basic matters—about the perception of time and tactual space, about intensity discrimination, and about topographic variations in sensitivity. There is not the slightest doubt that a host of other observable cutaneous phenomena—adaptation, masking, reaction latencies, spatial interactions, temporal summations, "loudness" and "pitch" functions, recruitment effects, and so on—are more than peripherally related to the central problem. We have not yet really begun to look carefully into the communication possibilities offered by the human integument or even into the bare facts that provide the possibilities (*13*).

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The Mössbauer Radiation

Low-energy gamma rays provide the most precisely defined electromagnetic frequency yet discovered.

Winston E. Kock

One of the latest discoveries in physics which is now intriguing scientists in many fields remained relatively unknown for a year after its publication. Early in 1958 Rudolph L. Mössbauer published in the *Zeitschrift für Physik* (*1*) his first report concerning an emission and absorption process for low-energy gamma rays. Between that time and September 1959 there was no published evidence of any related work going on at other laboratories, yet today there is extensive activity at many institutions, including Harvard, Los Alamos, Illinois, and the Argonne Laboratory in America, and Harwell, Birmingham, Cambridge, and Manchester in England.

What is it about this new effect that suddenly has brought it such attention from the scientific community? Most spectacular is the revelation that the gamma-ray radiation involved has a frequency which is more stable by many orders of magnitude than the best atomic clocks available today. Because the electromagnetic waves involved have frequencies of the order of 10^{18} cycles per second, ordinary radio techniques for observing their amazing frequency stability are not usable. For his detector, Mössbauer employed an absorber which was similar to his radiator in that its absorption effect exists over the extremely small frequency range of the radiator.

The author is director and general manager of the Research Laboratories Division of Bendix Aviation Corporation, Detroit, Michigan.

Experimental Techniques

Figure 1 shows how the narrowness of the frequency (or line width) of the radiator and absorber are measured. When the radiator is stationary relative to the absorber, the frequency of the radiated gamma ray and that of the absorber are identical and the counter reads a relatively low value. If, now, the radiator is set in motion relative to the absorber, a Doppler shift is imparted to the radiated electromagnetic wave and the two frequencies differ. The "stop band" of the absorber "filter" is no longer effective at the Doppler shifted frequency, and the counter reads a higher value than before.

From the velocity of the radiator as measured experimentally, the amount of Doppler frequency shift is known, and the frequency characteristics of the source and absorber can be ascertained. Figure 2 shows a plot of the measured line width of the gamma ray of the isotope of iron-57, as measured by R. V. Pound and G. A. Rebka, Jr., of Harvard University (*2*). As shown in the figures, the half-width point corresponds to a source velocity of 0.017 cm/sec. When one considers that the velocity of light is 3×10^{10} cm/sec, the remarkable frequency stability of the gamma ray is evident. A velocity of one million millionth that of light has shifted the radiating frequency an appreciable amount from the absorber "filter" band. The center frequency of the line is 10^{12} times the line width; if a regulation capability of one thousandth of the line width (the capability normally achieved in present atomic clocks) is assumed, "the 'least count' in the Pound and Rebka experiment is about 3 parts in 10^{16}" (*3*).

Applications

To what use has this remarkable discovery been put? One of the applications contemplated earlier for precise atomic clocks was that of checking, from satellites, the gravitational red shift predicted by relativity theory. Relativity maintains that two identical clocks would run at different rates if one were kept on earth and the other were removed to a point of lower gravitational potential (for example, by means of a satellite). This gravitational effect is quite small; thus it would cause a clock at 2000 miles above the earth to differ from an identical earth clock by one second in 500 years.

The discovery of the Mössbauer effect changed the picture dramatically. Pound and Rebka (*4*) first published the suggestion that Mössbauer's findings would eliminate the need for the great height difference demanded by the contemplated experiments with atomic clocks, that instead heights available in the laboratory should be adequate.

The technique would be to place the source and the absorber at different heights, and the difference in gravitational field would shift the frequency of one device relative to the other. The experiment was performed by T. E. Cranshaw, J. P. Schiffer, and A. B. Whitehead at Harwell in England (*5*) and by Pound and Rebka at Harvard. One parameter that unexpectedly turned out to be of importance was temperature; an extremely small temperature difference between the source and the receiver can swamp the sought-for effect. The Harwell group published their findings (which suggested confirmation of the gravitational effect, with some appreciable uncertainty) before this temperature dependence was appreciated. Pound and Rebka, on the other hand, found wide fluctuations in their results, due in part to the above-mentioned temperature effects. These effects were then taken into account, and Pound and Rebka's confirmation of the gravitational effect, appearing a month and a half after Harwell findings, is therefore quite convincing. Their quoted uncertainty error is quite small.

Mechanism of the Sharp Line

One wonders how such a narrow line of radiation can occur and why it has not been observed before. The gamma rays under consideration are emitted by nuclei, and normally the nucleus would experience a recoil upon emission of the gamma ray, thereby causing the frequency of the gamma ray to be shifted by various amounts.

