6-65
9-19-62 ✓

ARF

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

ARF 1166-22

MASTER

STUDIES OF NUCLEAR RESONANT ABSORPTION
OF GAMMA RAYS

by

J. J. Ezop

Prepared for

The Division of Isotopes Development
United States Atomic Energy Commission

May 1, 1962

"AEC Research and Development Report"

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

Printed in USA. Price \$2.00. Available from the Office of
Technical Services, Department of Commerce,
Washington 25, D. C.

ARF 1166-22

Category No. UC - 23
Isotopes - Industrial Technology
TID - 4500 (17th Ed.)

STUDIES OF NUCLEAR RESONANT ABSORPTION
OF GAMMA RAYS

This work performed for

The Division of Isotopes Development
United States Atomic Energy Commission
Contract Number AT(11-1)-578
Project Agreement Number 6

FINAL REPORT

by

ARMOUR RESEARCH FOUNDATION
of
Illinois Institute of Technology
Technology Center
Chicago 16, Illinois

Report written by
J. J. Ezop

May 1, 1962

DISTRIBUTION LIST

No. of Copies

565	Technical Information Service Extension U. S. Atomic Energy Commission P. O. Box 62 Oak Ridge, Tennessee
35	Division of Isotopes Development U. S. Atomic Energy Commission Washington 25, D. C.
3	Fred C. Mattmueller, Director Research Contracts Division Chicago Operations Office 9800 South Cass Avenue Argonne, Illinois
1	ARF Main Files
1	ARF Report Library
1	"A" Files via L. Reiffel and P. H. Wyckoff
1	Nuclear and Radiation Physics Files

This is the final report on ARF project 1166 entitled, "Studies of Nuclear Resonant Absorption of Gamma Rays," and covers the period from June 1, 1960 to March 31, 1962. This work was conducted for the Division of Isotopes Development, U. S. Atomic Energy Commission, under Contract No. AT(11-1)-578, Project Agreement No. 6.

Personnel who have contributed to the work described in this report include: J. J. Ezop, I. Filosofo, R. C. Greenwood, L. Reiffel and C. A. Stone.

Date pertaining to this program can be found in ARF logbooks C1059, C11411, C11618, C12322 and C12329.

Respectfully submitted,

ARMOUR RESEARCH FOUNDATION
of Illinois Institute of Technology

James J. Ezop
J. J. Ezop, Assistant Physicist

Reginald C. Greenwood
R. C. Greenwood,
Research Physicist - Group Leader
Nuclear and Radiation Physics Section

C. W. Terrell
C. W. Terrell, Manager
Nuclear and Radiation Physics Research

APPROVED:

P. H. Wyckoff
P. H. Wyckoff, Assistant Director
Physics Research

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

ARF 1166-22
(Final Report)

on

STUDIES OF NUCLEAR RESONANT ABSORPTION
OF GAMMA RAYS

ABSTRACT

The objective of this program was to study and evaluate the feasibility of employing the Mossbauer resonant absorption phenomenon for new and useful applications of radioisotopes. For these experimental studies we have chosen to work exclusively with radioactive Co^{57} sources which allow observations of the Mossbauer resonance in Fe^{57} at room temperatures. However, the results of our investigations can be extrapolated to other Mossbauer isotopes which, unfortunately, usually require low-temperature apparatus to obtain an appreciable fraction of recoilless emissions and absorptions.

Our investigations centered around the utilization of the Mossbauer effect for practical problems in measurement and control technology. The use of nuclear resonant techniques in the general areas involving small velocity, acceleration and displacement measurements appears very promising. For example, velocities in the range from 0.005 to 0.015 cm/sec are easily measured using Fe^{57} nuclear resonance, and this range can be extended several orders of magnitude in both directions if other sources and techniques

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

are employed. Measurements of gravitational fields in interplanetary space or on the surfaces of celestial bodies, together with altitude measurements of space vehicles, using Mossbauer techniques do not appear practical because the measurement times required to obtain reasonably accurate results is of the order of hours or days under the most favorable circumstances. Experimental measurements of the effects of high pressures on the fractional resonant absorptions showed no observable changes when a Co^{57} -stainless steel source was subjected to pressures up to 40,000 psi, although higher pressures or other Mossbauer sources may make pressure measurements practical. Experiments have shown that it is possible to determine the direction and strengths of homogeneous magnetic fields in a range from 300 to 1000 gauss by measuring the percentage of nuclear resonance in iron foils. Although the method is not, in general, as accurate as conventional techniques, such a system warrants further study since it might have definite practicality when hostile environments or accessibility problems limit or prohibit the use of conventional techniques. Initial studies also showed that nuclear resonance techniques could be used to measure the amplitudes of acoustical (mechanical) motion in the megacycle frequency region. The results gave every indication that such measurements could be extended to higher frequencies and possibly into the hypersonic, kilo-megacycle ranges where currently there are no suitable methods available to measure acoustical power or acoustical energy densities.

TABLE OF CONTENTS

	<u>Page No.</u>
ABSTRACT	iv
LIST OF ILLUSTRATIONS	viii
LIST OF TABLES	x
I. INTRODUCTION	1
II. TECHNICAL DISCUSSION	2
A. The Mossbauer Effect	2
B. Consideration of Sample Environment	6
III. EXPERIMENTAL APPARATUS	10
A. Sources	10
B. Resonant Absorbers	13
C. Detectors	16
D. Motional Transducers	19
E. Electronics	22
IV. PRACTICAL APPLICATIONS OF THE MOSSBAUER EFFECT	25
A. Measurements of Small Velocities	25
B. Measurements of Magnetic Fields	31
C. Measurements of Gravitational Fields Using Nuclear Resonance Absorption	39
D. Effects of Pressure on the Fraction of Recoil Free Gamma Emissions	44
E. Acoustical Energy Density Measurements	47
F. A Communication System Utilizing the Mossbauer Effect	53
G. Other Possible Applications Using Nuclear Resonance Absorption Techniques	54
V. SUMMARY AND CONCLUSIONS	55

	<u>Page No.</u>
APPENDIX I	
CALCULATED VALUES OF THE FRACTION OF RECOIL-FREE GAMMA EMISSION, $f(0)$, USING THE DEBYE MODEL AT ZERO DEGREES KELVIN	60
APPENDIX II	
MEASUREMENTS OF EXTREMELY SMALL ENERGY SHIFTS USING NUCLEAR RESONANCE ABSORPTION TECHNIQUES	63
APPENDIX III	
CALCULATED VALUES OF THE FRACTION OF RECOIL-FREE GAMMA EMISSIONS, $f(T)$, FOR SEVERAL MOSSBAUER ISOTOPES AT COMMONLY AVAILABLE TEMPERATURES USING THE DEBYE MODEL	67
BIBLIOGRAPHY	69

LIST OF ILLUSTRATIONS

<u>Fig. No.</u>		<u>Page No.</u>
1.	Spectrum of Co ⁵⁷ Source Using 1/8" Thick NaI(Tl) Scintillation Detector	18
2.	Flow Type Proportional Counter	20
3.	Spectrum of Co ⁵⁷ Source Using Proportional Counter	21
4.	Block Diagram of the System Used to Observe Resonant Line Structure	23
5.	Gate Circuit Used to Produce a Pulse Proportional to the Instantaneous Relative Velocity Between Source and Absorber When a 14.4 kev Gamma Ray is Detected	24
6.	The Resonant Absorption of 14.4 kev Gamma Rays from a Co ⁵⁷ Source in an Iron Foil Absorber as a Function of the Relative Velocity Between the Source and Absorber	26
7.	Typical Nuclear Resonant Transmission Spectrum	28
8.	Velocity Spectrum of Co ⁵⁷ Source and Iron Foil Absorber	32
9.	Effect of Polarized Magnetic Fields on Velocity Spectrum of Co ⁵⁷ Source and Iron Foil Absorber	34
10.	Block Diagram of Experimental Arrangement Used to Measure the Effect of Polarizing Magnetic Fields on Nuclear Resonant Absorption of Gamma Rays	36
11.	Transmission Intensity of Resonant Gamma Rays Through an Iron Foil in a Magnet Field of 800 gauss vs. Magnetic Flux Density About a Co ⁵⁷ Source	38
12.	Per Cent of Maximum Transmission of Nuclear Resonant Gamma Rays Through an Iron Foil Absorber vs. Magnetic Flux Density About a Co ⁵⁷ Source	40
13.	Pressure Assembly and Counting Equipment	45
14.	Pressure Bomb Window Assembly	46
15.	Block Diagram of Pressure Experiment Apparatus	48

Fig. No.

Page No.

16.	Block Diagram of Experimental Arrangement
Used to Measure the Effect of Acoustical
Modulation on the Amount of Nuclear Resonance
Absorption	51
17.	Relative Transmission Intensity of Nuclear
Resonant Gamma Rays vs. Applied Voltage
at Emitter High Frequency Transducer	52

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
I.	Per Cent of Resonant Absorption for Three Co ⁵⁷ Sources and Several Absorbers	17
II.	Velocity Ranges Which May Be Determined By Direct Transmission Measurements for Representative Mossbauer Isotopes	30
III.	Changes of Nuclear Resonant Absorption In Several Iron Absorbers Due to Effects of Polarized Magnetic Fields About the Emitter and Absorber	35
IV.	List of Parameters Used to Calculate the Gravitational Frequency Shift of Resonant Gamma Rays, and Calculated Counting Times Necessary to Obtain Reasonable Statistics In Measurements of the Gravitational Acceleration, g, or the Distance From the Attracting Body, r	43
V.	Effect of Pressure on Fraction of Recoil Free Gamma Emissions From a Co ⁵⁷ - Stainless Steel Mossbauer Source	49

STUDIES OF NUCLEAR RESONANT

ABSORPTION OF GAMMA RAYS

I. INTRODUCTION

The discovery of recoilless emission and absorption of gamma rays by R. L. Mossbauer⁹¹ in 1958, and the rapidly following discovery of the "Mossbauer Effect" by the scientific world in 1959, initiated an unprecedented flood of experiments and published materials (See Bibliography). The reasons for this intense interest and effort are that the Mossbauer effect permits experiments and measurements with previously unattainable sensitivity, and that it has a wide variety of potential scientific and practical applications in such diverse areas as solid state physics, nuclear physics, acoustics, mechanics, space technology, etc. The initial efforts of most researchers were directed towards a better theoretical and experimental understanding of the phenomenon, examination of the influence of the solid state environment on the effect, and notably, the measurement of gravitational red-shift of gamma ray energy. The techniques of measurements reported in the early experiments, i. e. low relative uniform velocity of sinusoidal motion between source and absorber, together with the observed effects of magnetic fields and solid state environment on the resonant absorption, led members of the Physics Research Division of the Armour Research Foundation to the conclusion that the Mossbauer effect, with its high sensitivity, should have a number of practical applications.

A number of subject areas and specific ideas were submitted to the Division of Isotope Development of the U. S. Atomic Energy Commission to form the basis for a program to investigate the feasibility of using nuclear resonance absorption for practical applications. This final report includes the results of a literature survey, theoretical and experimental investigations of specific applications, and discussions with a number of scientists and engineers to clarify existing measurement problems as well as to search out new problems.

II. TECHNICAL DISCUSSION

A. The Mossbauer Effect

Since the intent of this investigation is to explore possible practical applications of the Mossbauer effect and to bring the results to the attention of engineers, scientists, and industrialists who may profitably use them, it is worthwhile to review the subject of nuclear resonance absorption in semitechnical terms to provide background for all readers.

It has long been predicted that, in many cases, the energy distribution of electromagnetic radiation from excited states of an isotope should be very narrow. That is to say, the energy of an excited state of a nucleus is very precise, e. g. the line width of Fe^{57} is 4.56×10^{-9} ev. for the 14.4 kev level. From analogies with wave mechanics, one expects that a precisely tuned "resonant cavity" will preferentially absorb the gamma rays emitted in decay from such states. The classic example of a clear violin note causing a single piano string to vibrate is illustrative of this general class

of resonance absorption phenomena. Indeed, resonance absorption is the best way to observe these extremely well defined gamma ray energies. However, it has not been possible to satisfactorily observe such resonant absorption until the experiments of Mossbauer⁹¹⁻⁹³, since very small amounts of energy lost by the gamma ray during emission or absorption resulted in sufficient gamma ray energy change to destroy the resonance. The lost energy appears as recoil energy of the emitting or absorbing nucleus.

