THE MÖSSBAUER EFFECT AND ITS APPLICATION

IN 1958 the young German physicist Rudolf Mössbauer, while studying resonance absorption of γ rays, found that, under suitable conditions, one can obtain unusually sharp lines in emission and absorption of γ rays, and these lines coincide in frequency with one another. A slight shift in frequency (energy) of either of these lines produced, for example, by the Zeeman splitting of nuclear levels, or by a shift in energy of the quanta because of motion in a gravitational field, should result in a weakening or complete disappearance of the resonance absorption, which can be used for measuring such a shift. This interesting possibility, which promises new prospects for investigations in the domain of nuclear physics, solid state physics, and fundamental physical problems has attracted to the Mössbuaer effect a broad interest, far exceeding that for any occurrence in physics since the discovery of parity nonconservation and the explanation of superconductivity.

During the whole of 1960 there followed one after the other experimental papers devoted to a study of the Mössbauer effect and to the development of its applications. A discussion of this whole class of problems was held at two sessions of the Second All-Union Conference on Nuclear Reactions at Low and Medium Energies, which occurred in July, 1960 in Moscow. R. Mössbauer and R. Pound participated in this conference and presented papers. The latter (in collaboration with G. Rebka) carried out the work in which for the first time there was achieved with good accuracy a measurement of the gravitational red shift of photon frequencies as predicted by Einstein. The possibilities which have been opened are illustrated by the sensitivity achieved in this work, of 10^{-16} for a relative frequency shift; this is several orders of magnitude better than can be achieved by means of such record-breaking equipment as the molecular generator.

We publish here the reports of Mössbauer and Pound, and also a paper of F. L. Shapiro, which supplements these reports by a presentation of an elementary theory of the Mössbauer effect and a summary of work carried out in the U.S.S.R.*

The Editor, Uspekhi Fizicheskikh Nauk.

RECOILLESS RESONANCE ABSORPTION OF GAMMA QUANTA IN SOLIDS

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Usp. Fiz. Nauk 72, 658-671, (December, 1960)

INTRODUCTION

THE γ quanta which are emitted in the transition of a nucleus from an excited state to its ground state can usually not be used to transfer this same nucleus from its ground state to the excited state by the inverse process of resonant absorption. This is a consequence of the loss of energy to recoil which the γ quantum suffers in the process of emission or absorption, because the quantum imparts some recoil momentum to the emitting or absorbing atom. This loss of energy to the recoil is so large that the emission and absorption lines are shifted a considerable amount with respect to one another, as is shown in Fig. 1 for the case of the 129-kev γ transition in Ir^{191}. The large relative shift of the lines results in the fact that in experiments on absorption ordinarily only an insignificantly small fraction of the emitted quanta undergo resonance capture in an absorber consisting of stable atoms of the same kind as those decaying in the source.

There exist various methods which enable one, by using the Doppler shift or the Doppler broadening of the emission line, to increase the overlapping of the emission and absorption lines and thus achieve in favorable cases measurable effective cross sections for nuclear resonance absorption.[1]

In addition, as we have shown in earlier work, in individual cases it is possible to eliminate the energy loss of the γ quanta to recoil in emission and absorption, and thus to make the process of resonance absorption directly observable. This method of recoilless resonance absorption of photons is the subject of the following presentation. Immediately after a brief qualitative discussion of the basis for recoilless resonance absorption, we shall describe experiments which directly demonstrate this effect. Then we shall give a summary of the development in this field at present, and a brief presentation of the results of the most important investigations carried out up to now.

1. THE METHOD OF RECOILLESS RESONANCE ABSORPTION OF PHOTONS BY NUCLEI

The essential distinguishing feature of the method is the binding of the radiating and absorbing nuclei,

*The state of the problem of resonant absorption and scattering of γ rays before Mössbauer's discovery is described in the summary of papers of B. S. Dzhelepov [Usp. Fiz. Nauk 62, 3 (1957)] and F. R. Metzger [Progress in Nuclear Physics 7, 53 (1959)]

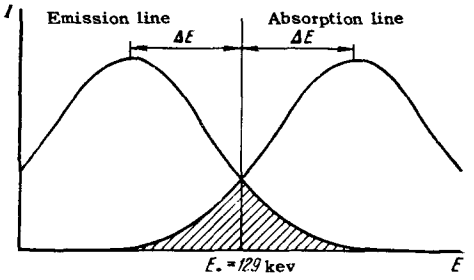

FIG. 1. Position and shape of emission and absorption lines for the 129 kev transition in Ir^{191} at T = 300° K.

which until now has been accomplished exclusively by putting the nuclei into crystals. Under these conditions the transitions in a nucleus are accompanied as a rule by a phonon transition, i.e., there occurs simultaneously a change in the internal state of the crystal. However, under certain definite conditions there are also possible nuclear transitions in which there is no change whatsoever in the internal energy of the crystal. In transitions of this latter type the law of conservation of momentum is satisfied at the expense of a recoil of the crystal as a whole. Since the crystal has an extremely large mass compared with the mass of an individual nucleus, the processes of emission and absorption, which are elastic with respect to the crystal as a whole, occur practically without energy loss; we shall therefore refer to these processes, because of the negligibly small loss in energy to recoil, as processes "without recoil."

