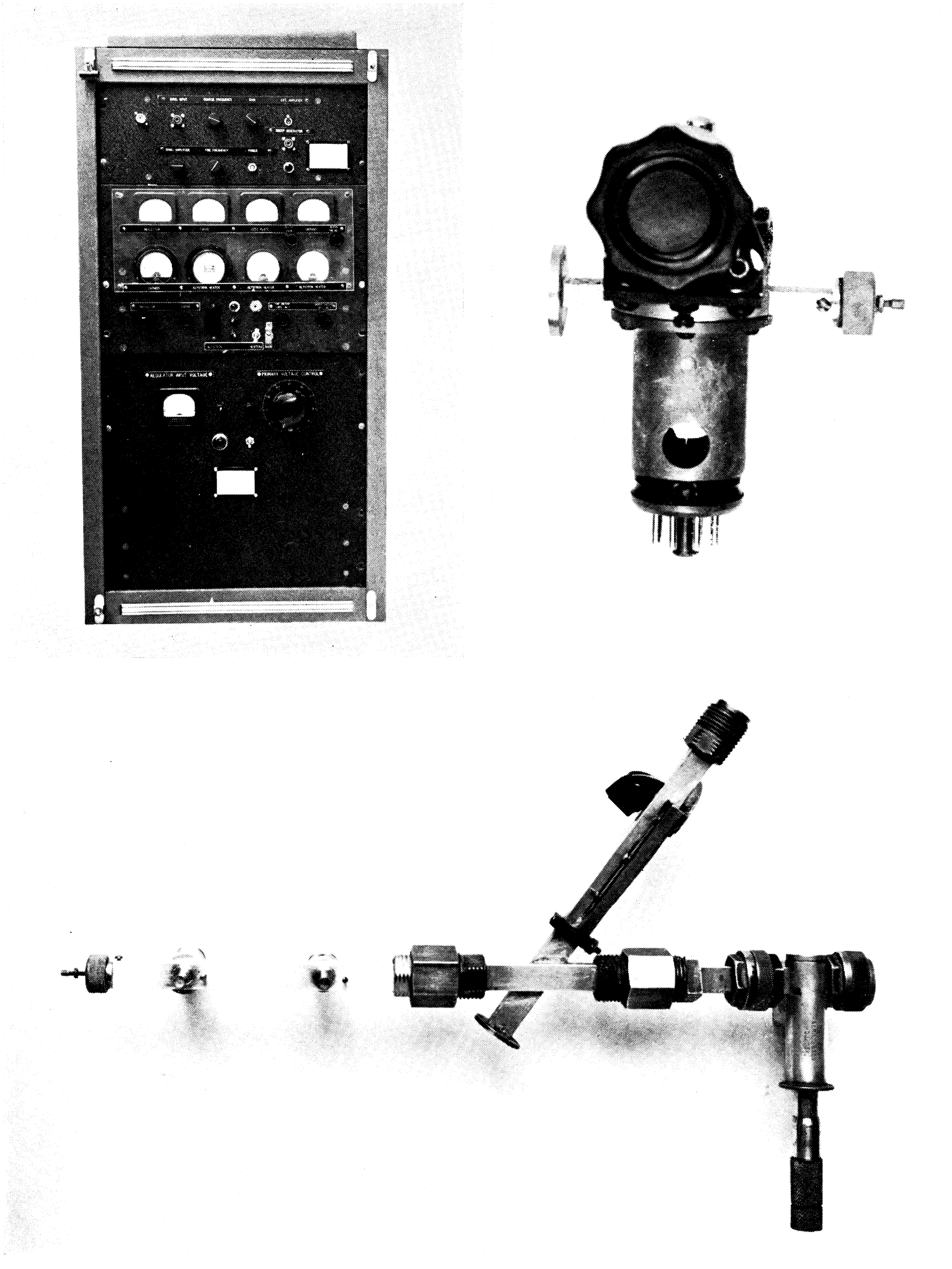
The expansion of man's spectrum of observation has led to an explosive increase in his physical knowledge and to unparalleled changes in his way of life. It has brought forth such inventions as radar, radio, television, medical uses of radiation, machines for chemical analyses, automatic factories and so on. It has in fact become our major instrument for investigating the nature of matter and many other mysteries of the universe.

The subject of this article is a new frontier region within the spectrum—namely, the millimeter and submillimeter range of radio microwaves. Centimeter microwaves were exploited for radar during World War II, but the millimeter range is only now beginning to be used extensively. The millimeter wavelength lies at the border between radio and the infrared. It was the last gap in the spectrum to be closed. The closing of the gap was not completed, in a practical sense, until three years ago, when our group at Duke University penetrated the submillimeter region with radio methods and L. Genzel and W. Eckhardt of Germany overlapped from the infrared side with an optical spectrometer.

Radio waves in this range are short enough to "see" molecules, atoms, the nuclei of atoms and electrons, and thus to give information about the shapes, sizes and other properties of submicroscopic particles of matter. The technique is still in too early a stage for commercial use. Scientifically, however, our millimeter-wave "eyes" are beginning to open.

How are such short radio waves generated? There are various possible methods: essentially the one we are using at Duke derives them from centimeter waves by developing harmonics—*i.e.*, multiples of the original frequency. Centimeter waves from a klystron tube are sent through a waveguide where they are picked up by a "cat whisker" assembly (like the crystal detector of the early radio sets). The small silicon crystal in this assembly distorts the pure sine wave of the received frequency into a complex wave containing higher harmonic components as well as the fundamental frequency of the centimeter radiation. The complex wave is rebroadcast by the tungsten whisker into a smaller waveguide—small enough to reject the low-frequency components and transmit only the higher harmonics. The particular harmonic selected as the frequency for studying a sample of matter is picked up by a second cat whisker of appropriate size at the other end of this waveguide. The sample of matter is placed in the path of the radiation, and its absorption of the radio energy at the selected frequency is measured [*see diagram on page 50*].