As an example of the nuclear resonance phenomena, let us consider the processes of emission and absorption of a gamma ray from an excited state of Fe^{57} . If one excites an Fe^{57} nucleus to an unstable state, the nucleus will return to the stable condition (ground state) by the emission of a gamma ray. The total energy available for this emission process is the difference between the energy levels of the stable and unstable states of the nucleus. If a gamma ray of energy $E = h\nu$ is emitted it possesses linear momentum $h\nu/c$. The law of conservation of momentum requires the emitter to acquire an equal amount of recoil momentum in the opposite direction. Therefore, associated with this momentum of recoil is a recoil energy, and consequently, the total energy available in the reaction is divided between the emitted gamma ray energy and the recoil energy of the nucleus. This is expressed in Eq. 1, where E_e is the nuclear level energy (total energy available), E is the energy of the emitted gamma ray, and M is the mass of the recoiling nucleus.

$$E_e = E + (E^2/2Mc^2) \quad (1)$$

Since the internal energy of the nucleus can only have discrete values, it will act as a resonant cavity or absorber only when an incoming gamma ray can contribute the exact energy equal to the difference between the ground and excited states. A stable Fe^{57} nucleus, therefore, will resonantly absorb any gamma ray which will contribute an excitation energy of 14.4 kev. But, in the process of absorption, as in emission, the incoming gamma ray has a momentum which must be conserved by the absorbing nucleus. Equation 2 expresses the energy balance for the absorption process where E is the gamma ray energy, E_a is the energy of the relevant nuclear level, and M is the mass of the recoiling absorbing nucleus.

$$E = E_a + (E^2/2Mc^2) \quad (2)$$

If one equates the gamma ray energy, E , in Eqs. 1 and 2, one finds that the total emission energy, E_e , required for absorption is given by Eq. 3.

$$E_e = E_a + (E^2/Mc^2) \quad (3)$$

But, since the emitting and absorbing nuclei are identical, E_e equals E_a , and Eq. 3 cannot exist unless M is infinite. Therefore, it would be concluded that the emission and absorption of gamma rays by like nuclei of finite mass will not exist because of the loss of energy, E^2/Mc^2 , to the recoiling nuclei.

The above conclusion was based on the assumption that the emission and excitation energies, E_e and E_a , had an exact value. In reality, this is not the case; the nuclear excited state energies are given by $E \pm \Delta E$, where ΔE is the natural line width of the level. This natural line width comes

about because of the uncertainty principal which states that

$$\Delta E \Delta t \approx h/2\pi \quad (4)$$

where Δt is the mean life of the excited state and h is Planck's constant.

For the 14.4 kev line of Fe^{57} , $\Delta E = 4.56 \times 10^{-9}$ ev. A calculation of the recoil energy, E^2/Mc^2 , for Fe^{57} yields approximately 4×10^{-3} ev. Therefore, even after correction for the broadening of the emission and absorption line width, the energy lost in recoil is still too large to permit nuclear resonance absorption.

If it were possible to reduce the recoil energy losses to a value less than the natural energy spread in the line, one should be able to observe nuclear resonance absorption. Mossbauer⁹¹ has shown that under certain conditions recoil energy loss is eliminated in a significant fraction of emissions permitting direct observation of the resonant absorption effect. This is possible in many instances when the emitting atom is effectively anchored to many other atoms as in a lattice, so that many thousands of atoms participate in recoil. The effective mass of the recoiling medium is thereby increased by many orders of magnitude and the recoil energy loss becomes negligible. Proper preparation of source and absorber materials has yielded resonance absorptions of as much as 75 per cent⁵⁵ of the emitted gamma rays.

With such a highly sensitive phenomena at one's disposal, several practical applications appear plausible. If one constructs a system composed of an iron lattice containing excited nuclei of Fe^{57} as a source and a similar lattice with stable Fe^{57} nuclei as an absorber, the intensity of 14.4 kev

gammas passing through the absorber can be counted using standard gamma ray detection techniques. Since nuclear resonance absorption is energy dependent, any perturbation of the system which causes an energy shift of the same order of magnitude as, or greater than, the natural line width will be observed. If one introduces a relative velocity of three inches per minute between the Fe^{57} source and absorber, the gamma ray energy shift due to the Doppler effect is sufficient to destroy resonance. Therefore, any relative velocity smaller than this can be measured by using the Mossbauer effect. If one plots the intensity of the 14.4 kev line passing through the absorber as a function of the relative velocity, the shape of the resonant line can be obtained. This technique can also be used to measure the effect of perturbations due to other influences such as magnetic fields, unknown relative velocities, vibrations, etc. For example, the splitting of the 14.4 kev energy level of Fe^{57} in an iron lattice due to the internal magnetic fields (nuclear Zeeman effect) has been observed.^{56, 133}

B. Consideration of Sample Environment

As stated above, Mossbauer demonstrated that under certain conditions during gamma emission and absorption, the energy of recoil can be taken up by the lattice as a whole. Based on the Debye model of lattice vibrations, the fraction of recoil-free gamma emissions can be expressed by:

$$f = \exp \left\{ -\frac{3}{2} \frac{E^2}{2Mc^2k\theta} \left[1 + \frac{2}{3} \left(\frac{\pi T}{\theta} \right)^2 \right] \right\} \quad (5)$$

where E is the gamma ray energy, M is the nuclear mass, θ the Debye temperature and T the ambient lattice temperature. From Eq. 5 it can be seen that nuclear resonance will be more easily observable for low energy gamma transitions, high Debye temperature, and low temperatures of emitter and absorber. In Appendix I calculated values of f are given for possible "Mossbauer isotopes" with $T=0^\circ\text{K}$. A more complete listing of possible Mossbauer isotopes and parent nuclei are given in reference.⁴³

Equation 5 may be used to estimate the recoilless gamma emission probability. Experimental data on Mossbauer effects are, however, in poor agreement with the calculated effect. The disagreement seems due to the fact that Eq. 5 is referred to the ideal case of a perfect lattice. There is clear experimental evidence that the magnitude of the Mossbauer effect is very much dependent on methods of source preparation. The features of this behavior suggest that the observable nuclear resonance depends strongly on solid state parameters and varies with chemical purity, microstructure of materials and with distribution of the Mossbauer isotope in the host lattice. It may be concluded that the phenomenon governing the Mossbauer effect is more complex than the Debye temperature dependence of Eq. 5 can predict.

The theory of resonance absorption which Mossbauer utilized, and which was based on Lamb's analysis for neutron resonance absorption, deals with the probability of no-phonon emission and absorption and relates it to the phonon spectrum of the solid used. Nagle et al.⁹⁸ point out the usefulness

of accurate measurements of the no-phonon emission probability in giving a value for the weighted mode density spectrum integral

$$\int_0^{\nu_m} \frac{g(\nu)}{\nu} d\nu \quad (6)$$

thus, providing a useful check on the spectrum derived by other methods such as specific heat analysis, and the powerful though complex technique of neutron diffraction. Nagle's results indicate the error which can arise from assuming the Debye distribution, i. e. $g(\nu) = \nu^2$, since for gold such an assumption gives a value of recoil-free probability which is a factor of seven too large. The formulae are applied to measurements at 4.2° K.

The analysis of the Mossbauer effect by Visschner¹³¹ applies to perfect crystal lattices with a well-defined $g(\nu)$ spectrum. When this is changed, by defects in a pure lattice, or by the inclusion of the resonant nucleus in a foreign host lattice, the absorption peak height and width will be changed. Experimental observations show that the absorption is reduced markedly unless care is taken to anneal both absorber and source correctly. There are several reasons why an imperfect lattice should cause a change of absorption line and we discuss here some of them together with the possible value of quantitative measurements of the change.

If the resonant nucleus lies near a lattice defect, the elastic potential well in which it lies will have a modified shape. This point can be illustrated by a very oversimplified argument. If we consider a one-dimensional model and imagine the well to be broadened, the nucleus will

then effectively be in a "soft spot," and local vibrational modes will occur having different frequencies, on the average, than those for the lattice as a whole. Thus, if one can still attach significance to Eq. 6, the integral could be increased due to the extra emphasis on the lower modes, and hence the no-phonon emission probability which depends on the negative exponent of this integral will be decreased. A more extreme case of a distorted site would occur if the atom could jump from one stable location to an alternate one with a small activation energy. For instance, an activation energy of 0.3 ev, normal for an interstitial atom, would lead to one jump about every 10^{-8} seconds at room temperature, virtually eliminating the possibility of a Mossbauer effect.

A further consequence of a modification of the potential well by defects would be a change of the temperature shift of gamma energy as a consequence of the change of the proportion of total lattice energy assigned to the atom. Overall, the distribution of defects would lead to a broadening of the absorption line at all but the lowest temperatures.

Investigation of crystal structure effects on line width and energy shift could lead to two important results; a better knowledge of environmental effects on nuclear resonance, which will permit a better analysis of experimental results, and methods of improving the sensitivity and energy resolution of nuclear resonance techniques. The importance of such studies cannot be overemphasized, although they are beyond the scope of this project, because the results will greatly enhance feasibility studies of practical

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

applications of nuclear resonance absorption techniques. Of equal importance, although again outside the scope of this program, is the possibility of using the Mossbauer absorption phenomenon as a sensitive probe studying crystal structure parameters.

III. EXPERIMENTAL APPARATUS

A. Sources

Of the several Mossbauer isotopes available, we have chosen to work exclusively with Fe^{57} resonant absorption because the high Debye temperatures of iron and iron alloy lattices yield the highest observable resonant absorptions at room temperatures (See Appendix III). In fact, the effect is so large under the proper circumstances that the nuclear resonant absorption exceeds the electronic absorption by approximately a factor of three hundred⁵⁵. Other emitters have been found to have useful resonance absorptions, and some of these emit appreciably higher energy radiation than does Fe^{57} , but these require low temperature apparatus to observe the resonance and, therefore, more sophisticated techniques are needed to carry out experiments designed to demonstrate feasible applications.

The low-lying excited state of Fe^{57} at 14.4 kev, with a half life of about 10^{-7} seconds, may be excited by the electron capture decay of Co^{57} . The natural line width of this state, given by eq. 4, is approximately 4.56×10^{-9} ev, and, therefore, the fractional energy resolution, defined as the ratio of twice the line width energy to the gamma ray energy, is approximately 6.3×10^{-13} . This is one of the smallest fractional energy

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

resolutions of all the Mossbauer isotopes, and it is this sharpness property along with the high probability of nuclear resonant absorption that makes Fe^{57} a very useful Mossbauer isotope.

Since recoil processes are so important to the magnitude of the observed resonant absorption, the precise conditions of binding between the emitter and its host lattice are of paramount importance. It has been found both in this laboratory and in other experiments that radioactive Co^{57} embedded in pure iron, iron compounds, or iron alloys, makes excellent sources. Resonant absorbers for such a source ideally would consist of only stable Fe^{57} nuclei bound in lattice positions identical to those occupied by the cobalt nuclei of the source. Since the resonant line widths are extremely narrow for states as long lived as the 14.4 kilovolt level of Fe^{57} , it is to be expected, and it has indeed been found, that the level can be significantly split by crystalline electric and magnetic fields as well as by other parameters of the microscopic environment of the nuclei. On the one hand, this sensitivity to environment is one of the things that makes the Mossbauer effect so rich in possibilities for scientific and industrial applications, and on the other hand, this sensitivity makes source and absorber preparations an important, although presently not well understood, art.

In this laboratory we have investigated the possibilities of constructing suitable resonant radiation sources by co-plating iron and cobalt onto thin copper foils. We found it was difficult to deplete a weak solution of radioactive Co^{57} and, therefore, rather uneconomical for us to

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

prepare small sources in this way. The cost of enriched Fe⁵⁷ and Co⁵⁷ makes this process unattractive for the present. It is likely, however, that the method could be developed if necessary. One of the reasons for abandoning further development of the co-plating technique was the fact that plated Co⁵⁷ sources became available through Nuclear Science and Engineering Corporation, Pittsburgh, Pennsylvania, at just the time our efforts got seriously under way. It was therefore expedient for us to procure such source from NSEC, and over the period of this program we purchased three Co⁵⁷ sources. The first source received was one millicurie of Co⁵⁷ plated on a 1/4 inch diameter, three mil thick Armco in foil. The other two sources were two millicuries of Co⁵⁷ each, one source plated on a 3 mil thick No. 316 stainless steel foil and the other on a 5 mil thick Armco iron foil.