In 1958, in Heidelberg, we first[2] proved the existence of processes of recoilless emission and absorption on the example of the 129-kev transition in Ir^{191}. Furthermore, we showed that the theory of resonance capture of slow neutrons in crystals, which was developed by Lamb,[3] can be applied to the case considered here of resonance absorption of γ rays. According to the theory, both in the emission spectrum as well as the absorption spectrum, at positions corresponding to the transition energy E_T, there appears a line with the natural width, corresponding to processes of recoilless emission and absorption.

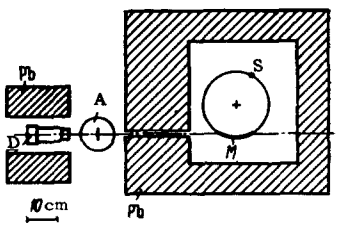

FIG. 2. Geometry of the experiment. A – cryostat with absorber (T = 88° K); M – rotating cryostat with source (T = 88° K); D – detector; S – source.

The occurrence of a line without recoil and having the natural width was demonstrated by us immediately in the following experiment.[4] In Fig. 2 is shown the arrangement of the experiment. We measured the absorption in an iridium absorber A of the 129-kev γ radiation of Ir^{191}, emitted by the source S for various relative velocities of source and absorber. In Fig. 3

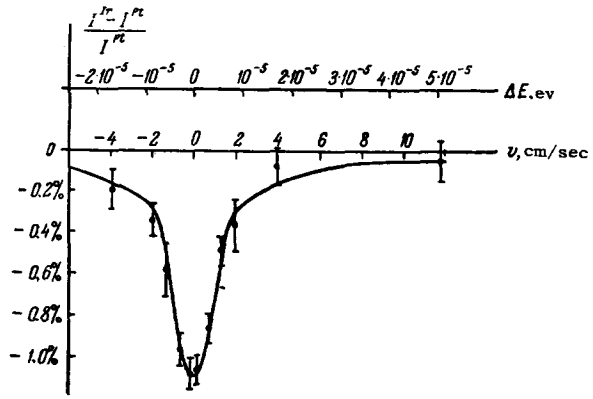

FIG. 3. Percentage difference in intensity of γ radiation passing through iridium and platinum absorbers as a function of relative velocity of source and absorber.

is shown the intensity of the radiation observed behind the iridium absorber (relative to the intensity observed behind a platinum absorber of the same thickness) as a function of the relative velocity of source and absorber. The distribution of measured points corresponds to a Doppler shift of the emission line relative to the absorption line; here, because of the smallness of the natural line width ($\Gamma = 4.6 \times 10^{-6}$ ev), even a relative velocity of a few cm/sec results in a complete destruction of the nuclear resonance absorption.

The heights of the recoilless emission and absorption lines and consequently the magnitude of the observed effect is determined essentially by the fraction of nuclear transitions in source and absorber which occur without recoil. This fraction is given by the Debye-Waller temperature factor. In the Debye approximation for the vibration spectrum of a crystal with Debye temperature θ, this factor is equal to $f = e^{-2W(T)}$, where

$$W = (3R/k\vartheta)\left[\frac{1}{4} + \left(\frac{T}{\vartheta}\right)^2 \int_0^{\vartheta/T} \frac{t}{e^t - 1}\, dt\right]. \qquad (1)$$

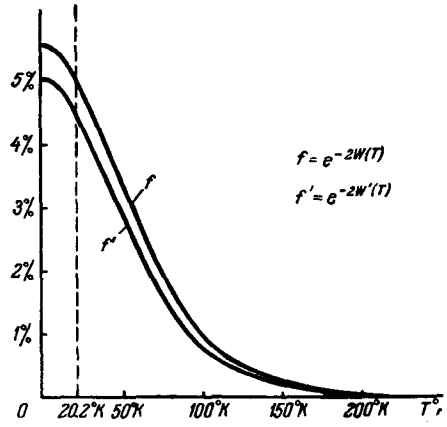

FIG. 4. Fraction f of 134 kev quanta of Re^{187}, emitted without recoil, for two different Debye temperatures of the source: f for $\theta = 310°$ K and f' for $\theta = 300°$ K.

Here there appears the same Debye-Waller factor which describes the coherent Bragg scattering of x rays[5] without recoil; f is strongly dependent on the energy of the nuclear transition, on the frequency distribution in the vibration spectrum, and on the temperature. For example, the fraction of quanta f emitted without recoil in the 134-kev transition in Re^{187} is shown in Fig. 4 as a function of source temperature.

The effective cross section at the maximum of the recoilless absorption line is given by the expression

$$\sigma_{max} = \frac{2I_a+1}{2I_g+1}(2\pi c^2\hbar^2/E_T^2)\frac{f'(T')}{1+\alpha}. \quad (2)$$

Here I_a and I_g are the spins of the excited and the ground states, α is the internal conversion coefficient, and f' is the Debye-Waller factor for the absorber at temperature T'.