Since the harmonic frequencies are exact (or very nearly exact) multiples of the generating frequency, they are measurable with the same accuracy as the original centimeter frequency, which can be determined with high precision by reference to the standard radio frequencies broadcast by Station WWV of the National Bureau of Standards. The gratifying result is that this system gives the spectroscopist an instrument of extraordinarily high resolution and high precision. The sharpest lines detectable with an infrared spectroscope are thousands of times broader than those that can be obtained with a microwave spectroscope in the overlapping radio region. This considerable difference in resolution is due to a basic difference between the optical and radio methods. The infrared spectroscopist produces radiation by heating something very hot. What he gets is a jumbled mixture of waves; he spreads out the component frequencies with a grating or prism and selects a small band of frequencies from this spectrum by means of a narrow slit. The narrowness of the band he is able to obtain for spectroscopic use, and therefore the sharpness of his resolution, is limited by the fact that the slit must be wide enough to let through a detectable amount of energy. The radio spectroscopist, on the other hand, obtains his radiation not from the haphazard vibrations of electrons agitated by heat but from the ordered motions of electrons waltzing in unison to the tune of a single



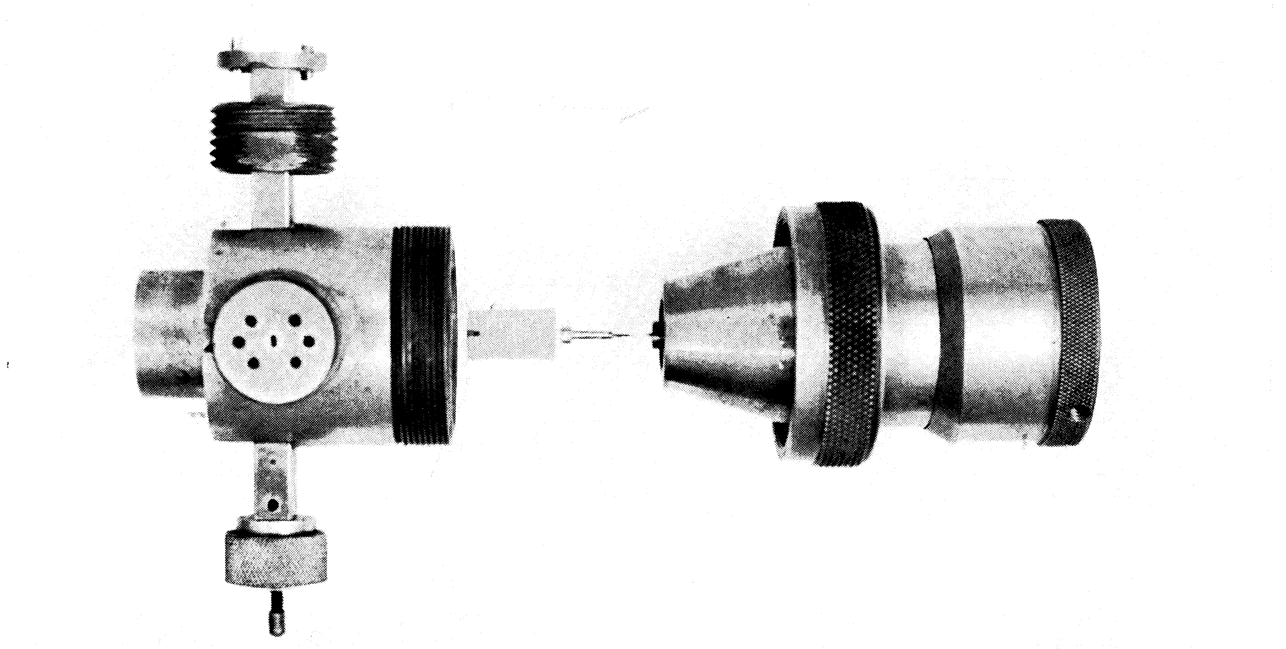
MILLIMETER WAVES ARE GENERATED at Duke University by means of the components shown on this and the next two pages. At upper left is a power supply. At upper right is a klystron tube capable of converting the power into waves measured in centimeters. These waves are fed into the short waveguide which runs diagonally across the picture at the bottom. The horizontal structure is a device to measure the length of waves passing through the waveguide. The objects in the pictures are not in the same scale.

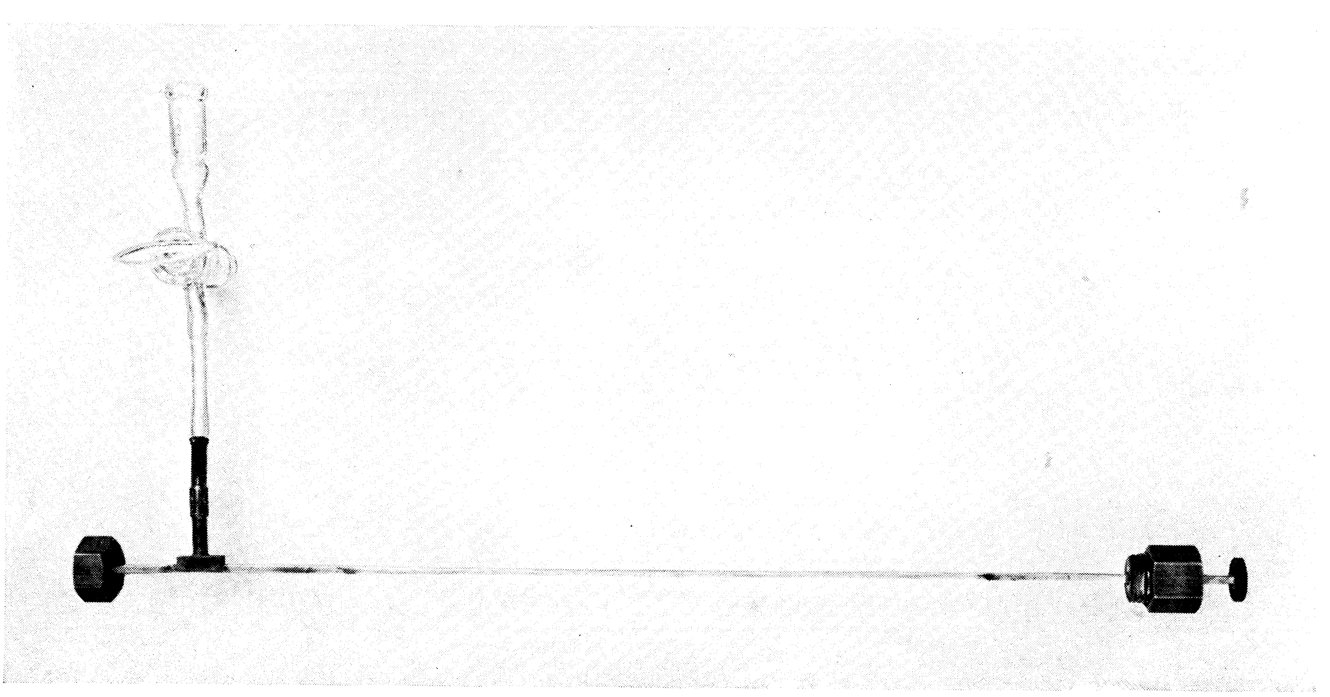
man-controlled circuit. Their radiant energy is concentrated in an extremely narrow band of frequencies. Thus the radio spectroscopist can detect narrow absorption lines and obtain higher resolution.