Annealing of the commercial sources was necessary to insure proper diffusion of the Co⁵⁷ into the host lattice.¹⁰⁵ For this purpose a hydrogen annealing furnace was constructed using a one-inch inside diameter by 30-inch long porcelain ceramic tube closed at one end. The open end of the tube was fitted with thermocouple leads and steel tubing which served as inlet and outlet for an exchangeable hydrogen atmosphere. A lavite boat was used to support the Co⁵⁷ sources during annealing in the porcelain tube. Prior to each annealing operation, the entire assembly was inserted in an electric oven and pre-heated to 950° centigrade to out-gas any component which might contaminate the sources.

The one millicurie Co^{57} -iron (3 mil) source was held at 900° centigrade for a few hours, while the other two sources were heated at 950° centigrade for one hour. Tests were carried out to determine the amount of nuclear resonant absorption with the annealed sources (see Table I in the following subsection on absorbers). Depending on the type of absorber used, the fraction of resonant absorption (i. e., the ratio of the number of 14.4 kilovolt gammas absorbed to the number of gammas transmitted when resonance was destroyed) ranged from 1 to 41 per cent. A comparison of the two Co^{57} -iron sources showed that the 2 m. c. source did not have as high a per cent of resonant absorption as the older 1 m. c. source. Since annealing times and temperatures were different, the 1 m. c. source was annealed for an additional 1/2 hour at 950° centigrade to see if the resonant absorption would increase. The per cent of resonant absorption decreased from approximately 21 per cent to 17 per cent with the 0.7 mil iron absorber. One would expect a decrease in the intensity of the 14.4 kilovolt gammas due to an increase in self-absorption^{87, 113} and any losses due to vaporization, but not a decrease in the per cent of recoil-free emissions with deeper diffusion of the Co^{57} into the host lattice. The cause for this decrease has not been resolved.

B. Resonant Absorbers

Three types of natural iron absorbers (containing approximately two per cent Fe^{57}) and a No. 316 stainless steel absorber were investigated during the course of this study.

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

1. Iron Powder Absorbers

An iron absorber was constructed using a mixture of finely divided iron powder and Duco cement dissolved in acetone. The mixture was deposited on a lucite foil having a thickness of 97 mgm/cm^2 . By weight difference, the iron absorber thickness was determined to be about 19.3 milligrams per square centimeter. Using apparatus to be described, the resonant absorption of this iron powder was found to be 20 per cent, which was surprisingly good compared with thin iron foils. (Table I at the end of this section lists the per cent of resonant absorption for the several iron absorbers tested.) Because most experimenters have used foils rather than powders for their absorbers and do not in general attain such good effects so easily, powdered iron absorbers may prove to be very useful for some applications utilizing nuclear resonant absorption techniques. It may be that there is something significantly different about the use of powdered absorbers. Two possibilities are: the high state of strain in thin foils may contribute to some lattice defects which inhibits recoil free absorption; or the perfection of the microcrystalline powder may be significantly higher than attainable with thin foils.

2. ARF Absorber Foils

Although powdered absorbers seemed very promising, it was felt that it would be worthwhile to invest some effort in attempting to roll thin metallic foils and to plate enriched Fe^{57} on copper foils. The ARF Metals Research Division made a number of attempts to produce uniform

foils with thicknesses of one mil or less. It was found that serious departures from uniformity developed when attempts were made to push the rolling equipment below a few mils thickness. As mentioned in the previous subsection on sources, it was found uneconomical to produce thin enriched Fe^{57} absorbers by plating techniques due to the cost of enriched Fe^{57} and the difficulty in depleting a weak plating solution.

3. Commercial Iron Foils

We succeeded in locating a commercial supplier of very thin iron foils after encountering difficulty in fabricating such materials in our own laboratory. The A. D. McKay Company of New York has supplied us with 0.7 and 0.5 mil soft iron foil. The foils are quite wavy in appearance and it was feared that they would be highly non-uniform in thickness. To test this, radiographs of these foils were made using soft x-ray radiation, and it appears from the radiographs that the inhomogeneousness was not serious. Samples of each thickness of foil were annealed for several hours in the hydrogen atmosphere at 900° Centigrade. Table I lists the per cent resonant absorption for these thin foils.

4. No. 316 Stainless Steel Foils

Because the absorption spectrum of an iron foil has several resonant peaks due to hyperfine splitting caused by the Nuclear Zeemann effect^{56, 133}, the monoenergetic gamma rays from Co^{57} imbedded in a No. 316 stainless steel lattice will not be resonantly absorbed due to the

mismatching of the energy levels involved. Therefore, a 1 mil thick No. 316 stainless steel foil was procured for use with the 2 m. c. Co^{57} - stainless steel source. Resonant absorption measurements showed a 41 per cent effect, which was the highest obtained in this laboratory, and consequently, this source-absorber combination was used in most of the experiments which did not involve magnet field effects.

C. Detectors

A wide range of common radiation detectors were available to us in these investigations. However, for work with the 14.4 kilovolt line of Fe^{57} , the most promising devices appear to be thin NaI(Tl) scintillation crystals and high resolution proportional counters.

At the start of the program, a NaI(Tl) scintillation crystal of thickness 0.125 inches was used. This detector, used during our initial observations of the Mossbauer effect using powdered absorbers, proved to have an energy resolution at the 14.4 kev iron line of approximately 35 per cent (See Fig. 1). Because the ratio of detection efficiencies of low energy gamma rays increases with decreasing crystal thickness, it appeared desirable to use still thinner crystals to further suppress interference from higher energy radiation from the Co^{57} source. We procured 0.015 inch NaI(Tl) crystals from Harshaw Chemical Company, but the first of these supplied to us had to be returned because of faulty potting. The second 15 mil crystal did not show any improvement in resolution. Light pipes were inserted between the crystal and photomultiplier tube to improve loss of resolution

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

TABLE I

PER CENT OF RESONANT ABSORPTION FOR THREE CO⁵⁷ SOURCES
AND SEVERAL ABSORBERS

Absorber	Source		
	Per cent Resonant Absorption		
	1m. c. Co ⁵⁷ -Iron (3 mil)	2m. c. Co ⁵⁷ -Iron (5 mil)	2 m. c. Co ⁵⁷ -Iron (3 mil)
0.5 mil-annealed	12.8		
0.5 mil-unannealed	16.2		
0.7 mil-annealed	18.6		
0.7 mil-unannealed	20.8 -(17)*	17.5	1
Powdered iron	20.4		
No. 316 Stainless Steel			41

* Per cent of resonant absorption decreased after source was reannealed for 1/2 hour at 950° C.

Fig. 1 SPECTRUM OF Co^{57} SOURCE USING 1/8" THICK NaI(Tl) SCINTILLATION DETECTOR

due to any nonuniformity of the photocathode response, since the scintillation light was generated very close to the cathode. This attempt was unsuccessful because there was a loss in efficiency and a deterioration in energy resolution when the light pipe was used.

To obtain significantly better energy resolution, a flow-type proportional counter approximately five inches in diameter and 12 inches long was constructed (See Fig. 2). The counter was equipped with large windows sealed with mylar and had both guard and field electrodes to assure maximum resolution. It was designed to operate using a gas mixture of 90 per cent argon and 10 per cent methane at atmospheric pressure. Pre-amplifier and pulse shaping circuits were mounted at one end of the counter. Figure 3 shows a spectrum of the Fe^{57} Mossbauer source obtained with the proportional counter and a 256 channel pulse height analyzer. An energy resolution of 11 per cent was obtained for the 14.4 kilovolt line, while the 6.4 kilovolt iron K x-ray line had a resolution of about 17 per cent. The 3.4 kilovolt argon escape peak can also be seen in the spectrum shown in Fig. 3. This peak is due to the escape of Argon K x-rays which are produced after the ionization of K shell electrons by the photoelectric absorption of the 6.4 kev photons. Because the proportional counter had very good energy resolution at low energies and low detection efficiency for high energy gamma rays, this detector was used for most of the laboratory experiments.

D. Motional Transducers

One of the problems of studying resonant absorption line shapes centers around the production of known and reproducible velocities in the

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Fig. 2 FLOW TYPE PROPORTIONAL COUNTER

Fig. 3. SPECTRUM OF Co^{57} SOURCE USING PROPORTIONAL COUNTER

millimeter per second range. Wheels, hydraulic devices, lead screws and cams have been employed to produce controlled motion. An alternative which we are now using in our laboratory is a transducer derived from a loudspeaker voice coil mechanically coupled with a similar coil used as a velocity sensing element. Two standard 12" speakers, Knight KN-820, were stripped of housings and cones. The ring type ceramic magnet assemblies were modified to provide a 1.1 inch diameter hole through the center. The magnets were mounted back to back and a thin walled 1 inch diameter aluminum tube was cemented to the coil-web assemblies. With this arrangement, it was possible to mount either the source or absorber on the motional transducer. When a sine wave voltage is applied to the driving coil, the absorber, or emitter, which is mounted on the sensing element, will experience a sinusoidal velocity motion. In this manner, the relative velocity range between source and absorber can be controlled, and a velocity versus counting rate spectra can be recorded with equipment to be described in the following paragraph.

E. Electronics

In addition to the standard detector electronics, which will not be discussed further, the study of resonant absorption is greatly facilitated by the system shown in Fig. 4. The velocity pickup which provides an instantaneous measure of the relative velocity between source and absorber, together with the output of a single channel analyzer set to detect only radiation around 14.4 kilovolts are fed into the gate circuit shown in Fig. 5, which

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Fig. 4. BLOCK DIAGRAM OF THE SYSTEM USED TO OBSERVE
RESONANT LINE STRUCTURE

Fig. 5 GATE CIRCUIT USED TO PRODUCE A PULSE PROPORTIONAL TO THE INSTANTANEOUS RELATIVE VELOCITY BETWEEN SOURCE AND ABSORBER WHEN A 14.4 kev GAMMA RAY IS DETECTED

provides an output pulse proportional to the instantaneous velocity at the time when the single channel analyzer gate pulse signals the detection of a 14.4 kilovolt radiation. The output of the gate is then used to drive a multi-channel pulse height analyzer which records and stores a spectrum of the intensity of gamma ray absorptions as a function of transducer velocity. With this circuit, resonant line structure can be determined with great speed and convenience. Figure 6 shows a typical velocity spectrum of the Fe^{57} source and absorber. Since this data was used only for qualitative information, no time corrections were made; below the recorded spectrum is a sketch of the approximate time corrected spectrum. The central dip corresponds to the absorption line around zero velocity, while the dips on either side of the central dip correspond to split levels due to internal magnetic fields i. e. due to the Nuclear Zeeman effect.

IV. PRACTICAL APPLICATIONS OF THE MOSSBAUER EFFECT

A. Measurements of Small Velocities

As was mentioned in Section II-A, each emitter-absorber combination exhibits a finite line width or energy distribution. In the ideal case using thin absorbers and with no broadening effects present, the expected observable line width at half maximum should be twice the natural line width of the emitted gamma¹³¹, and the line will have approximately a Lorentzian shape¹⁰⁵. Since small uniform relative velocities between source and absorber will Doppler shift the energy of the nuclear resonant gammas, and thereby decrease the amount of resonant absorption, it should be possible

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Fig. 6 THE RESONANT ABSORPTION OF 14.4 kev GAMMA RAYS FROM A Co^{57} SOURCE IN AN IRON FOIL ABSORBER AS A FUNCTION OF THE RELATIVE VELOCITY BETWEEN SOURCE AND ABSORBER

to determine the relative velocity by one of several means, depending upon the source-absorber combination and the extent of energy shift. The shift in energy, ΔE , for a relative velocity v between source and absorber is given by

$$E = E_0 \left(1 - \frac{c}{c \mp v} \right) \quad (7)$$

Figure 7 is a sketch of a typical nuclear resonant transmission spectrum with three velocities ranges marked by regions 1, 2, and 3, in which different techniques must be employed to determine the perturbing velocity.

In Region 1, the velocities are of such magnitude that resonance is essentially destroyed and a measurement of the transmission will give little or no information about the velocity. To correct for this, another velocity must be superimposed upon the system. This can be accomplished by introducing a variable calibrated velocity and thus 're-tune' the system back to resonance. If the transmission spectra exhibits an extremely sharp absorption with a well defined peak, the maximum absorption or null point can be tuned directly, and the unknown velocity will be equal in magnitude, and opposite in direction, to the calibrated tuning velocity. If the null point is difficult to define, then one can undertune to a point at the half maximum height of the resonance line and overtune to the corresponding point. By this method, the unknown velocity will be given by the sum of the two calibrated velocities divided by two.