Arguments concerning the necessary size of the effective cross section restrict the experimental investigation of nuclear transitions occurring without recoil to those transitions (with energy E_T) for which the energy lost to recoil by a free nucleus, $R = E_T/2Mc^2$ (M is the nuclear mass) satisfies the condition

$$R \leqslant 2\theta, \quad (3)$$

where θ is the Debye temperature in energy units. This means that one must restrict oneself to nuclear transitions with energies around or less than 100 kev and to nuclei of medium or large mass. If R is small compared to the upper limit of the vibration spectrum ($R \ll \theta$), then even at room temperature a significant fraction of nuclear transition are recoilless. If, however, R is approximately equal to or greater than the upper limit of energy in the vibrational spectrum, then to obtain measurable cross sections one must, by using low temperatures, reduce the probability of transitions of the crystal oscillators (see Fig. 4). Since even at liquid helium temperature (4°K) the large majority of the crystal oscillators are in their ground state, further reduction of temperature does not lead to any increase in the fraction of recoilless nuclear transitions. Even at absolute zero, it is still possible to have absorption of energy by crystal oscillators.

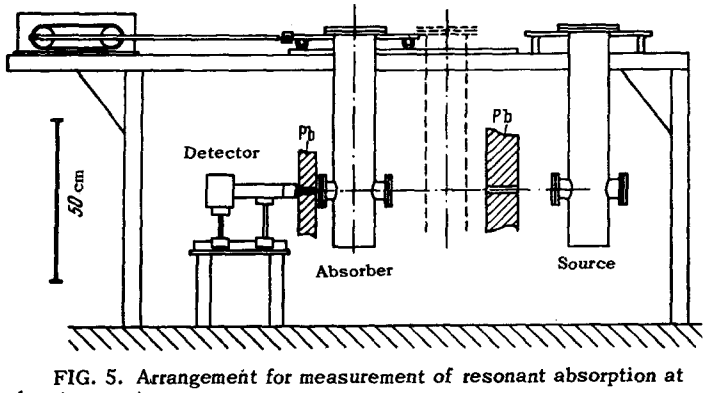

FIG. 5. Arrangement for measurement of resonant absorption at low temperatures.

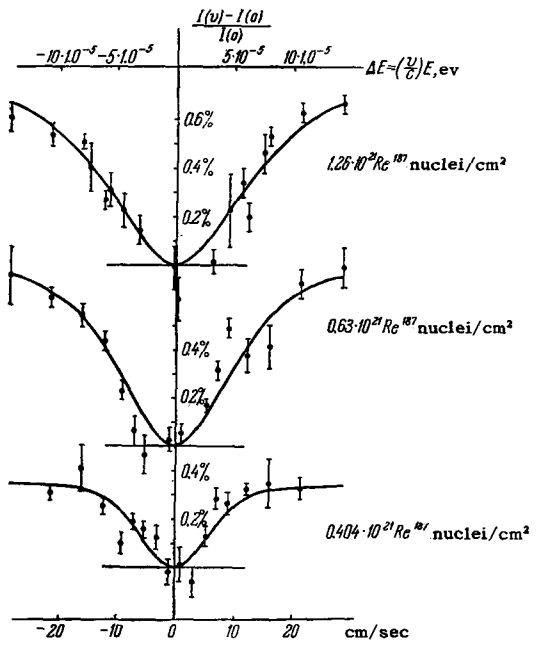

FIG. 6. Relative change in intensity of γ radiation $\frac{I(v)-I(0)}{I(0)}$, measured with rhenium absorbers of various thicknesses as a function of relative velocity of source and absorber.

2. OBSERVATION OF RECOILLESS RESONANCE ABSORPTION IN VARIOUS ISOTOPES

In Fig. 5 is shown the arrangement of the experimental apparatus by means of which we observed in Munich the recoilless resonance absorption in Re^{187}, Hf^{177}, and Er^{166}. In Fig. 6 we show, as an example, the results of our measurements on Re^{187}. The half-width of these absorption curves for the case of a thin absorber is equal to twice the natural width of the line. From an analysis of the absorption curves we determined the lifetimes of the first excited states of Re^{187}, Ir^{191} and Hf^{177}.

The method of recoilless resonance absorption permits us to measure energy differences with an accuracy beyond any previously attained. For the 129-kev transition in Ir^{191} the ratio of the natural line width to the transition energy is $\Gamma/E_T = 4 \times 10^{-11}$. Since a

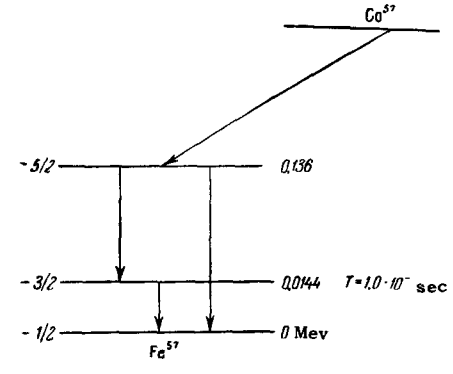

FIG. 7. Decay scheme of Co^{57}.