At Duke we have extended the range of microwaves usable for spectroscopic measurements down to wavelengths as short as .58 of a millimeter. This work has opened a whole new region for precision spectroscopy—a region consisting of about four octaves (from 60.000 megacycles to 510,000 megacycles) where accurate measurement of spectral lines has become possible for the first time.

The spectroscopist's objective is to measure the absorption of radiation by matter at specific frequencies, for this tells him a number of specific things about the properties of the atoms or molecules. A radio spectroscopist tunes his oscillator through the frequency at which the material he is examining is expected to absorb, in the same manner as you tune your radio set through the expected frequency of a broadcasting station. When the oscillator hits the precise frequency at which the substance under study has an absorption peak, a pip appears on his screen.

What sort of information do we get from absorptions in the microwave region? One of the chief items is information on the rotation, or spin, of molecules. In the gaseous state, molecules are constantly rotating. Their spin has a peculiarity which runs counter to com-

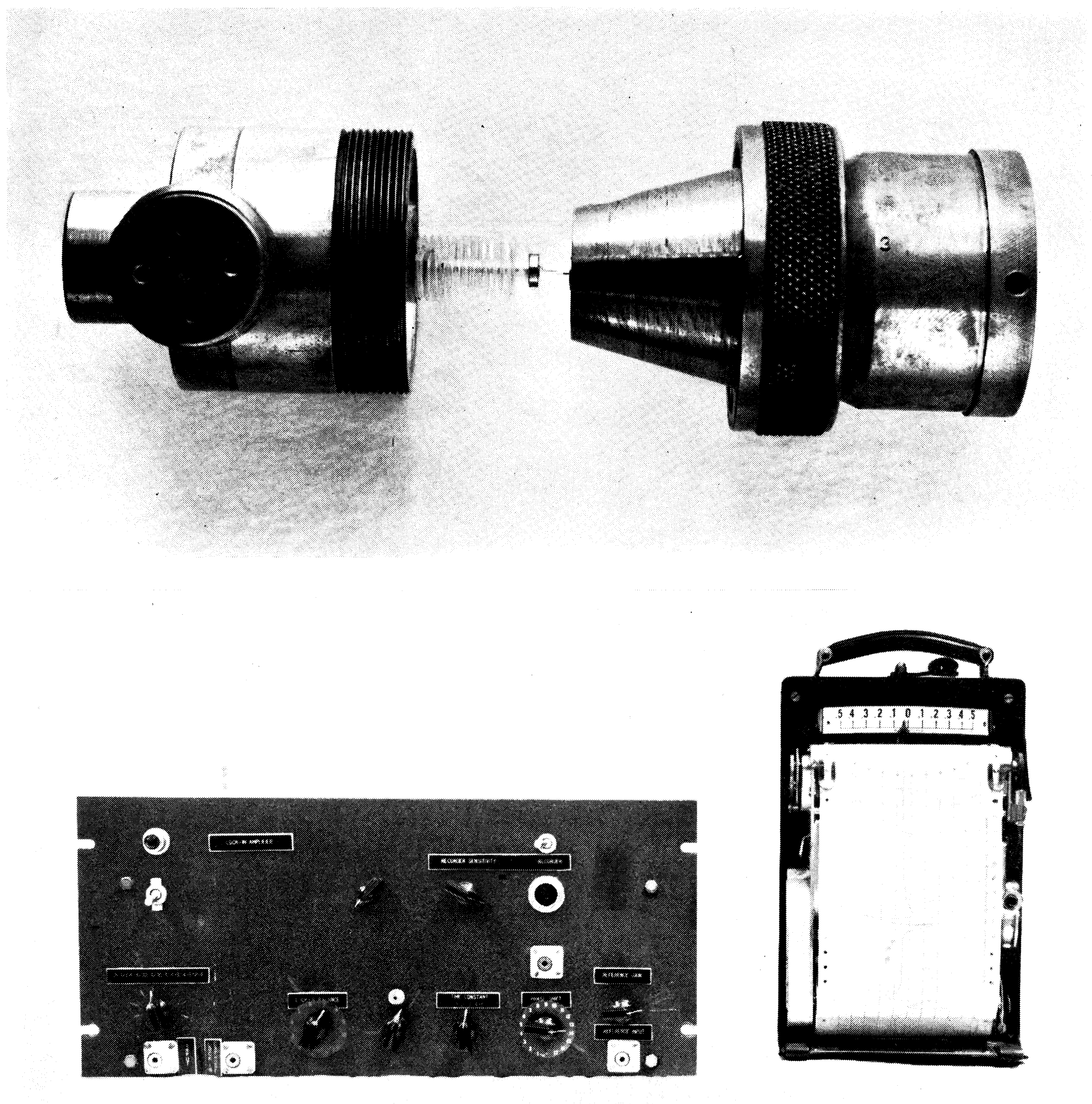




CRYSTAL AND CAT WHISKER at upper left, which are mounted at the end of the waveguide at the bottom of the preceding page, absorb the waves of centimeter length and distort their form. The distorted wave is then fed into the smaller waveguide at mon sense. A spinning top slows down gradually, but a spinning molecule cannot. Nor can it rotate at just any rate. It is constrained to rotate only at certain discrete rates, according to quantum rules. If it is to slow down, it must drop suddenly to the next lower permitted rate, and in doing so it gives up a specific amount