Another method of determining unknown velocities in Region 1, involving a more complicated system, is to superimpose a continuous

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Fig. 7. TYPICAL NUCLEAR RESONANT TRANSMISSION SPECTRUM

velocity spectra between zero and some predetermined maximum. By using an electronic detecting system, similar to that described in Section III-E, a velocity spectrum can be displayed and recorded against a calibrated scale; the perturbing velocity will be determined by the position of the absorption peak.

Velocities in Region 2 are the easiest to determine because a single transmission measurement will give the magnitude of the velocity (from comparison with a calibration curve). To determine the direction, one only needs to introduce a small known velocity and observe if the transmission increases or decreases. Table II lists some Mossbauer isotopes and their associated velocity ranges in which direct transmission measurements may be made. The calculations were made using the conservative assumption that Region 2 is limited to areas centered about the half maximum points, with a width equal to half the line width at half maximum.

Extremely small velocities which fall in Region 3 cause small energy shifts and direct transmission measurements will not have the sensitivity to determine the velocity. Appendix II shows a derivation of the technique used by Pound and Rebka⁴³ to detect small energy shifts due to the gravitational red shift. The same method can be used to measure small relative velocities, or any other small perturbing effect. The method employs the superposition of velocities which cause a shift corresponding to plus and minus $\Delta E_{1/2}/\sqrt{3}$, where $\Delta E_{1/2}$ is the natural line width of the emitted gamma. The unknown energy shift is then proportional to the ratio

TABLE II
VELOCITY RANGES WHICH MAY BE DETERMINED BY DIRECT
TRANSMISSION MEASUREMENTS FOR REPRESENTATIVE
MOSSBAUER ISOTOPES

Stable Nucleus	E_{γ} (Kev)	$T_{1/2}$ (m μ sec)	v (cm sec ⁻¹)
Zn ⁶⁷	93	9.3×10^3	.000008 - .000023
Fe ⁵⁷	14.4	100	.0047 - .014
Sn ¹¹⁹	24	19	.015 - .045
W ¹⁸²	100	1.3	.05 - .16
Ir ¹⁹³	139	.26	.19 - .57
Ta ¹⁸¹	136	.057	.88 - 2.64

of the difference of the observed counting rates to the sum of the counting rates (Eq. II-6). The unknown velocity can then be determined using Eq. 7.

The ideal types of sources and absorber combinations for the velocity measurements should exhibit only one absorption peak, that is, the gamma ray of interest should decay from an unsplit (by the nuclear Zeeman effect) excited nuclear state. If the level is split, as is the case of Fe⁵⁷ in an iron lattice, the secondary absorption peaks could cause a

misinterpretation of the transmission data. If a small amount of spectral broadening is present, as is usually the case, the range of Region 2 will increase, but the sensitivity in any measurement will decrease, due to the change of slope and the decrease in the amplitude of the resonant absorption peak.

The most promising applications for small velocity measurements using the Mossbauer effect center around measurements which are inaccessible to standard techniques, or which are influenced by hostile environments. Because the gamma rays used in the nuclear resonant absorption measurements can penetrate matter, small velocities of a completely enclosed body can be determined. Since gamma rays are not influenced by electric or magnetic fields or by temperature, high velocity fluid flow, etc., small velocity measurements in such hostile environments may be possible using Mossbauer techniques when other velocity sensitive devices cannot be used.

B. Measurements of Magnetic Fields

When the Co^{57} nucleus is embedded in an iron lattice, the internal magnetic fields of this ferromagnetic material cause a splitting of the emission and absorption levels due to the nuclear Zeeman effect⁵⁶. The degree of energy differences between the split levels in Fe^{57} is an order of magnitude greater than the observable line width, and they are, therefore, resolvable in an energy or velocity spectra. Figure 8 is a velocity spectrum of our Fe^{57} source and absorber combination using a sinusoidal velocity between the source and absorber.

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

FIG.8 VELOCITY SPECTRUM OF Co^{57} SOURCE AND IRON FOIL ABSORBER.

The split energy levels of Fe^{57} embedded in an iron lattice allow six transitions, and the observable spectra should consist of the zero energy shift peak and five satellite peaks, two of which are unresolvable doublets⁵⁶. When the source and absorber are polarized by an external magnetic field, the velocity spectra will be altered due to the polarization of the gammas from the different transitions. Figure 9, which shows the central peak and the first satellite peaks indicates the absorption behavior when the magnetic fields at the source and absorber are polarized parallel and perpendicular to each other. The central peak is enhanced with parallel polarization and diminished with perpendicular polarization whereas the first satellite shows just the opposite behavior.

Because of the absorption behavior mentioned above, measurements of the per cent of resonant absorption were made with the polarized fields and with the various absorbers mentioned in Sec. III-B. The field about the 1 m. c. Co^{57} -iron emitter was approximately 800 gauss while the absorber was placed across the pole pieces with a similar field strength. Table III shows the change in absorption for the various absorbers tested. The results of these initial tests indicate the possibility of using nuclear resonant absorption techniques to determine the direction and flux density of magnetic fields.

The measurements were extended to determine the amount of nuclear resonant absorption as a function of the polarizing magnetic field intensity about the emitter. Figure 10 is a block diagram of the experiment

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Fig. 9 EFFECT OF POLARIZED MAGNETIC FIELDS ON VELOCITY SPECTRUM OF Co^{57} SOURCE AND IRON FOIL ABSORBER

TABLE III
CHANGES OF NUCLEAR RESONANT ABSORPTION IN SEVERAL IRON
ABSORBERS DUE TO EFFECTS OF POLARIZED MAGNETIC
FIELDS ABOUT THE EMITTER AND ABSORBER
($B \approx 800$ GAUSS)

Absorber	Relative Counting Rates (Transmission)		Per cent Change
	Parallel Polarization	Perpendicular Polarization	
0.5 mil - annealed	549	631	13.0
0.5 mil - unannealed	508	586	13.3
0.7 mil - annealed	388	476	18.5
0.7 mil - unannealed	348	423	17.7
powdered iron	278	286	2.8

Fig. 10. BLOCK DIAGRAM OF EXPERIMENTAL ARRANGEMENT
USED TO MEASURE THE EFFECT OF POLARIZING
MAGNETIC FIELDS ON NUCLEAR RESONANT
ABSORPTION OF GAMMA RAYS

arrangement, and Fig. 11 shows the results of the initial measurement. The field strengths at the 1 mc Co^{57} source were varied between zero and 1000 gauss while the 0.7 mil iron absorber was placed across the pole pieces of a permanent magnet having a field of 800 gauss. Measurements were made with both parallel and perpendicular polarizing fields between the source and absorber. The results in Figure 10 are of a preliminary nature; however, they indicate the qualitative trend of the variation in resonant absorption as a function of field strength and relative polarization. The principle errors in the measurements are due to residual fields in the electromagnet and the uncertainty in the measured field strength. From Fig. 11 it can be seen that the rate of change of resonance absorption with magnetic field strength is greatest in the region between 300 and 1000 gauss. Therefore, it is in this region that magnetic field strengths would be most easily measured using this technique. The percentages of nuclear resonant absorptions at magnetic field intensities of one kilogauss were approximately 8.5 per cent for perpendicular fields, 26 per cent for parallel fields, and 15 per cent for no fields.

The above measurements were repeated using a different electromagnet whose flux density was calibrated, the 2 mc Co^{57} -Fe source and the 0.7 mil iron absorber which was placed in a permanent 1950 gauss field. The accuracy of the measurements were within 10 per cent statistics but unfortunately the Co^{57} -Fe source and 0.7 mil iron absorber exhibited only 8.2 per cent resonant absorption with no magnetic fields present.

(The cause of this decrease in resonance has not been determined). The

Fig. 11 TRANSMISSION INTENSITY OF RESONANT GAMMA RAYS THROUGH AN IRON FOIL IN A MAGNET FIELD OF 800 GAUSS vs. MAGNETIC FLUX DENSITY ABOUT A Co^{57} SOURCE

the results of this measurement are illustrated in Fig. 12, and they are comparable to Fig. 11. With parallel polarizing magnetic fields, the per cent of resonant absorption increases by approximately a factor of two at saturation, while perpendicular polarization decreases the per cent of resonant absorption by a factor of two.

The above results indicate a definite possibility of utilizing nuclear resonant gamma techniques for determining the strengths and directions of magnetic fields in the approximate region of 300 to 1000 gauss. The practicality of using such methods is again limited to application which involve hostile environments or accessibility problems which prohibit the use of standard techniques.

C. Measurements of Gravitational Fields Using Nuclear Resonance Absorption

Because of the successful gravitational red-shift experiments by R. V. Pound and G. A. Rebka¹⁰⁷, it was suggested that nuclear resonant absorption techniques could be used to measure gravitational fields and altitudes from space vehicles. Calculations were carried out based on a measurement technique described in Appendix II. In Table IV the results of these calculations are given. A brief summary of the theoretical basis for these calculations follows.

The shift in frequency of a photon emitted at some height to the absorber, due to the difference of gravitational potentials at source and absorber, is given by

$$\Delta \nu_h = \frac{\nu_o G M h}{c^2 r^2 (1 + \frac{h}{r})} \quad (8)$$

Fig. 12. PER CENT OF MAXIMUM TRANSMISSION OF NUCLEAR RESONANT GAMMA RAYS THROUGH AN IRON FOIL ABSORBER vs. MAGNETIC FLUX DENSITY ABOUT A Co^{57} SOURCE

where G is the gravitational constant, M is the mass of the attracting body, and r is the distance from the center of the body. If the measurements are made on the surface of the earth and h is small compared to r , Eq. 8 becomes

$$\Delta\nu_h = \frac{\nu_o gh}{c^2} \quad (9)$$

where g is the gravitational acceleration. Since the shift in frequency, $\Delta\nu_h$, can be measured using the Mossbauer effect and the technique described in Appendix II, the acceleration due to gravity and the distance r can be calculated from the following formulae:

$$g = \frac{c^2 K D \Gamma}{h \nu_o S} \quad (10)$$

$$r = \left(\frac{\nu_o G M h S}{c^2 K D \Gamma} \right)^{1/2} \quad (11)$$

and a fractional error of $\sqrt{S/D}$ in g and $\sqrt{S/2D}$ in r , where K is a constant associated with the method of measurement and depends upon the fraction of resonant absorption F , S and D are the sum and difference of the measured transmissions, and Γ is the natural line width of the emission spectrum.

Expected values of K , D and S are given by

$$K = \frac{8}{3\sqrt{3}} \left(\frac{1}{F} - \frac{3}{4} \right) \quad (12)$$

$$S = R^+ + R^- = \frac{1}{2} I_o (4 - 3F) \quad (13)$$

$$D = R^+ - R^- = \frac{3\sqrt{3}}{4} \frac{FI_0}{\Gamma} \Delta\nu_h \quad (14)$$

where I_0 is the transmission intensity when nuclear resonant absorption is destroyed.

In Table IV the various fixed parameters and some representative values for the variable parameters used in the above equations are given for two sources, Fe^{57} and Zn^{67} . These Mossbauer sources were chosen because the expected observable line widths are extremely small. Zn^{67} has a line width two orders of magnitude smaller than Fe^{57} , but the small fraction of recoil free gamma emissions requires the use of cryogenic techniques in any measurements involving nuclear resonant absorption in Zn^{67} . The intensity, I_0 , was calculated assuming $\frac{1}{3}$ of the gammas are lost due to scattering and that the detector is a 5 cm diameter scintillator. Also calculated are the counting times necessary to obtain 10 percent and 1 percent statistical accuracy in g which corresponds to 5 and 0.5 percent statistics in r , respectively, for experiments located at the earth's surface, two earth's radii and on the lunar surface. The results shown in Table IV indicate that very long counting times are required with these two sources. Consequently, the use of this technique for measurements of gravitational fields in space and of space vehicle altitudes does not appear to be promising. One possible improvement might be to use Zn^{67} at cryogenic temperatures, thereby increasing f .