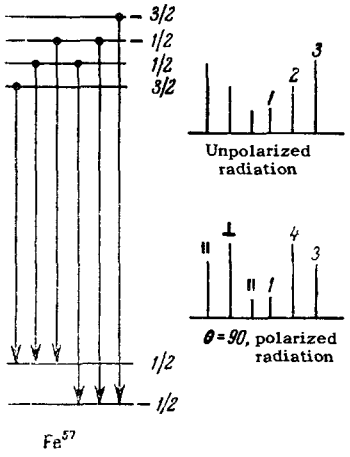

FIG. 8. 14.4 kev transition in Fe^{57}.

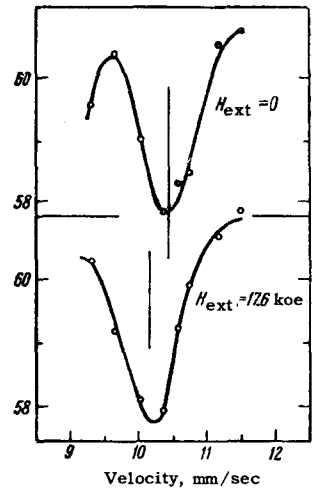

FIG. 10. Shift of one of the hyperfine structure lines of Fe^{57} under the action of an external magnetic field (Argonne National Laboratory).

shift of the line by an amount constituting 1% of the line width is still measurable, it turns out that one has a relative resolving power in energy which is better than 10^{-12}. Moreover, there have also been observed considerably narrower γ ray lines, for example, in Fe^{57} with $\Gamma/E_T = 3 \times 10^{-13}$ and in Zn^{67} with $\Gamma/E_T = 5 \times 10^{-16}$.

Investigations using the 14.4-kev γ radiation of Fe^{57}, which is emitted in the decay of Co^{57}, have proved to be especially fruitful. In Fig. 7 is shown the decay scheme of Co^{57}. The 14.4-kev line has such a small natural width that one can resolve the hyperfine structure of the 14.4-kev transition. In Fig. 8 at the left is shown the splitting of the ground and first excited states of Fe^{57} as a result of interaction of the internal magnetic field in the iron with the magnetic moments of the excited and ground states. On the right of the figure are shown the expected intensities, for pure M1 transition, of the various components of the hyperfine structure in accordance with the selection rules. At the top are shown the intensities of lines which correspond to random spatial orientation of the internal magnetic fields, and below the intensities for the case of oriented internal fields when one observes perpendicular to the direction of the field. In Fig. 9 are shown results of absorption measurements (the work of Hanna and co-workers[7]) in which they studied the hyperfine structure of Fe^{57} in the presence and absence of an external magnetic field on the source and absorber. The results of the measurements with unpolarized radiation are shown at the top of the figure. In the middle and at the bottom of the figure are shown the results of measurements for the case where source and absorber are magnetized by external fields which are parallel or perpendicular to one another, and where the external fields are perpendicular to the direction of observation. The absorber here served as an analyzer of the polarized radiation emitted by the source. Assuming that there are equal splittings in source and absorber, one would expect that when there is a motion of the source spectrum (the six lines of the hyperfine structure) with respect to the spectrum of the absorber (also consisting of six lines) one will observe for one direction of motion of the source eight lines including the central maximum. Of these eight lines they were able, according to Fig. 9, to resolve six lines. The analysis of these absorption spectra, using the already known value of the magnetic dipole moment of the ground state, gave a value of $-(0.153 \pm 0.004)$ nuclear magnetons for the magnetic moment of the 14.4-kev level of Fe^{57}, and a value of $(3.33 \pm 0.10) \times 10^5$ oe for the magnitude of the internal magnetic field at the position of the nucleus of Fe^{57}. Later, after it was shown by this experiment that there is a strong correlation of the internal field at the position of the nucleus with the magnetization, in a further experiment they also determined the sign of this correlation.[8] For this purpose they studied the change in the hyperfine structure splitting of the Fe^{57} nucleus under the action of

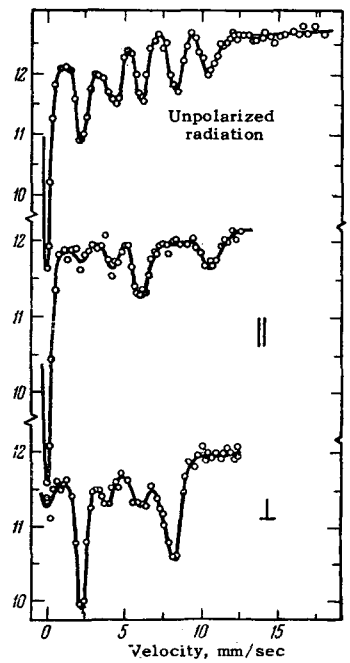

FIG. 9. Hyperfine structure of absorption spectrum in Fe^{57} as a function of relative velocity of source and absorber (Argonne National Laboratory).

a strong external field of the order of 20 koe, which is added to the internal field. The results are shown in Fig. 10. The decrease of the hyperfine splitting as a result of the direct action of the external field on the magnetic moment of the nucleus shows that the internal field in the region of the nucleus and the external magnetization are oppositely directed, and thus the correlation is negative. The internal field was also found to be negative in cobalt.[9] From measurements of the Knight shift* it is known that the internal fields in Mn and Pt are also negative. Thus there has been obtained the interesting result: For all internal fields so far observed in metal there is a negative correlation. The reason for this has as yet not been completely clarified.