of energy. Likewise it cannot speed up unless it receives a certain amount of energy—the energy needed to raise it to the next higher rotational rate. Microwave radiation will give the molecule this energetic promotion, provided that it is at the precise frequency which supplies the necessary energy. The quantum of energy required is defined by the famous formula $h\nu$—ν being the frequency and h a constant. This remarkable equation is a connecting link between electromagnetic radiation and all energy transformations of molecules, atoms and nuclei.

Thus molecules and atoms, in their strange quantum way, act as radio transmitters and receivers. I have indicated that a spectroscopist uses microwaves to look at molecules and atoms; it is perhaps more accurate to say that he uses radio to communicate with them.

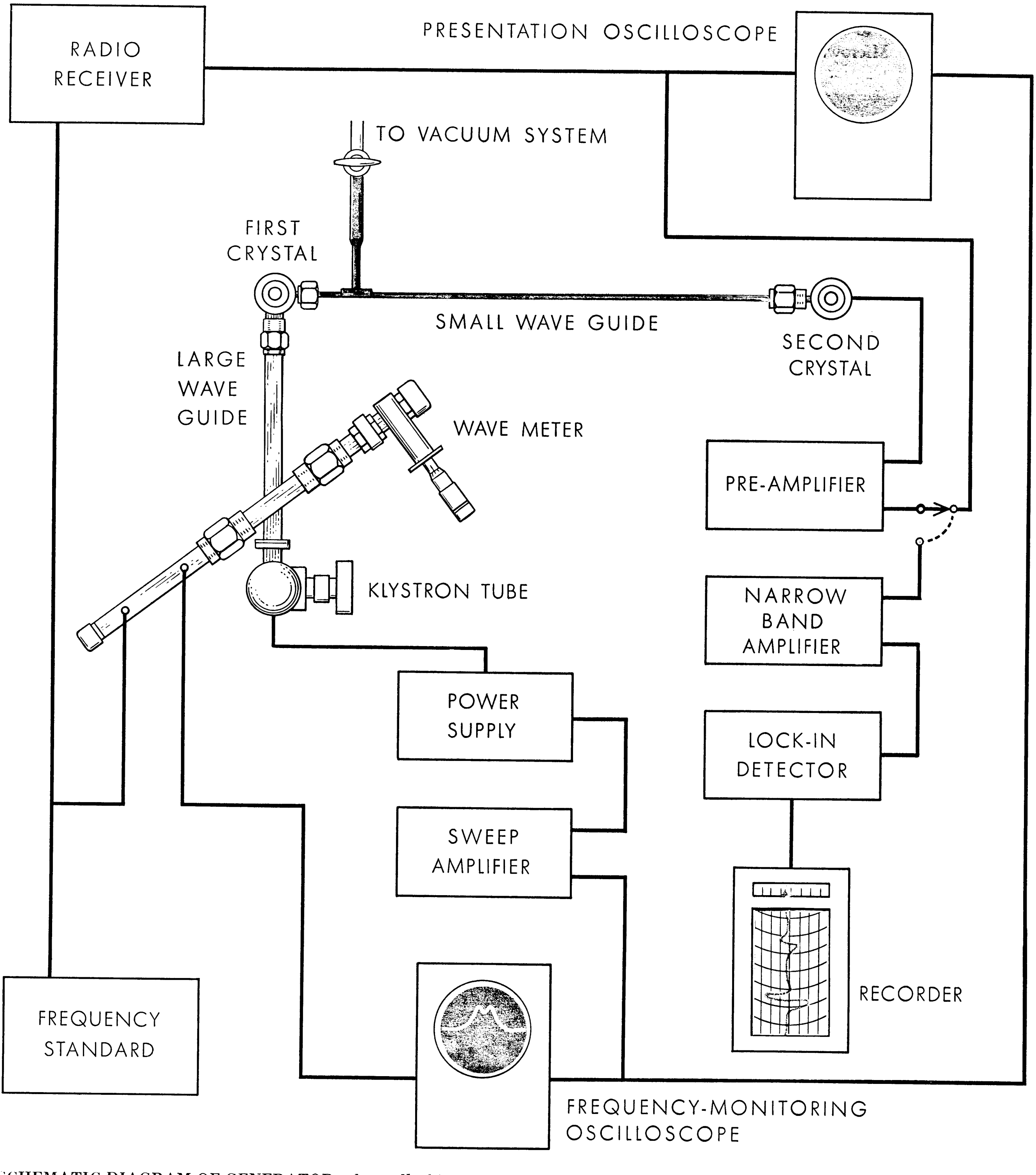
From the rotational absorption spectra of molecules the microwave spectroscopist obtains basic information of several types. From them he can calculate very accurately the distances between the atoms in a molecule and can gain important information about how the molecule is held together by its electrons. From them he can find the rela-



lower left, which passes only its millimeter-wave component. The crystal and cat whisker at upper right, which are mounted at the end of the smaller waveguide, detect the millimeter-wave signal. They are amplified and recorded by the apparatus at lower right.

tive weights of the different isotopes of an atom. From them he can determine whether the nucleus of an atom is spinning about an internal axis, can measure its magnetism and can even learn something about its shape: for example, whether the nucleus's field of charge is spherical like a basketball, elongated like a football or flattened like the hypothetical flying saucer.