Mössbauer considered the possibility that a nucleus held by the strong binding forces in a crystal lattice might cause the entire crystal lattice to absorb the recoil, and that this sharing of the recoil among huge numbers of atoms would permit the observed line width to be limited only by the length of the wave train of the gamma-ray photon. A wave train of an iron-57 photon has roughly 10^{12} waves, its frequency being 3×10^{18} cycles per second and its half-life 10^{-7} seconds. From the uncertainty relation $\Delta\gamma\Delta t \approx 1$, one arrives at the half-line width of 1 part in 10^{12}. The crystal recoil effect is also present in the absorber; its nuclei are accordingly in exact resonance with the unshifted line from the source.

History

It is interesting to follow the history of the developments since Mössbauer's orginal discovery, as the more recent ones have a sort of Horatio Alger touch.

As mentioned above, Mössbauer's publications were the only ones in the field for about a year. Then there appeared, in the 1 September 1959 issue of *Physical Review Letters*, two notes, both received 3 August. One reported on work by a group at the Los Alamos Scientific Laboratory; it essentially indicated that Mössbauer's experiments and results had been confirmed through the use of Mössbauer's original choice of the iridium isotope 191. The other was communicated by a group at the Argonne National Laboratory, also describing a verification of Mössbauer's results and reporting on a similar effect observed with tantalum-182 as a gamma-ray source against a tungsten-182 absorber.

An important advance occurred with the publication, in the 1 November issue of the same journal, of Pound and Rebka's note (*4*) suggesting (i) that

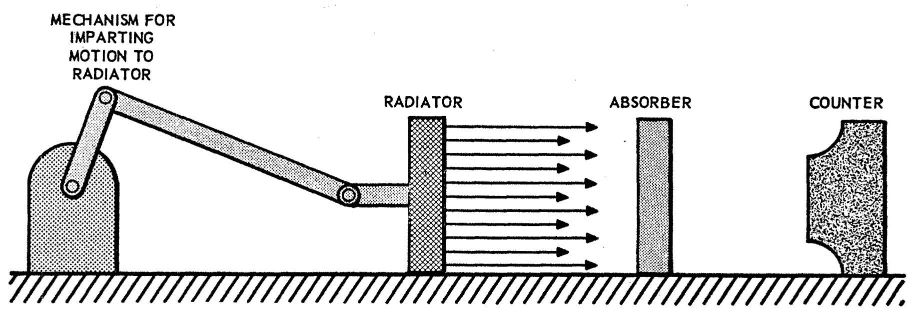

Fig. 1. When motion is imparted to the source of radiation, a Doppler shift occurs and the originally matched absorber is then less capable of absorbing the electromagnetic waves, as is indicated by the counter on the right. A loud-speaker drive is usually employed as the means of imparting vibration.

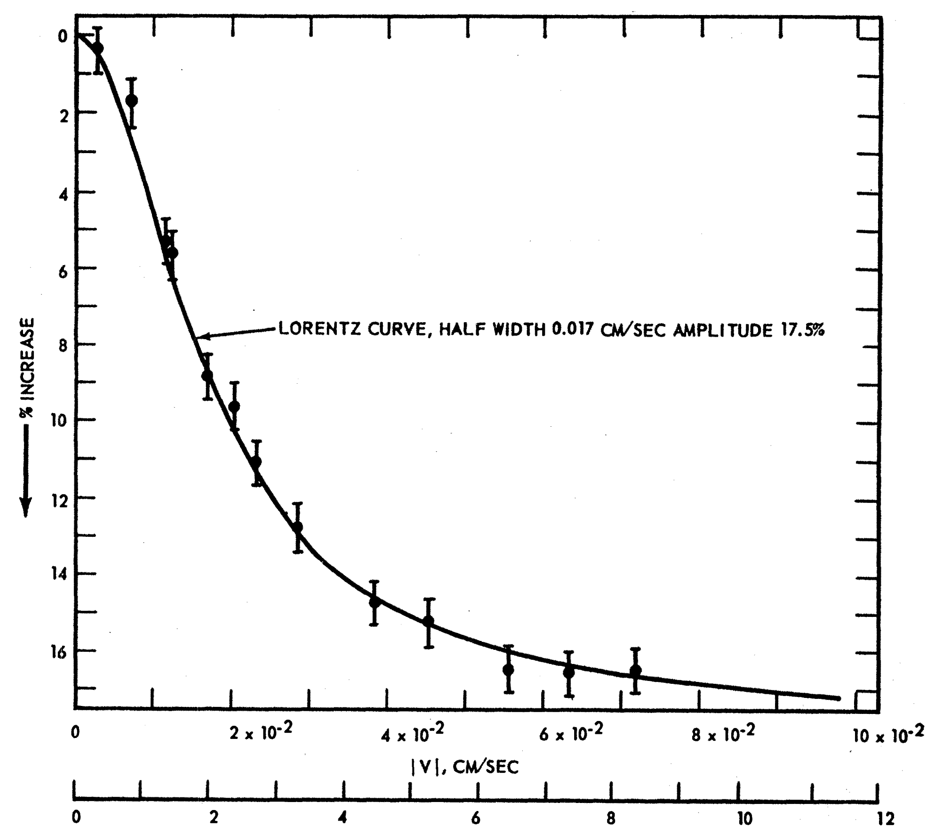

Fig. 2. The line width, expressed in megacycles per second, of the iron-57 radiation (3×10^{12} Mcy/sec), is obtained from calculations of the Doppler shift resulting from the relative velocity between source and absorber. [Pound and Rebka]