A group at Los Alamos[10] has succeeded in observing the resonance absorption in Zn^{67} for the 93 kev level whose natural width ($\Gamma = 4.8 \times 10^{-11}$ ev) is approximately 100 times smaller than the width of the 14.4-kev level in Fe^{57}. Because of the relatively high energy of the transition and the small mass of the isotope, one may expect only a small effect, even with cooling down to 2° K. The extreme narrowness of the line required special precautions for reducing the relative velocities of motion of source and absorber which occur for even the slightest disturbances in their rigidity. The difficulties of this experiment are demonstrated by the fact that mechanical vibrations with velocities of only 10^{-5} cm/sec would already give rise to a Doppler broadening of the order of magnitude of the line width. To avoid these difficulties the source and absorber were rigidly fixed to one another and hung on wires inside the cryostat. The indication of the presence of resonance was achieved by applying to the absorber a magnetic field whose action on the source was eliminated by means of a thin lead foil which was superconducting under the conditions of the experiment. The condition of resonance (when one includes the shift in the energy of the emission and absorption lines caused by the different isotopic compositions of source and absorber) should occur only for definite values of the magnetic field: namely, when the energy of one of the hyperfine structure components of the absorber coincides with the energy of the emission line. In Fig. 11 are shown preliminary results of the measurements. Even though up to now they have been able to resolve only a part of the spectrum, these measurements nevertheless demonstrate the narrowest resonance so far achieved.

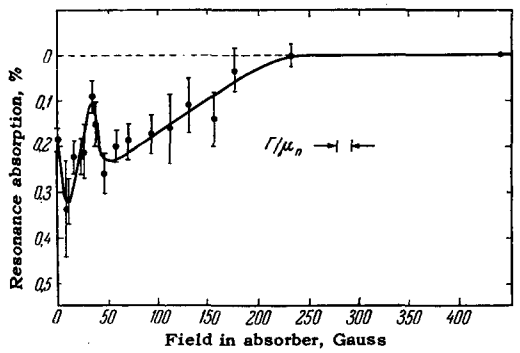

FIG. 11. Resonance absorption in Zn^{67} as a function of the applied external magnetic field (Los Alamos National Laboratory).

3. METHODS OF PREPARATION OF SOURCES

A general problem which occurs in the measurement of recoilless resonance absorption by nuclei is the preparation of the radioactive source. The emission of the quanta which are used for recoilless resonance absorption occurred in the course of the decay of a parent isotope; for example, the 14.4-kev line of Fe^{57} was emitted in the decay of Co^{57}. Since in this case the excited nuclei of Fe^{57} are in a source in an environment of cobalt, the internal field acting on the nucleus of the source and on the nucleus of the absorber differ in magnitude and lead to a different value of the hyperfine structure splitting of the combining levels. Thus the absorption spectrum determined as a function of the relative velocity becomes extremely complicated because of the reduction in the number of simultaneously overlapping lines in emission and absorption. The inhomogeneities of crystal structure and impurities also, in addition to this, result in non-identical magnetic fields acting on the nucleus, which causes a broadening of the emission and absorption lines. Analogous broadenings may be caused by interactions of the nuclear quadrupole moment with the electric field gradients at the nucleus, which vary from place to place. To eliminate such broadenings, Perlow[11] used the following procedure for preparing the Co^{57} source. First Fe^{56} was deposited electrolytically on a copper foil. Then there was deposited on this backing active Co^{57}, which is separated from a sample of natural iron irradiated at the cyclotron; the deposition of the Co^{57} occurred simultaneously with a further electrolytic deposition of Fe^{56}. By using enriched Fe^{56} they achieved a reduction in the recoilless self-absorption in the source which would lead to a more favorable absorption of the central frequencies of the line and thus to a broadening of the emission line. In conclusion, there followed the most important step: a heating in vacuum to a temperature of at least 800° C for one hour. This operation causes the nuclei of active Co^{57} to diffuse into the iron so that the environment of the Fe^{57} which appears in the source as a result of the decay of the Co^{57} becomes to a large extent identical with the environment of the iron nuclei in the absorber. By means of these or similar methods it has now become possible to obtain a line width for the 14.4-kev radiation of Fe^{57}

*The Knight shift is the difference in frequency of nuclear magnetic resonance in metallic and non-metallic samples (cf., for example, E. Andrew, Nuclear Magnetic Resonance, Cambridge University Press, 1955, p. 196).

which coincides within 10% with the values expected on the basis of the measured lifetime, as determined by means of electronic equipment.