For exploration of these properties the best subjects are simple molecules consisting of two or three atoms, and such molecules usually show rotational absorption lines only in the millimeter or submillimeter wave region, because they turn over too fast to absorb the centimeter waves. Many lightweight molecules have already been examined with microwaves shorter than four millimeters. Among them are hydrogen, deuterium and tritium halides (compounds with chlorine, bromine or iodine), carbon monoxide, nitrous oxide, hydrogen cyanide, phosphine (PH_3), arsine (AsH_3) and hydrogen sulfide. The millimeter-wave frequencies of hydrogen cyanide and carbon monoxide have been used in measurements of the velocity of light [see "The Speed of



SCHEMATIC DIAGRAM OF GENERATOR relates all of its components. If the investigator wishes to study the absorption of millimeter waves by a gaseous substance, he evacuates the air from the small waveguide and admits the substance to it (*colored area*).

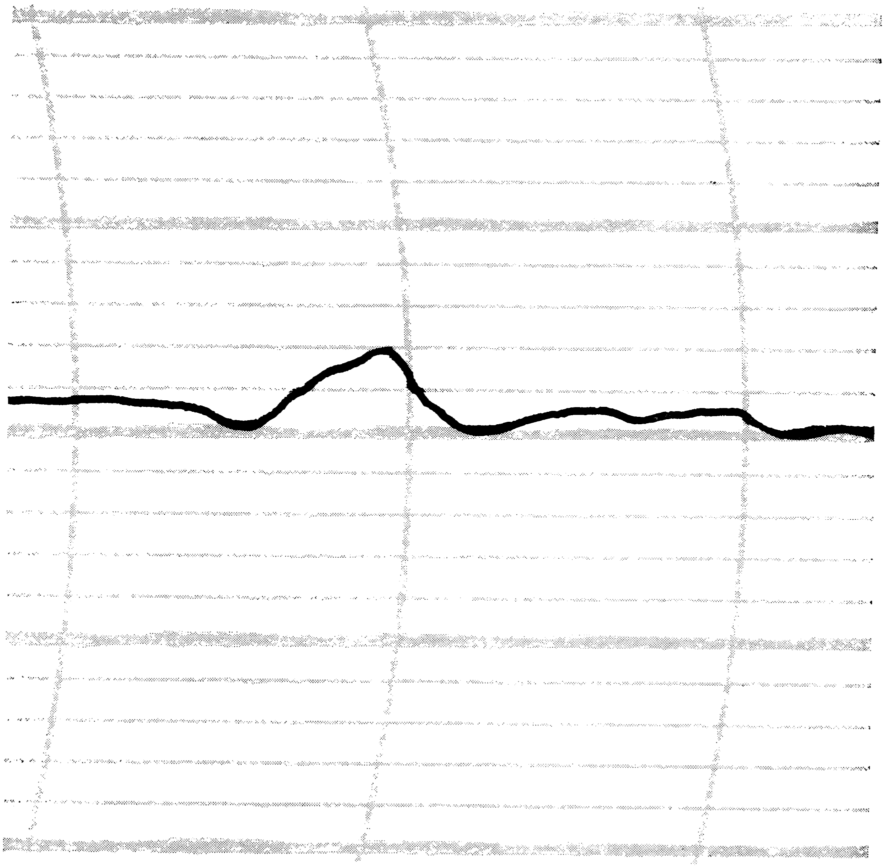
Light," by J. H. Rush; SCIENTIFIC AMERICAN, August, 1955]. The ratio of the millimeter-wave frequencies of deuterium bromide and tritium bromide was used to "weigh" the tritium atom.

Millimeter waves offer a promising means of measuring properties of radioactive isotopes which can be produced only in very small amounts. They can show absorption spectra in samples of material amounting to less than a millionth of an ounce. Three radioactive isotopes of iodine have already been studied, and other likely candidates are isotopes of chlorine, bromine, phosphorus, arsenic, antimony and selenium.

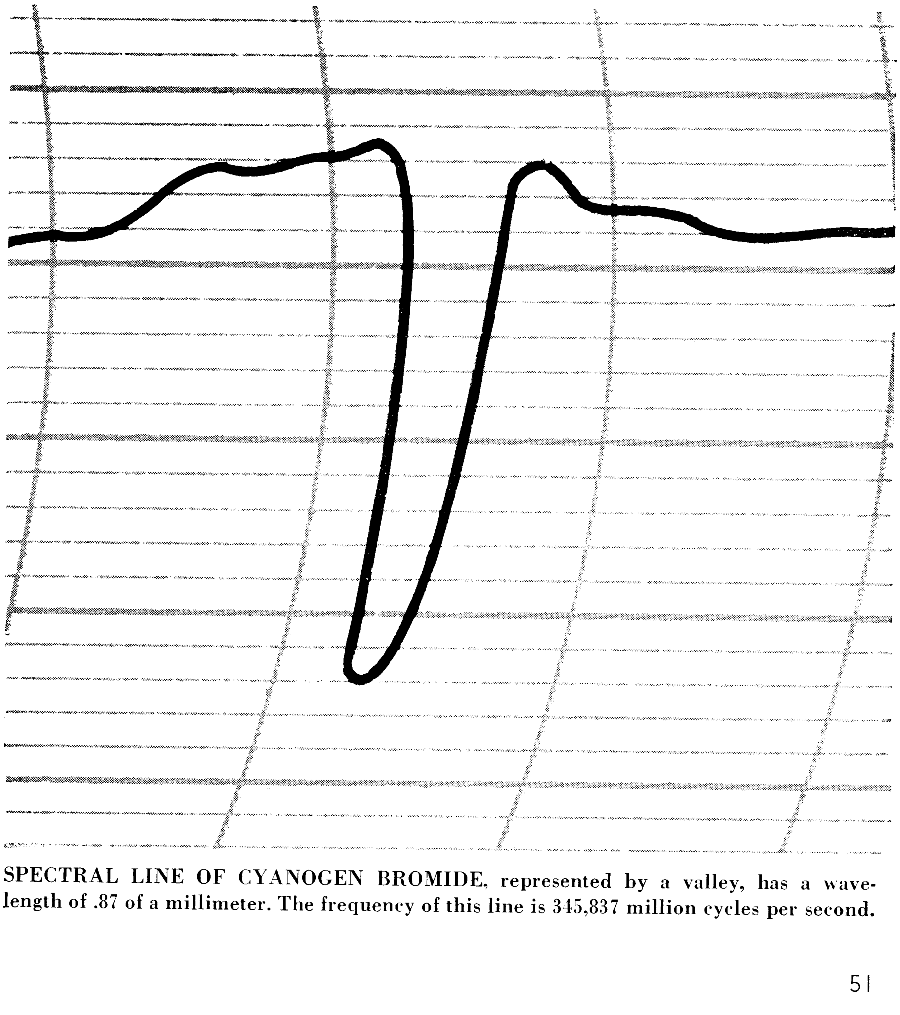
Industrial chemists sometimes ask me when microwave spectroscopy will become a practicable tool of analysis in industry. I think this will come when the technique in the millimeter region can be reduced to a routine procedure. In the centimeter region analysis is almost impractical because of the sparseness of spectral lines; at millimeter and submillimeter wavelengths the lines are far stronger and more plentiful.