the Mössbauer effect be used to check the gravitational red shift and (ii) that iron-57, along with zinc-67, should furnish even sharper lines than Mössbauer's iridium-191. Shortly before this, one member of the Argonne group, J. P. Schiffer, went as a John Simon Guggenheim fellow to the British Atomic Energy Research Establishment at Harwell, and in the 15 December issue of *Physical Review Letters* two letters appeared, both received on 23 November, one from Schiffer and W. Marshall at Harwell and the other, a new note from Pound and Rebka. Both letters discussed experiments with iron-57, and Pound and Rebka produced actual curves showing the line width (Fig. 2) and the hyperfine structure. The 15 January issue also had two notes describing work on iron-57; one, by the University of Illinois group, included a hyperfine structure curve matching Pound and Rebka's, and the other, by the Argonne group, demonstrated polarization of the gamma radiation.

In the 15 February issue, Cranshaw, Shiffer, and Whitehead of Harwell published their conclusions on the gravitational red shift, with the rather large uncertainty of 0.96 ± 0.45 times the expected red shift. Another Harwell group reported in the same issue their measurements of the red shift in an accelerated system. The race, if one could call it that, appeared to be over, with Harwell (and Schiffer) the uncontested winner, when, to everyone's consternation, the 15 March issue appeared carrying the letter by Pound and Rebka which pointed out the strong frequency dependence on temperature of the iron-57 rays, as determined by theory and experiment. This letter had been submitted before the Cranshaw letter appeared in print, so no comment was made on the Harwell results. The reader, however, could readily recognize the importance of this parameter, and the Harwell letter was thereby placed under a cloud. Did the gravitational effect really exist or did it not?

What is probably the final chapter was the publication of Pound and Rebka's gravitational results in the 1 April issue of *Physical Review Letters* (*6*). It removed all doubt concerning the existence and extent of the gravitational red shift, the results matching the theoretical expectations by a factor of 1.05 ± 0.10. Fortuitously, a letter from B. D. Josephson at Trinity College, Cambridge, in the same issue (referring to the Harwell letter and to Pound and Rebka's earlier suggestions) pointed out the definite necessity of taking into account the dependence of frequency on temperature in such experiments.

The Future

Apparently one important relativity question is now settled, and scientists will be searching for other experiments which can capitalize on this very precisely defined electromagnetic frequency. Surely there will soon be practical applications of this narrow line. Pound and Rebka pointed out that at 10 cycles per second, the 0.017 cm/sec velocity which was equivalent to a half-line width corresponds to a peak-to-peak amplitude of 0.0009 centimeters. Were the source to be vibrated at, say, 1 megacycle per second, a velocity of 0.017 centimeter per second would correspond to a peak-to-peak amplitude of 9×10^{-9} centimeter (less than twice the radius of the hydrogen atom). Velocity- and distance-measuring methods of the future may well be based on this interesting new discovery.

Whether the actual electromagnetic frequency itself can be used as a stable source of frequency for subharmonic scaling circuits or for comparison with quartz clock oscillators remains an open question. Suffice it to say that much thought will be given to finding ways of utilizing the remarkable stability of the Mössbauer radiation in this way.

Nuclear experiments in this field will also continue, and through the results of these experiments more will be learned about the properties of matter and the solid state (*7*). Unquestionably, the Mössbauer effect has provided the experimental physicist with a powerful tool for the exploration of many of the remaining secrets of atomic physics (*8*).

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8. I am indebted to Dr. Pound and to Dr. S. A. Goudsmit for helpful discussions on this subject.

Donald J. Hughes, Nuclear Physicist

Donald J. Hughes, who died on 12 April at the age of 45, was a scientist who had played a unique role in the development of the field of neutron physics. Not only have his own researches yielded results of first importance and opened up new avenues of endeavor toward a basic understanding of many aspects of nuclear physics, but as a central driving force Donald Hughes had been the main factor responsible for the collation and unification of most of the information related to the interactions of neutrons with matter. In his extensive contacts with practically all of the neutron scientists of the world he had been instrumental in stimulating a tremendous amount of vital new research; furthermore, he had been one of the main U.S. scientific ambassadors responsible for our fruitful international relationships in the field of neutron physics and nuclear science in general. A most significant aspect of Hughes' work has been the fact that many of his various researches in fundamental neutron physics have led to almost immediate practical uses and are of major significance to reactor technology. Hughes was an eminent and respected member of the scientific community. He showed a deep