TABLE IV

LIST OF PARAMETERS USED TO CALCULATE THE GRAVITATIONAL FREQUENCY SHIFT OF
 RESONANT GAMMA RAYS, AND CALCULATED COUNTING TIMES NECESSARY TO OBTAIN
 RESONABLE STATISTICS IN MEASUREMENTS OF THE GRAVITATIONAL ACCELERATION,
 g , OR THE DISTANCE FROM THE ATTRACTING BODY, r

	Fe^{57}			Zn^{67}		
ν_0	3.48×10^8 cycles/sec			2.24×10^9 cycles/sec		
Γ	1.1×10^6 cycles/sec			1.18×10^4 cycles/sec		
F	0.3			0.01		
h	20 meters			2 meters		
Source Strength	16.5 curies*			0.2 curies *		
I_0	5×10^4 counts/sec			5×10^4 counts/sec		
D	$1.77 \times 10^{-2} \Delta \nu_h$ counts/(sec)(cps)			$5.5 \times 10^{-2} \Delta \nu_h$ counts/(sec)(cps)		
S	7.75×10^4 counts/sec			9.9×10^4 counts/sec		
r	earth's surface	2 earth's radius	moon's surface	earth's surface	2 earth's radius	moon's surface
$\Delta \nu_h$	7.3×10^3 cps	1.9×10^3 cps	1.22×10^3 cps	4.88×10^3 cps	1.22×10^3 cps	3.8×10^2 cps
time for 10 % in g, 5% in r	7.1 min	114 min	4.6 hours	2.3 min	36.6 min	1.5 hours
time for 1% in g, 1/2 in r	12 hours	8 days	19 days	3.8 hours	2.5 days	6.2 days

* The internal conversion coefficients were assumed to be 15 and $\frac{1}{2}$ for Fe^{57} and Zn^{67} , respectively.

D. Effects of Pressure on the Fraction of Recoil Free Gamma Emissions

Because the fraction of recoil free gamma emissions depends upon the probability of transfer of momentum to the host lattice as a whole, one would expect an increase of this fraction as the lattice becomes more rigid under pressure. To measure this effect, a pressure bomb was constructed in which the Fe^{57} source can be subjected to 40,000 psi. The pressure bomb was fitted with a window assembly consisting of a 0.675 inch diameter beryllium disk 0.100 inch thick, and a 3/8 inch thick harder steel supporting collimator. The surfaces of the beryllium window and steel collimator were lapped to within one half wavelength and polished to a one micro-inch rms finish so that they would be optically flat for sealing purposes. The beryllium window attenuated approximately 12 percent of the 14.4 Kev Fe^{57} gamma rays. The steel supporting collimator consisted of twenty-one holes, 0.020 inch in diameter, symmetrically drilled over a 1/4 inch diameter area. (See Figs. 13 and 14 for photographs of the pressure bomb and window assembly.)

The source used for the pressure experiment was the 2 mc Co^{57} source plated on a 1/4 inch diameter No. 316 stainless steel foil 3 mils thick. The resonant absorber foil was a 1 mil thick No. 316 stainless steel foil. A 45 percent resonant absorption was achieved with this emitter-absorber combination and with the source in the pressure unit: see Table V, Run A-A'.

Fig. 13 PRESSURE ASSEMBLY AND COUNTING EQUIPMENT

Fig. 14 PRESSURE BOMB WINDOW ASSEMBLY

The detection and counting system, Fig. 15, consisted of a flow type proportional counter whose output was fed into a multichannel pulse height analyzer. The background with no sources present was approximately 200 counts per hour per channel in the energy region of interest.

In Table V the results of the pressure experiments are shown. Each run consisted of alternately measuring the transmission, for 15 minute intervals, at two fixed pressures. This procedure was followed to compensate for any changes in background and drifts in the electronic equipment with time. With the intensities observed, a 2 percent change in the transmission intensity could be detected. Because the changes in transmission intensities, after correction for background, were constant within the statistical error in all cases but one, it can be concluded that any changes in the fraction of resonant absorption due to ambient pressures up to 40,000 psi were less than three percent. Recent theoretical calculations⁵³ indicate that pressures an order of magnitude greater than those used in these measurements are required to observe a pressure effect in stainless steel.

E. Acoustical Energy Density Measurements

The difficulties of measuring acoustical power in the ultra high frequency range by conventional methods have led us to undertake a feasibility study of utilizing nuclear resonant absorption techniques for these measurements. Because the acoustical power is a function of the acoustical

Fig. 15 BLOCK DIAGRAM OF PRESSURE EXPERIMENT APPARATUS

TABLE V
EFFECT OF PRESSURE ON FRACTION OF RECOIL FREE GAMMA EMISSIONS
FROM A Co⁵⁷ - STAINLESS STEEL MOSSBAUER SOURCE

Run	Pressure at emitter (psi)	Time of run (min)	Total counts (Transmission)	Estimated Background	Difference in Transmis- sion Intensities
A	3,000 $\pm$ 500 (off resonance)	120	18,518	8,500	4539 $\pm$ 180 ($\sim$ 45%)
A'	3,000 $\pm$ 500 (on resonance)	120	13,979	8,500	
B	3,000 $\pm$ 500	180	20,810	12,000	-91 $\pm$ 204
B'	1 atm.	180	20,719	12,000	
C	3,000 $\pm$ 500	240	31,934	19,875	249 $\pm$ 252
C'	10,000 $\pm$ 500	240	31,685	19,875	
D	3,000 $\pm$ 500	180	23,225	15,000	437 $\pm$ 215
D'	20,000 $\pm$ 500	180	22,788	15,000	
E	3,000 $\pm$ 500	180	21,852	13,500	282 $\pm$ 208
E'	30,000 $\pm$ 500	180	21,570	13,500	
F	3,000 $\pm$ 500	180	20,080	12,000	-114 $\pm$ 201
F'	40,000 $\pm$ 500	180	20,194	12,000	

frequency amplitude, it is expected that the transmission, through an absorbing foil, of resonant gamma rays emitted from an acoustically modulated source will be a function of the acoustical power. If a Mossbauer source is mounted on an acoustical transducer, the amount of nuclear resonant absorption of the emitted gamma rays will be proportional to the fraction of time the source is not sufficiently Doppler shifted to completely destroy resonance. If the transducer velocity is a sine wave function, the transmission intensity of the resonant gamma rays will be a function of the maximum transducer velocity or amplitude.

Experimental measurements were carried out to determine the effect of high frequency modulation of a Mossbauer source on the fraction of nuclear resonant absorption of gamma rays. For these investigations, the 2 mc Co^{57} source plated on a 3 mil thick No. 316 stainless steel foil was mounted on a quartz crystal transducer. The intensity of the 14.4 kev gammas transmitted through a similar absorbing foil 1 mil thick as a function of the applied frequency and voltage across the acoustical transducer, and therefore a function of the acoustical power, was measured using the flow type proportional counter. Measurements were made at approximately 10, 30 and 50 megacycles (the fundamental, 3rd and 5th resonant harmonics of the quartz transducer, respectively), with applied voltages ranging from zero up to a sufficient value to destroy the resonance. (See Fig. 16 for a block diagram of the experimental arrangement.) The results of these measurements are plotted in Fig. 17, and indicate that nuclear resonant

Fig. 16 BLOCK DIAGRAM OF EXPERIMENTAL ARRANGEMENT USED TO MEASURE THE EFFECT OF ACOUSTICAL MODULATION ON THE AMOUNT OF NUCLEAR RESONANCE ABSORPTION

Fig. 17 RELATIVE TRANSMISSION INTENSITY OF NUCLEAR RESONANT
GAMMA RAYS vs. APPLIED VOLTAGE AT EMITTER HIGH
FREQUENCY TRANSDUCER

absorption techniques can be used to measure acoustical power in the megacycle frequency range.

The feasibility of extending the measurements to higher frequencies appears very good, although the techniques of bonding the source to the high frequency transducer becomes more complex. If the frequency range is extended to the kilomegacycle region, the emitting atoms would have to be an integral part of the transducer since the oscillations are due to a skin or surface phenomena. The frequency of the transducer may also be obtained by observing the shape of the velocity spectrum of the modulated source.¹¹¹ The basic phenomenon involved is frequency modulation where the carrier is the gamma ray frequency and the modulator is the transducer. The velocity or frequency spectrum should consist of the carrier line, centered around zero relative velocity and an infinite number of side-band lines spaced at velocities corresponding to the modulation frequency.

F. A Communication System Utilizing the Mossbauer Effect

One application of the Mossbauer effect which may have great potential at some future time is in the field of communications. In such a communications system, a photon beam modulated by the Mossbauer effect would be used to transmit information. Such a system seems to have potential use in space communications between satellites and for short distance point to point communications on earth. This latter case seems to have particular applications to Civil Defense and the Military under conditions of extreme emergency when conventional communications systems are

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

inoperative. Currently, because of the limitations of source strength of suitable Mossbauer isotopes, and the softness of the gamma rays emitted by the available Mossbauer sources, it seems more feasible to use strong Co^{60} or Cs^{137} sources with a movable shutter to give a simple dot-dash communications system. However, when the above mentioned limitations on Mossbauer isotopes are overcome, a higher density of information should be able to be carried on a Mossbauer modulated photon beam.

G. Other Possible Practical Applications Using Nuclear Resonance Absorption Techniques

Besides the applications discussed in the previous subsections, there are many specific applications which might utilize the Mossbauer effect. One of the most promising fields would be control systems. The signal from a velocity sensitive nuclear resonant system could be fed into servo systems, integrating and differentiating systems, gyros, etc., and thereby provide a means of measuring and/or controlling displacement, velocity or acceleration. Such applications would be of considerable interest to industries involved with control of machine tools, the percussion of gyros, machine performance, high precision synchronization problems, etc.

Measurements of the amplitude of vibration (if the frequency is known) and under certain conditions the frequency of oscillation¹¹¹ can be made by a non-contact-method using the Mossbauer effect. Sonic Doppler methods are available for this purpose but do not cover the same velocity range nor are they immune to the conditions of the intervening medium.

Nuclear resonance methods can be used through high temperature media or media containing material velocity gradients such as winds, shock waves, etc.

Another field of applications might well be found in problems pertaining to the exploration of space, particularly because low temperature Mossbauer systems might be useful because the accuracies and nature of many of the problems encountered in rocket and satellite vehicles are unique. In particular, nuclear resonant absorption techniques may provide velocity and acceleration sensing in guidance systems.

V. SUMMARY AND CONCLUSIONS

During the course of this program the use of the Mossbauer effect in a number of varied practical applications has been considered. It is known that Mossbauer absorption provides a powerful method for fundamental investigations of the solid state. In fact, much of the current research on this resonant absorption phenomenon is aimed at utilizing the effect for such solid state studies. However, investigations of the solid state utilizing the Mossbauer effect were considered outside the scope of this program. Instead, our investigations were limited to the potential use of the Mossbauer effect in the solution of practical problems in measurement and control technology. Applications considered in this program were: the use of the Mossbauer effect in the general areas of velocity measurements, acceleration measurements in suitable velocity ranges, the measurement

of gravitational fields in interplanetary space and on the surface of the moon and planets together with altitude measurements from space vehicles, the measurement of high pressures, the measurement of magnetic field strengths and polarizations, and acoustical power measurements in the ultrasonic and hypersonic region.

The results of several of the experiments undertaken proved rather discouraging from the standpoint of practical applications of the Mossbauer effect although encouraging results were obtained in most cases. Details and conclusions of the individual experiments undertaken and considered are given in Section IV of this report; however, it seems worthwhile to bring together these conclusions in this summary.

The Mossbauer effect can be used to measure extremely small velocities in the range of approximately $(0.005 - 0.015)$ cm/sec if Fe^{57} alone is considered. However, this range can be extended several orders of magnitude in both directions if other sources are considered; although the majority of these other sources require cryogenic temperatures to obtain a reasonable fraction of resonant absorptions. From such velocity measurements and by the use of suitable electronic differentiating circuitry the measurement of accelerations becomes feasible. The use of this technique to measure small velocities, and accelerations in these velocity regions, can be expected to have many advantages over current methods in a variety of circumstances (some of which are enumerated in Section IV., A.).

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

The successful gravitational red-shift experiments by Pound and Rebka¹⁰⁷ suggested a potential use of this effect to measure gravitational fields in interplanetary space and on the surface of the moon and the planets together with altitudes of space vehicle. Calculations revealed however, that the time required to obtain reasonably accurate results would be of the order of hours or days even under the most favorable circumstances. Consequently, this application of the Mossbauer effect does not appear too promising since conventional techniques can give the required results in a much shorter time and with much greater accuracy.

Experiments were also undertaken to determine the effects of high pressures on the fraction of recoil free gamma emissions. These experiments were conducted using pressures up to 40,000 psi without any change in the fraction of resonant absorption being observed. This proved to be in agreement with subsequent theoretical calculations which predicted a much greater pressure (by a factor of ten or so) would be required before any effect could be detected.