Chemistry is only one of many fields in which these short waves will be useful. Much of the radio astronomy of the future may be in the millimeter region. Already the 50-foot parabolic reflector of the Naval Research Laboratory is being used to look at the sun with eight-millimeter waves. To demonstrate that even shorter waves can penetrate the earth's atmosphere, a group of us at Duke recently picked up three-millimeter waves from the sun at Durham, N. C., a notoriously humid location. Our antenna was a discarded searchlight reflector, and we used a highly selective superheterodyne receiver with a harmonic multiplier.

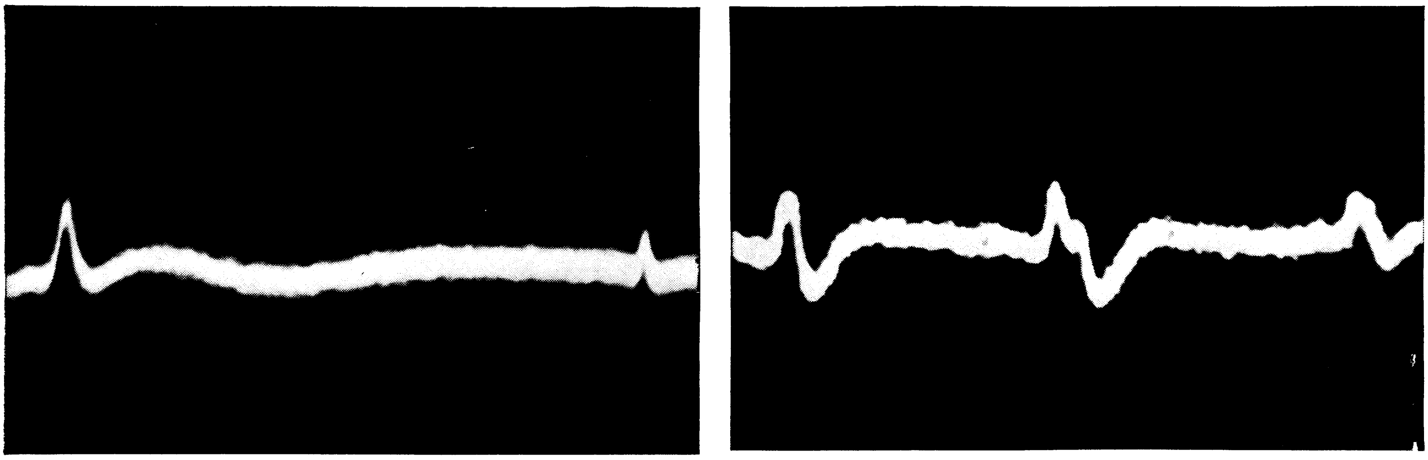
What can be learned in astronomy with millimeter waves that has not already been learned with the longer radio waves or the optical telescope? I am glad I do not know the many answers to this question, for research would not be fun without its surprises. (Physicists still work partly for fun.) I have the hopeful opinion that new information will be gained about the earth's upper atmosphere, about the sun and possibly even about the outer spaces. One of the enticing possibilities is a more intensive study of sunspots. At the three-millimeter wavelength it would be practicable to make an antenna large enough to focus on a single sunspot: a 100-foot reflector would do it, whereas it would take one many times that size to focus centimeter waves on a sunspot. Obvi-



SPECTRAL LINE OF CARBONYL SULFIDE, represented by the pip on this curve, is the shortest wavelength measured by radio methods. The wavelength is .58 of a millimeter.



SPECTRAL LINE OF CYANOGEN BROMIDE, represented by a valley, has a wavelength of .87 of a millimeter. The frequency of this line is 345,837 million cycles per second.