4. THE SECOND-ORDER DOPPLER EFFECT

The extremely small energy width of the 14.4 kev line of Fe^{57} permits one to study various interesting effects of higher order. First we should mention the experimental observation of the second order Doppler effect. Even though in the recoilless emission and absorption there are no phonon transitions in the crystal lattice, there nevertheless occurs a change in the internal energy of the crystal at the expense of the photon energy. The nuclear transition always gives rise to a small change in the vibrational spectrum of the crystal (because of the difference in masses of the nucleus in the excited and ground states). The second-order Doppler effect which results from this leads to a reduction in the energy of the quantum which corresponds to an increase in internal energy of the crystal during the transition of the nucleus from the excited state to the ground state. This effect is calculable either from the difference in mass of the nucleus in the two states, or from the relativistic time translation caused by the motion of the nucleus.[12] The shift in the emission and absorption lines which occurs as a result of this second-order Doppler effect depends on the mean squared velocity of the nuclei in source and absorber respectively. If the source and absorber have exactly the same temperatures and the nuclei are located in identical crystalline environments, the emission and absorption lines will experience identical energy shifts as a result of the second-order Doppler effect, i.e., there will be no relative energy shift of the lines. On the other hand, a difference in the temperatures of source and absorber, or of their Debye temperatures, gives rise to a relative shift of the emission and absorption lines and causes the observed absorption spectrum to be no longer symmetric with respect to the zero of relative velocity. In Fig. 12 are shown results of experimental observation of the second-order Doppler effect carried out by Pound and Rebka.[12] As a function of the temperature of the absorber, they determined the relative shift of the energy transition of the nuclei of the absorber and of the source which is at room temperature. On the figure, in addition to the experimental points, is shown the theoretical behavior of the relative energy shift for a Debye vibrational spectrum of source and absorber with a Debye temperature $\theta = 420°K$.

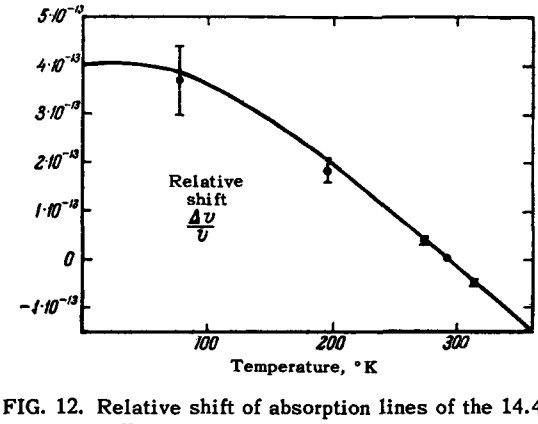

FIG. 12. Relative shift of absorption lines of the 14.4-kev transition in Fe^{57} as a function of absorber temperature (Pound and Rebka).

Sherwin[13] pointed out that the agreement of theory with experiment for the case of the second order Doppler effect is a confirmation of the clock paradox of the special theory of relativity. The radiating and absorbing nuclei act in this case as "clocks" with different histories of previous motion. The nucleus of the absorber compares the frequency of the radiation emitted by the source nucleus without recoil with the proper frequency of absorption, where the precision in the case of the Fe^{57} transition is so high that for a difference in frequencies of only $1:10^{12}$ there would be practically no resonance absorption. The agreement of theory and experiment confirms the clock paradox, and moreover shows that, within the limits of experimental error, the large accelerations to which the nucleus is subjected in the crystalline lattice (equal to values up to 10^{16} g) have no effect on the emission.

5. APPLICATION OF THE METHOD OF RECOILLESS RESONANCE ABSORPTION BY NUCLEI

The method of recoilless resonance absorption of photons has had various interesting applications. First we should mention the measurements of Pound and Rebka in which they verified the principle of equivalence of the general theory of relativity.[14] According to this principle the frequencies of spectral lines emitted by a system are proportional to the gravitational potential at the place where the system is located. If we place a source of Fe^{57} and an absorber of Fe^{57} at different distances from the surface of the earth, then under the action of the earth's gravitational field there will occur a shift in the emission and absorption lines relative to one another. A shift by an amount equal to the line width would require a difference in height of 2.9 km. Pound and Rebka used a much smaller relative shift of the lines, since they chose the difference in altitudes of source and absorber to be 22 m. The second-order Doppler effect

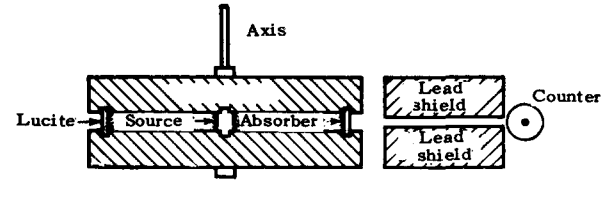

FIG. 13. Arrangement of experiment with rotor (Harwell Laboratory).

produced by the vibrations of the nuclei in the lattice made it necessary to have a precise control of temperature, since differences in temperature of source and absorber amounting to only 1° C already lead to an energy shift of the same magnitude as the expected gravitational effect. In order to eliminate other energy shifts caused by inhomogeneities of source and absorber, the source and absorber were periodically interchanged, and the gravitational shift was determined as the difference in the line shifts for the two directions of flight of the quanta: up and down. The final result of the measurements, which are still continuing, is the following:[15]

$$\frac{\Delta\nu_{exp}}{\Delta\nu_{theor}} = \begin{cases} 0.99 \pm 0.047 \text{ for measurements without control absorber} \\ \text{(monitor) and } 0.97 \pm 0.054 \text{ for measurements with a monitor.} \end{cases}$$

An English group has carried out measurements of the transverse Doppler effect for the 14.4-kev line of Fe^{57}. In Fig. 13 is shown the experimental arrangement.[16] The source and absorber rotate at different distances around a common axis.