When an Fe^{57} emitter or absorber nucleus is embedded in an iron lattice the nuclear Zeeman effect causes a splitting of the energy levels. Because of the narrowness of the 14.4 kev Fe^{57} line, the six allowed transitions between the split levels are all clearly resolved from each other. The relative populations of these split levels will vary with the polarization and magnitude of an applied magnetic field. Investigations were therefore undertaken to determine whether this effect could be used to measure field

strengths and polarizations at the emitter or absorber. The results of these investigations were very encouraging and showed that such magnetic field measurements were possible in the approximate range of from 300 to 1000 gauss. Such measurements then, although probably not as accurate generally as conventional techniques, do hold a definite possibility when hostile environments or accessibility problems limit or prohibit the use of such conventional techniques. This application then appears to warrant further study to delineate the range of magnetic field strengths over which the Mossbauer effect can be used as a measurement device, the accuracy with which such field measurements can be made, and potential applications of this measurement technique.

In another phase of the program, experiments were undertaken to determine the possibility of using the Mossbauer technique to measure acoustical power in the (10 - 100) megacycle region. The results of these investigations were extremely encouraging and showed that such power measurements in this frequency range could be made using this technique. Furthermore, the results gave every indication that such measurements could be extended to even higher frequencies and possibly into the hypersonic region where there is currently no suitable method available for such acoustical power measurements. Power measurements in this higher frequency range were not attempted on this program because of the additional difficulties in generating and detecting such acoustical power. However, it is felt that further investigations exploring the potential application of the

Mossbauer effect to measurement of acoustical power in the high ultrasonic and hypersonic region should be undertaken in the near future.

Apart from the general applications of Mossbauer effect discussed above, there are innumerable specific applications which can utilize the effect. Many such applications are briefly discussed in preceeding sections and will not be further enumerated here. However, one of the most interesting of these applications, proposed by C. W. Terrell, although far from being feasible at present, is the prospect of using a photon beam modulated by the Mossbauer effect in a communications system in space or short distance point to point communications on earth.

APPENDIX I

CALCULATED VALUES OF THE FRACTION OF RECOIL-FREE GAMMA
EMISSION, $f(0)$, USING THE DEBYE MODEL AT ZERO DEGREES KELVIN

APPENDIX I

CALCULATED VALUES OF THE FRACTION OF RECOIL-FREE GAMMA
EMISSION, $f(0)$, USING THE DEBYE MODEL AT ZERO DEGREES KELVIN

Stable Nucleus	Energy of Gamma Ray (kev)	Half life of excited state (sec)	Debye Temp. (°K)	$f(0)$
Fe ⁵⁷	14.4	1.0(-7)	420	.92
Ni ⁶¹	71	7.9(-9)	410	.15
Zn ⁶⁷	93	9.3(-6)	300	.02
Pd ¹⁰⁵	64		275	.26
Ag ¹⁰⁷	93	44	210	.03
Ag ¹⁰⁹	88	39	210	.04
Sn ¹¹⁹	24	1.9(-8)	200	.8
I ¹²⁷	57		100	.09
Nd ¹⁴⁵	67	3.3(-8)	100	.06
Nd ¹⁴⁵	71		100	.04
Gd ¹⁵⁵	60		150	.23
Gd ¹⁵⁵	87		150	.05
Gd ¹⁵⁵	105		150	.01
Gd ¹⁵⁶	89	1.9(-9)	150	.04
Dy ¹⁶⁰	87	1.8(-9)	160	.06
Dy ¹⁶¹	26	2.7(-8)	160	.78

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Dy ¹⁶¹	75	2.3(-9)	160	.13
Er ¹⁶⁶	81	1.7(-9)	160	.10
Er ¹⁶⁸	80		160	.11
Hf ¹⁷⁶	88	1.4(-9)	150	.06
Hf ¹⁷⁷	113		150	.01
Hf ¹⁷⁸	93		150	.05
Hf ¹⁸⁰	93	1.4(-9)	150	.05
Ta ¹⁸¹	136	5.7(-11)	225	.01
W ¹⁸²	100	1.3(-9)	310	.19
W ¹⁸⁴	111	1.3(-9)	310	.13
Re ¹⁸⁷	134		300	.05
Ir ¹⁹¹	129	1.0(-10)	285	.06
Ir ¹⁹³	73	5.7(-9)	285	.42
Ir ¹⁹³	139	2.6(-10)	285	.04
Pt ¹⁹⁵	99		225	.12
Pt ¹⁹⁵	130		225	.03
Au ¹⁹⁷	77	1.9(-9)	165	.18
Hg ²⁰¹	1.5		90	1
Hg ²⁰¹	32		90	.59
Th ²³²	50		80	.29

APPENDIX II

MEASUREMENTS OF EXTREMELY SMALL ENERGY SHIFTS USING
NUCLEAR RESONANCE ABSORPTION TECHNIQUES

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

APPENDIX II

MEASUREMENTS OF EXTREMELY SMALL ENERGY SHIFTS USING NUCLEAR RESONANCE ABSORPTION TECHNIQUES

Although the line widths or energy distributions of observable Mossbauer lines are very narrow, some perturbations are still too small to observe directly by looking for a change in counting rate due to a decrease in resonant absorption. A method for measuring small energy shifts⁴³ is available by introducing a known energy shift, as will be shown by the following derivation.

It is assumed that the observable transmission line has a Lorentzian shape and a line width at half-maximum equal to twice the expected natural line width of the emission spectrum^{105, 131}, then the intensity of the absorption spectrum will also have a Lorentz shape given by:

$$I(E) = A / [(E - E_0)^2 + B^2] \quad (\text{II-1})$$

Where $I(E)$ is the intensity at energy E , and E_0 is the energy for maximum absorption, i. e., no energy changes between emitter and absorber. The maximum absorption intensity is therefore

$$I(E_0) = A / B^2 \quad (\text{II-2})$$

and the intensity at half maximum is given by

$$I(E_0 \pm B) = A / 2B^2 \quad (\text{II-3})$$

The observable line width is therefore $2B$, where B is equal to Γ , the

natural line width of the emitted spectrum, as was assumed above.

The intensity at some point ΔE from E_0 is given by

$$I(E_0 \pm \Delta E) = A/(\Delta E^2 + B^2) \quad (\text{II-4})$$

If the peak energy, E_0 is shifted by some increment $|\epsilon| \ll B$ due to some perturbation, and one repeats the intensity measurements at the same two points $E_0 \pm \Delta E$ as before, the intensities will be given by

$$I^+(E_0 + \Delta E) = \frac{A}{(\Delta E - \epsilon)^2 + B^2} \approx \frac{A}{\Delta E^2 + B^2 - 2\epsilon \Delta E} \quad (\text{II-5})$$

$$I^-(E_0 - \Delta E) = \frac{A}{(-\Delta E - \epsilon)^2 + B^2} \approx \frac{A}{\Delta E^2 + B^2 + 2\epsilon \Delta E} \quad (\text{II-6})$$

The difference in the two intensity measurements is proportional to the shift ϵ , and is given by

$$I^+ - I^- \approx \frac{4A\Delta E}{(\Delta E^2 + B^2)^2} \epsilon \quad (\text{II-7})$$

Since A and B are fixed for any source-absorber combination, one can find the ΔE which maximizes the proportionality constant and thereby maximizes the sensitivity, $(I^+ - I^-)/\epsilon$. Taking the derivative of Eq. II-7 with respect to ΔE , and setting it equal to zero, and solving for ΔE , one gets

$$\Delta E = B/\sqrt{3} \quad (\text{II-8})$$

Because the observed line is measured by a reduction in transmission through the absorber due to nuclear resonance absorption, the transmission intensity expected at some point $E + \Delta E$ is given by

$$R = I_0 - I(E + \Delta E) \quad (\text{II-9})$$

where I_0 is the maximum intensity with no resonant absorption. Letting

$$\Delta E = B/\sqrt{3}$$

for maximum sensitivity and defining

$$R_1 = I_o - I^- \quad (\text{II-10})$$

and

$$R_2 = I_o - I^+ \quad (\text{II-11})$$

where I^- and I^+ are defined in Eqs. II-5 and II-6, one finds the difference in transmission intensities due to a shift $|\epsilon| \ll B$ is given by

$$R_1 - R_2 = I^+ - I^- = \frac{3\sqrt{3}}{4} \frac{A}{B^3} \epsilon \quad (\text{II-12})$$

The sum of the intensities is found to be

$$R_1 + R_2 = 2I_o - \frac{3A}{2B^2} \quad (\text{II-13})$$

and is independent of the shift ϵ .

The fraction of absorption at the resonance peak is given by

$$F = A/B^2 I_o \quad (\text{II-14})$$

Substituting Eq. II-14 into Eqs. II-12 and II-13, and solving for the ratio of the difference of intensities, Eq. II-12, to the sum of intensities, Eq. II-13, it follows that

$$\frac{R_1 - R_2}{R_1 + R_2} = \frac{3\sqrt{3}}{8(\frac{1}{F} - \frac{3}{4})B} \epsilon \quad (\text{II-15})$$

Therefore, a small shift in energy, ϵ , due to some perturbation is given by

$$\epsilon(E) = \frac{8}{3\sqrt{3}} \left(\frac{1}{F} - \frac{3}{4} \right) \left(\frac{R_1 - R_2}{R_1 + R_2} \right) \Gamma(E) \quad (\text{II-16})$$

where Γ is expected natural line width of emission spectrum.

APPENDIX III

CALCULATED VALUES OF THE FRACTION OF RECOIL-FREE GAMMA
EMISSIONS, $f(T)$, FOR SEVERAL MOSSBAUER ISOTOPES AT COMMONLY
AVAILABLE TEMPERATURES USING THE DEBYE MODEL

APPENDIX III

CALCULATED VALUES OF THE FRACTION OF RECOIL-FREE GAMMA EMISSIONS, $f(T)$, FOR SEVERAL MOSSBAUER ISOTOPES AT COMMONLY AVAILABLE TEMPERATURES USING THE DEBYE MODEL

Stable Nucleus	Gamma Ray Energy (kev)	Debye Temp. (° K)	Fraction of Recoil-Free Emissions, $f(T)$			
			0° K	77° K (liquid nitrogen)	195° K (Dry Ice)	295° K (room temp.)
Fe-57	14.4	420	0.92	0.90	0.82	0.71
Ni-61	71	410	0.15	0.10	0.01	----
Pd-105	64	275	0.26	0.13	----	----
Sn-119	24	200	0.80	0.64	0.19	0.03
Dy-161	26	160	0.78	0.54	0.07	----
W-182	100	310	0.19	0.10	----	----
Fr-193	73	285	0.42	0.28	0.03	----
Hg-201	1.5	90	1	0.99	0.96	0.91

BIBLIOGRAPHY

1. Abragam, A.
Effect of Ultrasonics on the Emission and Absorption of Radiation Without Recoil
Compt. rend. , 250, 4334 (1960)
2. Abragam, A. and Bautron, F.
Quadrupole Moment of the First Excited Nuclear State of Iron-57
Compt. rend. , 252 2404 (1961)
3. Alff, C. and Wertheim, G. K.
Hyperfine Structure of Fe^{57} in Yttrium-Iron Garnet from the Mossbauer Effect
Phys. Rev. , 122, 1414 (1961)
4. Barit, J. Ja. , Pobjoretzkij, M. J. and Schapiro, F. L.
Several Possible Applications of the Resonant Scattering of γ -Rays
JETP, 11, 218 (1960) (Tr. in English)
5. Barloutaud, R. , Cotton, E. , Picou, J. L. and Quidort, J.
Absorption Resonante Sans Recul du Rayonnement de 23.8 kev de Sn^{119}
Compt. rend. , 250, 319 (1960)
6. Barloutaud, R. , Picou, J. L. and Tzara, C.
Diffusion Resonante du Rayonnement γ de 23.8 kev de Sn^{119} Emis Sans Recul
Compt. rend. , 250, 2705 (1960)
7. Baumgardner, J.
Linear-Motion Generator for Mossbauer Experiments
ANL-6169, 35 (1960)
8. Bauminger, R. , Cohen, S. G. , Marinov, A. , and Ofer, S.
Hyperfine Interactions in the Ground State and First Excited State at Dy^{161} in Dysprosium Iron Garnet.
Phys. Rev. Letters, 6, 467 (1961)
9. Bauminger, R. , Cohen, S. G. , Marinov, A. and Ofer, S.
Study of the Internal Fields Acting on Iron Nuclei in Iron Garnets Using the Recoil-Free Absorption in Fe^{57} of the 14.4 kev Gamma Radiation from $\text{Fe}^{57\text{m}}$
Phys. Rev. , 122, 743 (1961)