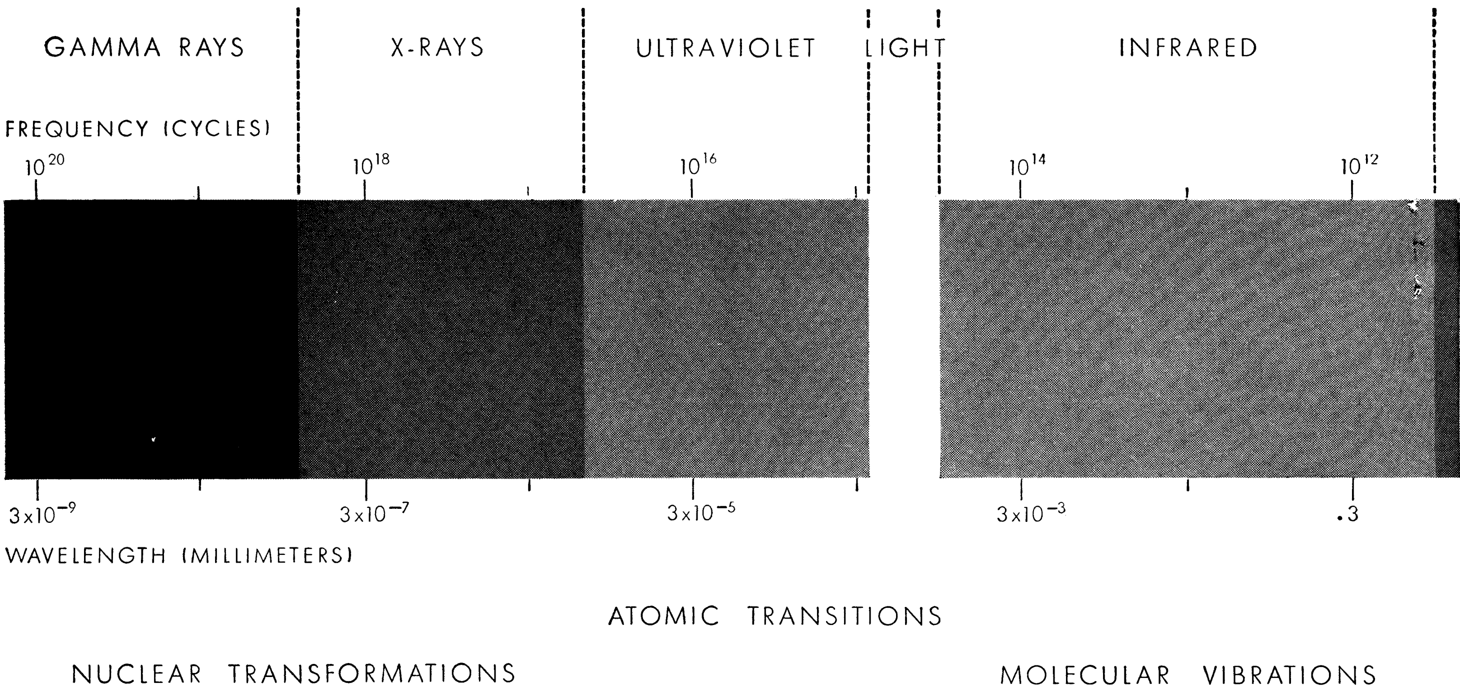
SPLIT SPECTRAL LINES of hydrogen iodide (*left*) and deuterium chloride (*right*) are shown by these photographs of oscilloscope traces. The wavelength of the hydrogen iodide line is .78 of a millimeter; of the deuterium chloride line, .93 of a millimeter.

ously the millimeter waves begin to have some of the advantages of light while retaining the advantages of radio waves.

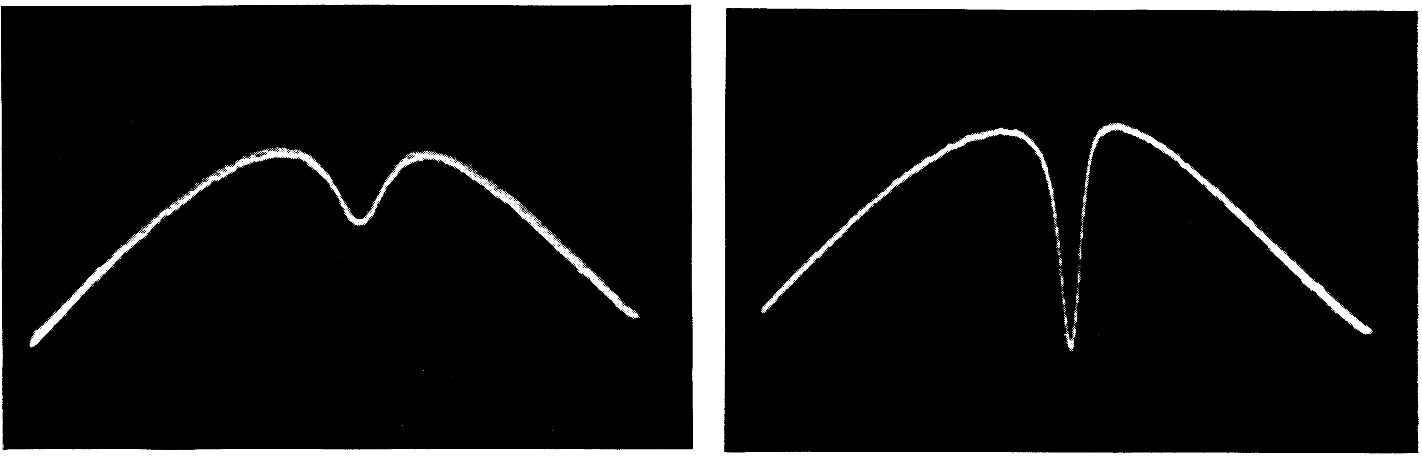
The shortest radio waves may throw some light on the mystery of superconductivity. In certain metals at a temperature near absolute zero you can start a current flowing, disconnect the battery, walk away and come back three months later to find the current still flowing. This puzzle attracts us all—whether through holy curiosity or a submerged desire to get something for nothing. Newton would seem to have lifted part of the veil from this mystery almost 300 years ago when he announced that an object doesn't really have to be pushed along to keep moving—provided nothing gets in the way. But how can trillions of electrons move around in a piece of metal without ever suffering from collisions with the trillions of atoms? The late Fritz London of Duke made the boldest and possibly the best guess about the way such a phenomenal traffic problem may be solved in the superconducting metal. After describing his guess we shall see how the shortest radio waves may provide a test of it.

As is well known, or generally believed, the electrons in an atom or a molecule can move indefinitely in their orbits without dissipating energy. Electrons in the benzene ring, for example, travel around and around the ring with no evident traffic jams. London suggested that quantum conditions might account for the "perpetual motion" of electrons in a superconducting metal as they do for unimpeded travel in atomic orbits. Superconducting electrons might somehow form a well-defined quantum state of substantially lower than normal energy and thus avoid collisions.