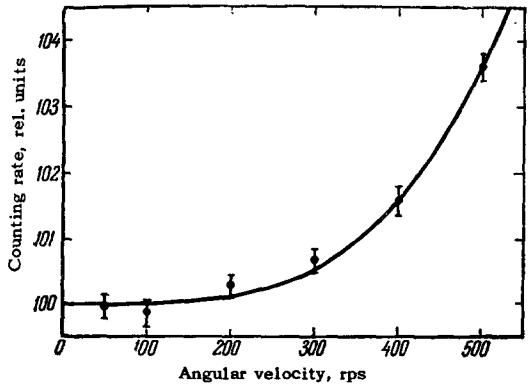

FIG. 14. Intensity through a resonant absorber of Fe^{57} as a function of angular velocity (Harwell Laboratory).

The different magnitudes of the acceleration potentials in the region of source and absorber cause shifts in the lines which, according to Fig. 14, agree within the limits of experimental error with the theoretically expected values.

An important possibility for applying recoilless resonance absorption of γ quanta, from which one should expect particularly fruitful results, is in the determination of magnetic dipole moments and electric quadrupole moments of excited states of nuclei, and also in investigating the nature of the internal magnetic and electric fields. Closely related with this is the question of the shift in energy of nuclear levels as a function of the structure of the electronic shells surrounding the nucleus (nuclear isomeric shift). A whole series of papers has already been devoted to these questions. In Fig. 15 we give as an example the data of Kistner and Sunyar.[17] They studied the resonance absorption of the 14.4 kev line of Fe^{57} in an absorber of Fe_2O_3. In such measurements of the hyperfine structure it is important to have one of the lines, either the absorption or emission line, remain unsplit; in this case, the number of lines in the absorption spectrum when measured as a function of velocity will be reduced, and the interpretation of the pattern obtained for the splitting will be simpler.

In this work the splitting of the emission line was eliminated by introducing the active Co^{57} nuclei into stainless steel (by diffusion), so that the observed absorption spectrum showed directly the structure of the pattern in Fe_2O_3. The absorption spectrum in Fig. 15 is very clearly asymmetric with respect to the velocity $v = 0$. In Fig. 16 is shown a scheme of the splitting needed for explaining the experimental results. At the right of the figure is shown the unsplit emission line, while on the left we again show the magnetic splitting in ordinary iron. In the central pattern of the splitting in Fig. 16 is shown the shift in the magnetic terms of the hyperfine structure resulting from the interaction of the nuclear quadrupole moment with the inhomogeneous electric field which is present in the region of the nucleus. The observed asymmetric position of the absorption spectrum relative to zero velocity requires the introduction of an additional shift in energy between the centers of gravity of the emission and absorption spectra: although

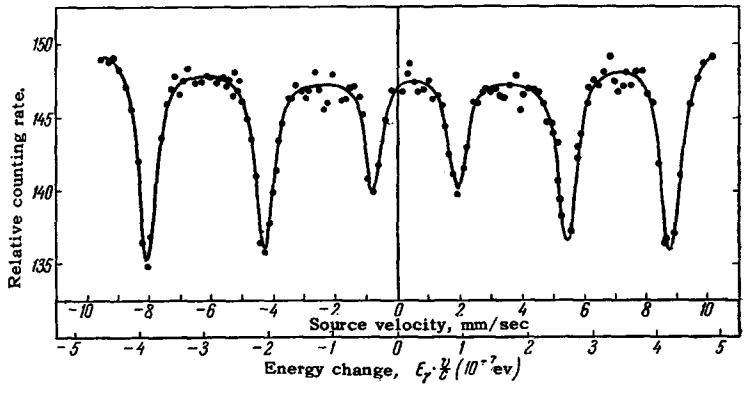

FIG. 15. Absorption of the 14.4-kev line in Fe^{57} contained in a sample of Fe_2O_3 when irradiated by the unsplit line at 14.4 kev.

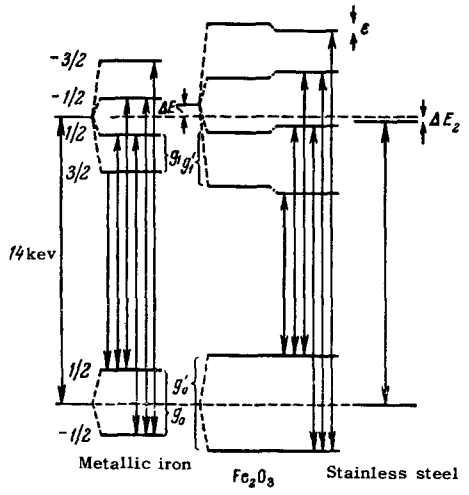

FIG. 16. Splitting of excited and ground states of Fe^{57} for different crystalline environments of the Fe^{57} nuclei (Kistner and Sunyar). The energy of the transition is E = 14.4 kev.