10. Bauminger, R., Cohen, S. G., Marinov, A., Ofer, S. and Segal, E.
Study of the Low-Temperature Transition in Magnetite and the
Internal Fields Acting on Iron Nuclei in Some Spinel Ferrites Using
Mossbauer Absorption
Phys. Rev., 122, 1447 (1961)
11. Belozerskii, G. N. and Nemilow, Yu A.
Resonance Scattering of γ Rays in Crystals.
Uspekhi Fiz. Nauk., 72, 433 (1960)
12. Black, P. J. and Moon, P. B.
Resonant Scattering of the 14 kev Iron-57 γ -Ray, and its Interference
with Rayleigh Scattering
Nautre, 188, 481 (1960)
13. Boyle, A. J. F., Bunbury, D. St. P., and Edwards, C.
Polarization of the Conduction Electrons in Ferromagnetic Metals
Phys. Rev. Letters, 5, 553 (1960)
14. Boyle, A. J., Bunbury, D. St. P., Edwards, C. and Hall, H. E.
The Mossbauer Effect in Tin from 120° K to the Melting Point
Proc. Phys. Soc. (London), 77, 124 (1961)
15. Bradley, J. E. S. and Marks, J.
Method of Measuring the Mossbauer Effect
Nature, 192, 1176 (1961)
16. Bussiere de Nercy, A., Langevin, M. and Spighel, M.
Resonant Absorption of γ Radiation Without Recoil from the Nuclei of
Ho¹⁶⁶ and Os¹⁹³
J. Phys. Radium, 21, 288 (1960)
17. Champeney, D. C. and Moon, P. B.
Absence of Doppler Shift from Gamma Ray Source and Detector on
Same Circular Orbit
Proc. Phys. Soc. (London), 77, 350 (1961)
18. Clark, M. A. and Robson, J. M.
Nuclear Resonant Absorption in Fe⁵⁷
Bull. Am. Phys. Soc., 5, 369 (1960)
19. Cocconi, G. and Salpeter, E. E.
Upper Limit for the Anisotropy of Inertia from the Mossbauer Effect
Phys. Rev. Letters, 4, 176 (1960)

20. Cordey - Hayes, M., Dyson, N. A. and Moon, P. B.
Width and Intensity of the Mossbauer Line in Fe^{57}
Proc. Phys. Soc. (London), 75, 810 (1960)
21. Cotton, E.
Emission and Absorption of Gamma Radiation Without Recoil from
an Emitter Nucleus Fixed in a Crystalline Lattice
J. Phys. Radium, 21, 265 (1960)
22. Cotton, E.
The Mossbauer Effect and its Applications
Nucleus (Paris), No. 3, 174 (1960)
23. Cotton, E., Gastebois, J. and Picou, J. L.
Research on the Recoilless γ Emission Following Coulomb Excitation
of Fe^{57}
J. Phys. Radium, 22, 538 (1961)
(note: 136 kev level)
24. Craig, P. P., Dash, J. G., McGuire, A. D., Nagle, D. E. and
Reiswig, R. R.
Nuclear Resonance Absorption of Gamma Rays in Ir^{191}
Phys. Rev. Letters, 3, 221 (1959)
25. Craig, P. P., Nagle, O. E., and Cochran, D. R. F.
Zeeman Effect in the Recoilless γ -Ray Resonance of Zn^{67}
Phys. Rev. Letters, 4, 561 (1960)
26. Craig, P. P.
Experimental Aspects and Applications of the Mossbauer Effect
"Proceedings of the VIIth International Conference on Low Tem-
perature Physics." Graham and Hallet eds., U. of Toronto Press,
1961, p. 22
27. Cranshaw, T. E., Schiffer, J. P. and Whitehead, A. B.
Measurement of Gravitational Red Shift Using the Mossbauer Effect
in Fe^{57}
Phys. Rev. Letters, 4, 163 (1960)
28. Dash, J. G., Taylor, R. D., Craig, P. P., Nagle, D. E.,
Cochran, D. R. F. and Keller W. E.
Mossbauer Effect in Fe^{57} at Very Low Temperatures
Phys. Rev. Letters, 5, 152 (1960)

29. Dash, J. G., Taylor, R. D., Nagle, D. E., Craig, P. P., and Visscher, W. M.
Polarization of Co^{57} in Fe Metal
Phys. Rev. 122, 1116 (1961)
30. De Benedetti, S.
The Mossbauer Effect
Scientific American, 202, 72 (1960)
31. De Benedetti, S., Lang, G. and Ingalls, R.
Electric Quadrupole Splitting and the Nuclear Volume Effect in the Ions of Fe^{57}
Phys. Rev. Letters, 6, 60 (1961)
32. Delyagin, N. N., Shpinel, V. S., Bryukhanov, V. A. and Zvenglinskii, B.
Hyperfine Structure of Gamma Rays Produced by Quadrupole Interaction in a Crystal Lattice
JEPT, 12, 159 (1961) (Tr. in English)
33. Delyagin, N. N., Shpinel, V. S., Bryukhanov, V. A. and Zvenglinskii, B.
Nuclear Zeeman Effect in Sn^{119}
JETP, 39, 844 (1960)
34. Delyagin, N. N., Shpinel, V. S. and Bryukhanov, V. A.
Resonance Absorption of 23.8 kev γ -Quanta by Sn^{119} Nuclei in Crystals
JETP, 41, 1347 (1961)
35. De Pasquali, G., Frauenfelder, H., Margulies, S. and Peacock, R. N.
Nuclear Resonance Absorption and Nuclear Zeeman Effect in Fe^{57}
Phys. Rev. Letters, 4, 71 (1960)
36. Dicke, R. H.
The Effect of Collisions Upon the Doppler Width of Spectral Lines
Phys. Rev., 89, 472 (1953)
37. Dzhelepov, B. S.
Resonance Scattering of γ -Rays on Nuclei
Uspekhi Fiz. Nauk., 62, 3 (1957) (in Russian)
AEC-tr-3972 (p. 1-57) (In English)
38. Dzyub, I. P. and Lubchenko, A. F.
On the Theory of the Mossbauer Effect
Doklady, 6, 33 (1961) (Tr. in English)

39. Dzyub, I. P. and Lubchenko, A. F.
Emission, Absorption and Reabsorption of γ -Quanta by Impurity
Nuclei Present in a Solid Solution
Izvest. Akad. Nauk. S. S. S. R., Ser, Fiz., 25, 893 (1961)
40. Dzyub, I. P. and Lubchenko, A. F.
The Resonance Scattering of γ -Quanta by Nuclei Present in a Solid
Izvest. Akad. Nauk, S.S.S. R., Ser. Fiz., 25, 901 (1961)
41. Ewan G. T., Graham, R. L., and Geiger, U. S.
M 1/E2 Mixing Ratios in the Fe^{57} 14.41 keV γ -Transition
Nuclear Phys., 19, 221 (1960)
42. Felsner, G. and Rose, M. E.
Resonance Scattering of Linearly Polarized Gamma Rays on Nuclei
ORNL - 3042 (1961)
43. Frauenfelder, H. and Lustig, H. (eds)
Mossbauer Effect: Recoilless Emission and Absorption of Gamma
Rays
Proceedings of Meeting Held at U. of Ill., June 6, 1960
44. Frauenfelder, H., Cochran, D. R. F., Nagle, D. E., and Taylor, R. D.
Internal Conversion from Resonance Absorption
Nuovo cimento, 19, 183 (1961)
45. Gastebois, J. and Quidort, J.
Evidence of the Quadrupole Moment of the Nucleus of Iron-57
Compt. rend., 253, 1257 (1961)
46. Gelberg, A.
Anisotropy of Gamma Radiation in the Mossbauer Effect
JEPT, 14, 86 (Tr. in English)
47. Grodzins, L., and Genovese, F.
Experimental Investigation of Parity Conservation in the 14.4 keV
Gamma Transition in Fe^{57}
Phys. Rev., 121, 228 (1961)
48. Grodzins, L. and Phillips, E. A.
Measurements of the Refractive Index of Lucite by Recoilless
Resonance Absorption
Phys. Rev., 124, 774 (1961)

49. Hack, M. N. and Hamermesh, M.
Effect of Radiofrequency Resonance on the Natural Line Form
Nuovo cimento, 19, 546 (1961)
50. Hack, M. N.
Interference Effects of Radiofrequency Fields in Resonance
Radiation
Nuovo cimento, 22, 168 (1961)
51. Hamermesh, M.
Time Spectra of Filtered Resonance Radiation in Fe⁵⁷, II. Theory
ANL-6111, (1960)
52. Hamilton, W. D. and Sood, B. S.
The Resonant Scattering of Gamma Rays in Hf¹⁷⁷
Nuclear Physics, 27, 66 (1961)
53. Hanks, R. V.
Pressure Dependence of the Mossbauer Effect
Phys. Rev., 124, 1319 (1961)
54. Hanna, S. S., Holland, R. E., Lynch, F. F., and Perlow, G. J.
Time Spectra of Filtered Resonance Radiation of Fe⁵⁷. I. Experimental
ANL-6111, (1960)
55. Hanna, S. S., Heberle, J., Littlejohn, C., Perlow, G. J.,
Preston, R. S. and Vincent, D. H.
Observation on the Mossbauer Effect in Fe⁵⁷
Phys. Rev. Letters, 4, 28 (1960)
56. Hanna, S. S., Heberle, J., Littlejohn, C., Perlow, G. J.,
Preston, R. S., and Vincent, D. H.
Polarized Spectra and Hyperfine Structure in Fe⁵⁷
Phys. Rev. Letters, 4, 177 (1960)
57. Hanna, S. S., Heberle, J., Perlow, G. J., Preston, R. C. and
Vincent, D. H.
Direction of the Effective Magnetic Field at the Nucleus in Ferro-
magnetic Iron
Phys. Rev. Letters, 4, 513 (1960)

58. Hanna, S. S., Meyer-Schutzmeister, L., Preston, R. S. and Vincent, D. H.
Nuclear Zeeman Effect in Sn^{119}
Phys. Rev., 120, 2211 (1960)
59. Harris, S. M.
Quantum Mechanical Calculations of Mossbauer Transmission
(To be published - Phys. Rev. Letters)
60. Hay, H. J., Schiffer, J. P., Cranshaw, J. E. and Eglestaff, P. A.
Measurement of the Red Shift in an Accelerated System Using the Mossbauer Effect in Fe^{57}
Phys. Rev. Letters, 4, 165 (1960)
61. Holland, R. E., Lynch, F. J. Perlow, G. J. and Hanna, S. S.
Time Spectra of Filtered Resonance Radiation of Fe^{57}
Phys. Rev. Letters, 4, 181 (1960)
62. Holm, M. W.
Debye Characteristic Temperatures
AEC Res. and Dev. Report IDO-16399 (1957)
63. Homura, S. et al
Mossbauer Effect of the Intermetallic Compound UFe_2
J. Phys. Soc. Japan, 16, 1479 (1961)
64. Jackson, H. E., Bollinger, L. M., and Cote, R. E.
Capture of Slow Neutrons by Nuclei bound in Crystals
Phys. Rev. Letters, 6, 187 (1961)
65. Jho, S., Gupta, R. K., Devare, H. G., Pramila, G. C., and Srinivase Raghavan, R.
Recoilless Emission and Absorption of 26 kev γ -Ray of Dy^{161}
Nuovo cimento, 19, 682 (1961)
66. Johnson, G. E. Ridout, M. L. Cranshaw, T. E. and Madsen, P. E.
Hyperfine Field and Atomic Moment of Iron in Ferromagnetic Alloys.
Phys. Rev. Letters, 6, 450 (1961)
67. Josephson, B. D.
Temperature Dependent Shift of γ -Rays Emitted by a Solid
Phys. Rev. Letters, 4, 341 (1960)