Could appropriate energy quanta lift these electrons from the superconducting state to the normal state? Radio waves at frequencies up to 36,000 megacycles fail to do this, for superconductivity persists in tin for currents gener-



ELECTROMAGNETIC SPECTRUM is arrayed to show the location of millimeter radio waves with respect to radiation of other wavelengths. The shorter electromagnetic waves (and higher frequencies) are to the left; the longer waves (and lower frequencies)

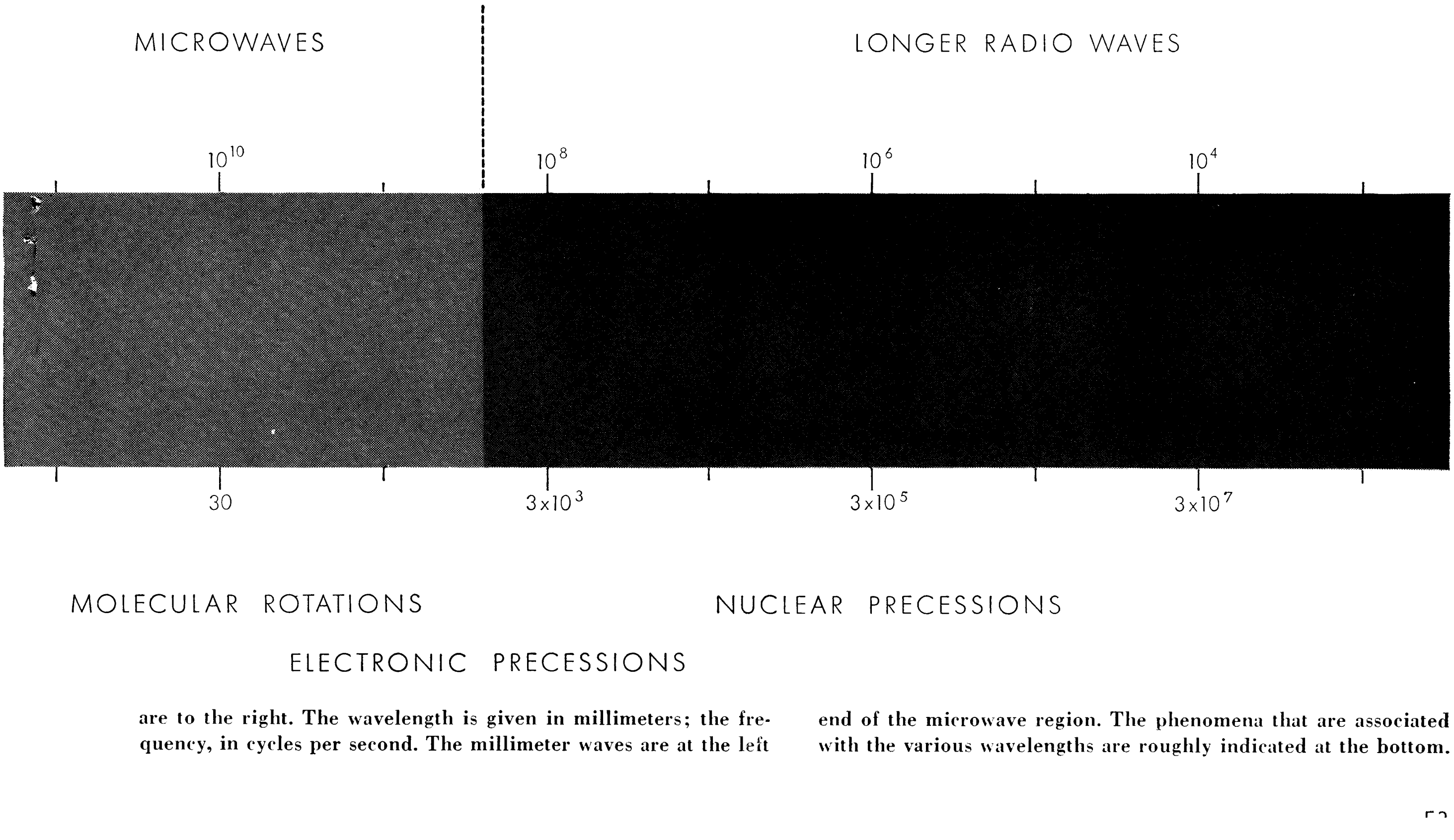


SUPERCONDUCTIVITY OF TIN was explored with currents of 150,000 million cycles (two-millimeter waves). The dip in the trace at left is the response curve of a non-superconducting cavity of tin; the dip at right, of the cavity when it is superconducting.

ated with this frequency. But suppose we used frequencies 10 times higher, which would multiply the energy quantum tenfold? We are investigating this question at Duke. So far we have gone only to 150,000 megacycles, sending alternating currents with this frequency through tin waveguides and resonant cavities at low temperatures. The preliminary evidence indicates that there is indeed a quantum gap between the superconducting and normal states of electrons, and that the gap may become larger as the temperature is lowered below the critical temperature for direct-current superconductivity.

Undoubtedly, many solid-state phenomena besides superconductivity will be studied with the shortest radio waves.

The method I have described for generating and detecting millimeter waves is but one of several, though it is the only one yet used for scientific measurements. In 1923 E. F. Nichols and James D. Tear produced millimeter radio waves with a spark-gap generator. The Columbia University Radiation Laboratory has developed magnetrons which operate in the three-millimeter wave region and has detected harmonics at wavelengths as low as 1.1 millimeters. Stephen J. Smith and Edward M. Purcell of Harvard University have crossed the gap between radio and light by passing 300,000-volt electrons near the slits of an optical grating and generating visible light. A group at Stanford University is reported to have generated infrared rays by directing million-volt electrons through a bumpy magnetic field. It remains to be seen whether these methods will prove feasible for spectroscopy or for gadgets such as radar. Whenever a practical method is developed for generating high-power radio waves in the region between one-half millimeter and five millimeters—a source which is tunable and produces highly monochromatic waves—it will be of great value to science and to industry.



are to the right. The wavelength is given in millimeters; the frequency, in cycles per second. The millimeter waves are at the left end of the microwave region. The phenomena that are associated with the various wavelengths are roughly indicated at the bottom.