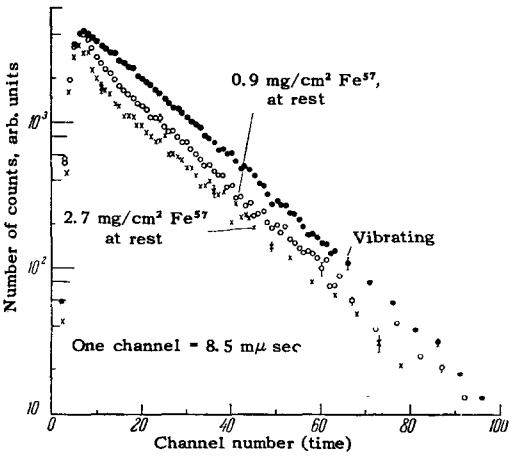

FIG. 18. Intensity of the 14.4-kev transition of Fe^{57} as a function of delay time of the quanta in the excited state for an absorber at rest and in motion (Argonne National Laboratory).

the nature of such a shift is as yet not completely understood, it must be due mainly to the difference in the chemical environments of the nuclei in the source and absorber.

Similar measurements were made by Solomon.[18] In Fig. 17 we give as an example the absorption spectrum in FeS_2 of the 14.4-kev line of iron. The observed splitting pattern can be understood if we assume that the excited state of Fe^{57} in the FeS_2 absorber is split into a doublet (with separation Δ) as a result of quadrupole interaction. When one carries out the motion of the six emission lines from the Fe^{57} source with respect to the two lines of the absorber, there appear in the observed absorption spectrum six absorption doublets with a separation Δ between the lines of each doublet.

Recoilless resonance absorption has also made it possible to observe the time dependence of the frequency spectrum emitted in nuclear transitions. An investigation of this type was carried out by Holland and co-workers.[19] A resonance absorber of Fe^{57} served as an analyzer of the frequency distribution of the radiation emitted by the Fe^{57} source. The intensity of the radiation passing through the resonance absorber was measured as a function of the delay time τ of emission of the 14.4-kev quantum relative to the emission of the 122-kev quantum in the preceding γ transition (cf. Fig. 7). In Fig. 18 are shown preliminary results of these measurements. For delay times τ less than the lifetime of the resonance level one should expect a broadening of the resonance line and a corresponding reduction of resonance absorption, as one actually sees in the figure. Later measurements show that at certain times one observes behind the resonance absorber an even greater intensity than that which would be obtained in the absence of the absorber.

6. RESONANCES WHICH HAVE BEEN OBSERVED UP TO NOW

In concluding this summary we given in the table a list of isotopes in which the recoilless resonance absorption has already been observed.

E, kev	Resonant isotope (absorber)	Debye temperature θ of the element (absorber)	Parent isotope (source)	$T_{1/2}$, sec	Γ/E	Literature
8.4	Tm^{169}	166° K	Er^{169}	$4.0\cdot10^{-9}$	$1\cdot10^{-11}$	20
8.4	Tm^{169}	166° K	Yb^{169}	$4.0\cdot10^{-9}$	$1\cdot10^{-11}$	21
14.4	Fe^{57}	420° K	Co^{57}	$1.0\cdot10^{-7}$	$3\cdot10^{-13}$	22
26	Dy^{161}	158° K	Tb^{161}	$2.8\cdot10^{-8}$	$6\cdot10^{-13}$	23
73	Ir^{193}	285° K	Os^{193}	$5.7\cdot10^{-9}$	$1\cdot10^{-12}$	24
77	Au^{197}	170° K	Pt^{197}	$1.9\cdot10^{-9}$	$3\cdot10^{-12}$	25
77	Au^{197}	170° K	Hg^{197}	$1.9\cdot10^{-9}$	$3\cdot10^{-12}$	25
80.6	Er^{166}	163° K	Ho^{166}	$1.7\cdot10^{-9}$	$3\cdot10^{-12}$	24,27
93	Zn^{67}	260° K	Ga^{67}	$9.4\cdot10^{-6}$	$5\cdot10^{-16}$	10
100	W^{182}	310° K	Ta^{182}	$1.3\cdot10^{-9}$	$4\cdot10^{-12}$	26,24
113	Hf^{177}	213° K	Lu^{177}	$4.0\cdot10^{-10}$	$1\cdot10^{-11}$	27
129	Ir^{191}	285° K	Os^{191}	$1.0\cdot10^{-10}$	$4\cdot10^{-11}$	2
134	Re^{187}	300° K	W^{187}	$1.0\cdot10^{-11}$	$3\cdot10^{-10}$	6

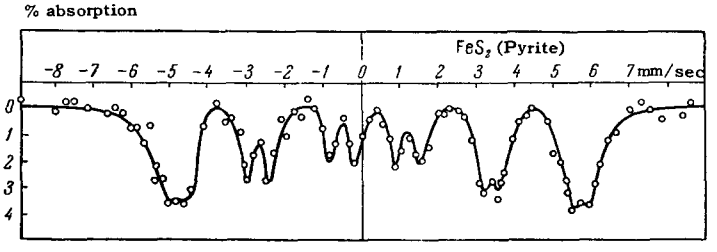

FIG. 17. Absorption of the 14.4-kev line of iron in FeS_2 (Solomon).

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Translated by M. Hamermesh