68. Kagan, Yu
The Anisotropy of the Mossbauer Effect
Doklady Akad. Nauk. S. S. S. R., 140, 796 (1961)
69. Kaipov, D. A. and Shubnyi, Yu, K.
The Influence of the Nuclear Recoil Effects on the Cross Section
of γ -Ray Resonance Scattering of Ni^{60} Nuclei
JEPT, 39, 888 (1960)
70. Kistner, O. C. and Sunyar, A. W.
Evidence for Quadrupole Interaction of Fe^{57m} and Influence of
Chemical Binding on Nuclear Gamma-Ray Energy
Phys. Rev. Letters, 4, 412 (1960)
71. Kistner, O. C., Sunyar, A. W. and Swan, J. B.
Hyperfine Structure of the 24-kev Transition in Sn^{119}
Phys. Rev., 123, 179 (1961)
72. Kock, W. E.
The Mossbauer Radiation
Science, 131, 1588 (1960)
73. Kranendonk, J. Van
Theoretical Aspects of the Mossbauer Effect
"Proceedings of the VII th International Conference on Low
Temperature Physics."
Graham and Hallet eds., U. of Toronto Press, 1961, p. 9
74. Krause, I. Y. and Luders, G.
Nuclear Resonance Absorption Without a Recoil
Naturwiss., 47, 532 (1960)
75. Krivoglaz, M. A.
Effect of Diffusion on the Scattering of Neutrons and Photons by
Crystal Imperfections and on the Mossbauer Effect
JETP, 13, 1273 (1961). (Tr. in English)
76. Krivoglaz, M. A.
Width and Shape of Mossbauer Lines in Solid Solutions
JETP, 41, 765 (1961)
77. Lamb, W. E. Jr.
Capture of Neutrons by Atoms in a Crystal
Phys. Rev. 55, 190 (1939)

78. Lee, L. L., Meyer-Schutzmeister, L. Schiffer, J. P. and Vincent, D.
Nuclear Resonance Absorption of Gamma Rays at Low Temperatures
Phys. Rev. Letters, 3, 223 (1959)
79. Lipkin, H. J.
Some Simple Features of the Mossbauer Effect
Annals of Physics, 9, 332 (1960)
80. Lipkin, H. J.
Debye-Waller Factor in Mossbauer Interference Experiments
Phys. Rev., 123, 62, (1961)
81. Low, W.
The Effect of Relaxation Phenomena on Mossbauer Experiments
"Proceedings of the VII th International Conference on Low
Temperature Physics" Graham and Hallet eds., U. of Toronto Press,
1961, p. 20
82. Lustig, H.
The Mossbauer Effect
Am. J. of Phys., 29, 1 (1961)
83. Lynch, F. J., Holland, R. E. and Hamermesh, M.
Time Dependence of Resonantly Filtered x-Rays from Fe⁵⁷
Phys. Rev., 120, 513 (1960)
84. Lyubimov, V. A. and Alikhanov, A. I.
Magnetic Field Effect on the Resonance Absorption of γ Rays
Izvest. Akad. Nauk. S. S. S. R. der. Fiz., 24, 1076 (1960)
85. Maleev, S. V.
On the Use of the Mossbauer Effect for Studying localized Oscillations
of Atoms in Solids
JETP, 12, 617 (1961) (Tr. in English)
86. Maradudin, A. A., Flinn, P. A., and Rubs, S.
Velocity Shift of the Mossbauer Resonance
Phys. Rev. Letters (To be Published)
87. Margulies, S. and Ehrman, J. R.
Transmission and Line Broadening of Resonance Radiation Incident
on a Resonance Absorber
Nuclear Instr. and Methods, 12, 131 (1961)

88. Meyer-Schutzmeister, L., Preston, R. S. and Hanna, S. S.
Internal Magnetic Fields in Manganese-Tin Alloys
Phys. Rev., 122, 1717 (1961)
89. Miller, V. V.
An Accuracy of One Millionth of One Billionth - The Laboratory
Verification of the General Theory of Relativity
Priroda, 49, 7 (1960)
90. Moon, P. B.
Interference Between Rayleigh and Nuclear Resonant Scattering of
 γ -Rays.
Proc. Roy. Soc. (London), A263, 309 (1961)
91. Mossbauer, R. L.
Kernresonanzabsorption von Gammastrahlung in Ir¹⁹¹
Naturwiss., 45, 538 (1958)
92. Mossbauer, R. L.
Kernresonanzabsorption von Gammastrahlung in Ir¹⁹¹
Z. f. Naturforschung, 14a, 211 (1959)
93. Mossbauer, R. L.
Kernresonanzabsorption von Gammastrahlung in Ir¹⁹¹
Z. Physik., 151, 125 (1959)
94. Mossbauer, R. L. and Weidemann, W. H.
Kernresonanzabsorption nicht Dopplerverbreiteter Gammastrahlung
in Re¹⁸⁷
Z. Physik., 159, 33 (1960)
95. Mossbauer, R. L.
Nuclear Resonance Absorption of γ -Quanta in Solid Bodies Without
Recoil
Uspekhi, 3, 866 (1961) (Tr. in English)
96. Mossbauer, R. L., Staneek, R. W. and Weidemann, W. H.
Hyperfine Structure Splitting of Recoilless γ Lines
Z. Physik., 161, 388 (1961)
97. Nagle, D. E., Craig, P. P. and Keller, W. E.
Ultra High Resolution γ -Ray Resonance in Zn⁶⁷
Nature, 186, 707 (1960)

98. Nagle, D. E., Craig, P. P., Dash, J. G. and Reiswig, R. R.
Nuclear Resonance Fluorescence in Au¹⁹⁷
Phys. Rev. Letters, 4, 237 (1960)
99. Nagle, D. E., Frauenfelder, H., Taylor, R., Cochran, D. R. F.
and Mattias, B. T.
Temperature Dependence of the Internal Field in Ferromagnets
Phys. Rev. Letters, 5, 364 (1960)
100. Obenshain, F. E. and Wegener, H. H. F.
Mossbauer Effect with Ni⁶¹
Phys. Rev., 121, 1344 (1961)
101. Ofer, S., Avivi, P., Bauminger, R., Marinow, J. and Cohen, S. G.
Nuclear Resonance Absorption in Dy¹⁶¹ Situated in Dy₂O₃ and
Dysprosium Iron Garnet
Phys. Rev., 120, 406 (1960)
102. Perlow, G. J., Hanna, S. S., Hamermesh, M., Littlejohn, C.,
Vincent, D. H., Preston, R. S. and Heberle, J.
Polarization of Nuclear Resonance Radiation in Ferromagnetic Fe⁵⁷
Phys. Rev. Letters, 4, 74 (1960)
103. Pomerance, H. S.
Recoilless Gamma Emission
ORNL - 3213, p. 141
(note: resonant absorption of 77 kev γ of Au¹⁹⁷)
104. Pound, R. V. and Rebka, G. A. Jr.
Gravitational Red-Shift in Nuclear Resonance
Phys. Rev. Letters, 3, 439 (1959)
105. Pound, R. V. and Rebka, G. A. Jr.
Resonant Absorption of the 14.4 kev γ -Ray from 0.10 μ sec Fe⁵⁷
Phys. Rev. Letters, 3, 554 (1959)
106. Pound, R. V. and Rebka, G. A. Jr.
Variation with Temperature of the Energy of Recoil-Free γ -Ray
from Solids
Phys. Rev. Letters, 4, 274 (1960)
107. Pound, R. V. and Rebka, G. A. Jr.
Apparent Weight of Photons
Phys. Rev. Letters, 4, 337 (1960)

108. Pound, R. V. and Rebka, G. A. Jr.
Attempts to Detect Resonance Scattering in Zn^{67} ; the Effect of Zero Point Vibrations
Phys. Rev. Letters, 4, 397 (1960)
109. Pound, R. V., Benedek, G. B. And Drever, R.
Effect of Hydrostatic Compression on the Energy of the 14.4 keV Gamma Ray From Fe^{57} in Iron.
Phys. Rev. Letters, 7, 405 (1961)
110. Effect of an External Field on the Nuclear Resonance of the Nucleus of Iron-57 in a Local Field of Yttrium Iron Garnets
Compt. rend. 252, 1442 (1961)
111. Ruby, S. L. and Bolef, D. I.
Acoustically Modulated γ -Rays from Fe^{57}
Phys. Rev. Letters, 5, 5 (1960)
112. Ruby, S. L. and Sun, K. H.
Mossbauer Effect in Ferrocyanide
Rev. Sci. Instr., 31, 580 (1960)
113. Ruby, S. L. and Hicks, J. M.
Line Shape in Mossbauer Spectroscopy
Rev. Sci. Instr., 33, 27 (1962)
114. Ruderfer, M.
First-Order Terrestrial Ether Drift
Experiment Using the Mossbauer Radiation
Phys. Rev. Letters, 5, 191 (1960)
115. Schiffer, J. P. and Marshall, W.
Recoilless Resonance Absorption of Gamma Rays in Fe^{57}
Phys. Rev. Letters, 3, 556 (1959)
116. Shapiro, F. L.
The Mossbauer Effect
Uspekhi., 3, 881 (1961) (Tr. in English)
117. Sherwin, C. W., Frauenfelder, H., Garwin, E. L., Luscher, E., Margulies, S. and Peacock, R. N.
A Search for the Anisotropy of Inertia Using the Mossbauer Effect in Fe^{57}
Phys. Rev. Letters, 4, 399 (1960)

118. Sherwin, C. W.
Some Recent Experimental Tests of the "Clock Paradox"
Phys. Rev., 120, 17 (1960)
119. Singwi, K. S. and Sjolander, A.
Resonance Absorption of Nuclear γ -Rays and the Dynamics of Atomic Motions
Phys. Rev., 120, 1093 (1960)
120. Sklyarevskii, V. V., Samoilov, B. N. and Stepanov, E. P.
Temperature Dependence of Hyperfine Splitting of Dy^{161} Levels in Paramagnetic Dysprosium Oxide
JETP, 13, 1316 (1961) (Tr. in English)
121. Solomon, I.
Mossbauer Effect in Pyrites and Marcassite
Compt. rend., 250, 3828 (1960)
122. Sood, B. S.
Resonance Scattering of Gamma Rays
"Proceedings of the Symposium on Low Energy Nuclear Physics.", 1961, Bombay, India p. 64
123. Sood, B. S.
Recoil-Free Resonance Scattering of 14.4 keV Gamma Rays in Fe^{57}
"Proceedings of the Symposium on Low Energy Nuclear Physics", 1961, Bombay, India p. 109
124. Snyder, H. L. and Wick, G. C.
Broadening of the Mossbauer Line
Phys. Rev., 120, 128 (1960)
125. Taylor, R. D.
A Low Temperature Thermometer Utilizing the Mossbauer Effect
TID-12627, Los Alamos Sci. Lab., 1961
126. Trammel, G. T.
Gamma-Ray Diffraction by Resonant Nuclei
"Chemical Effect of Nuclear Transformations. Vol. I", Vienna, IAEA Agency, 1961, p. 75
127. Tseng, P. K., Shikazono, N., Takekoshi, H. and Shoji, T.
Temperature Dependence of Nuclear Resonance Absorption Line Width in Dy^{161}
J. of Phys. Soc. of Japan, 16, 1790 (1961)

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

128. Tzara, C. and Barloutaud, R.
Recoilless Rayleigh Scattering in Solids
Phys. Rev. Letters, 4, 405 (1960)
129. Tzara, C.
Sur l'Excitation Résonante de Niveaux Nucleaires Métastables de
Vie Très Longue
Compt. rend., 250, 1466 (1960)
130. Visscher, W. M.
Neutrino Detection by Resonance Absorption in Crystals at Low
Temperatures
Phys. Rev., 116, 1581 (1959)
131. Visscher, W. M.
Study of Lattice Vibrations by Resonance Absorption of Nuclear
Gamma Rays
Annals of Physics, 9, 194 (1960)
132. Walker, L. R., Wertheim, G. K. and Jaccarino, V.
Interpretation of the Fe^{57} Isomer Shift
Phys. Rev. Letters, 6, 98 (1961)
133. Wertheim, G. K.
Measurement of Local Fields at Impurity Fe^{57} Atoms Using the
Mossbauer Effect
Phys. Rev. Letters, 4, 403 (1960)
134. Wertheim, G. K.
Mossbauer Effect: Applications to Magnetism
J. Appl. Phys., 32, No. 3, Suppl., 1105 (1961)
135. Wertheim, G. K.
Hyperfine Structure of Fe^{57} in Paramagnetic and Antiferromagnetic
 FeF_2 From the Mossbauer Effect
Phys. Rev., 121, 63 (1961)
136. Wertheim, G. K. and Wernick, J. H.
 Fe^{57} Mossbauer Effect in Cu-Ni Alloys
Phys. Rev., 123, 755 (1961)
137. Wertheim, G. K.
Hyperfine Structure of Divalent and Trivalent Fe^{57} in Cobalt Oxide
Phys. Rev., 124, 764 (1961)

138. Wu, C. C. , Lee, Y. K. , Benczer-Koller, N. and Simms, P.
Frequency Distribution of Resonance Line Versus Delay Time
Phys. Rev. Letters, 5, 432 (1960)