The work described in this thesis involves the Mössbauer effect in a precision experiment, which was conducted in a search for a preferred frame of reference. The experiment, sensitive to anisotropies in the propagation of light, is a direct test of the fundamental postulates of the special theory of relativity and the Lorentz transformation. The limit set on effects arising from a preferred frame of reference, or a classical aether, is $2.0 \pm 5.2 \text{ cm/sec}$ which represents the most sensitive test of the theory.

Chapter I gives a short account of the "Aether Drift" experiment and resonance fluorescence. Those aspects of the Mössbauer effect of interest for the experiment are described in Chapter II, and Chapter III deals with the practical problems of analyzing the transmission profile and obtaining narrow line width.

Chapter IV discusses the significance of the present experiment and gives also an account of the experiments previously conducted using the Mössbauer effect and those that preceded this experiment.

The design and operation of the ultracentrifuge are described in Chapter V, which also gives a semiquantitative analysis of the magnetic suspension and acceleration mechanisms. Chapter VI describes the characteristics of the sources and absorbers used, the development of the proportional counters, and the response of the counting electronics under high counting rates. The statistical behaviour of the data are analyzed in detail, and future improvements are discussed.
ACKNOWLEDGEMENTS

The author would like to express his gratitude to Professor P. B. Moon and Dr. G. R. Isaak for their interest, support, and valuable guidance during the course of the work reported in this thesis.

The work was performed in collaboration with Dr. G. R. Isaak and Dr. J. H. Broadhurst. During the author's stay at the University of Birmingham, he enjoyed the help of many members of the department and would like to express his special gratitude to Mr. D. B. Smart for machining the rotor structure, Mr. J. B. Saul for machining the rotor, Mr. D. Newton for making the proportional counters and assisting with modifications to the rotor structure, Mr. L. Terry for building the battery charger and the electronic gates for the kicksorter, Mr. F. W. Jukes for preparing the photographs, and Miss E. B. Smith for the careful typing of this thesis.

He is also grateful for the valuable advice received from Mr. G. H. Guest and Mr. J. Harling during the building of the rotor structure and from Dr. J. H. Broadhurst in developing some of the electronic circuitry. Special thanks are due to his father, Mr. F. K. Preikschat, who provided the preliminary circuits for the magnetic suspension of the rotor and who also provided several operational amplifiers at a time when they were not yet available in this country.

Finally he would like to thank Dr. G. R. Isaak and Dr. Ś. Isaak for their friendly assistance throughout his stay and is grateful to his fiancé for her great moral support during the preparation of this thesis.
## TABLE OF CONTENTS

### SYNOPSIS

### ACKNOWLEDGEMENTS

### CHAPTER I  INTRODUCTION

1. The Theory of Relativity and the Search for a Preferred Frame of Reference ....... 1-1
2. Resonance Fluorescence....................................................................................... 1-4

### CHAPTER II  THE MÖSSBAUER EFFECT

1. Cross-section ......................................................................................................... 2-1
2. Lattice Binding........................................................................................................ 2-2
3. Debye-Waller Factor .............................................................................................. 2-4
4. Transmission Line Width........................................................................................ 2-8
5. Isomeric Shift ......................................................................................................... 2-8
6. Electric Quadrupole Splitting ................................................................................ 2-10
7. Magnetic Hyperfine Splitting................................................................................. 2-12
8. Thermal Shift........................................................................................................ 2-14
9. Pressure Effects................................................................................................... 2-15
10. Relaxation Effects ................................................................................................ 2-16

### CHAPTER III  EXPERIMENTAL PARAMETERS OF THE MÖSSBAUER EFFECT

1. Sources and Absorbers.......................................................................................... 3-1
2. Transmission Spectra ............................................................................................ 3-3
   2.1 Background Correction..................................................................................... 3-4
   2.2 Resonance Dip.................................................................................................. 3-4
   2.3 Transmission Line Width ............................................................................. 3-5
   2.4 Shift ............................................................................................................ 3-5
3. Transmission Intensity ...........................................................................................3-6
  3.1 Unbroadened Emission and Absorption Lines.............................................3-6
  3.2 Broadened Lines ......................................................................................... 3-8
  3.3 Lorentz Broadened Lines .......................................................................... 3-12

4. Recoilless Fraction ...............................................................................................3-14

CHAPTER IV THE THEORY OF RELATIVITY

1. Introduction ............................................................................................................ 4-1
2. The Lorentz Transformation ...................................................................................4-1
3. Time Dilatation and the Doppler Effect ...............................................................4-4
4. The Aether Drift Experiment ................................................................................4-8
  4.1 Historical Considerations .............................................................................4-8
  4.2 Theory of the "Aether Drift" Experiment ..................................................... 4-11
  4.3 Past Experiments ......................................................................................4-16

CHAPTER V BUILDING OF THE ULTRACENTRIFUGE

1. Introduction ............................................................................................................ 5-1
2. Rotor Structure .......................................................................................................5-2
3. Magnetic Suspension .............................................................................................5-5
  3.1 General Considerations ................................................................................5-6
  3.2 Core Material .............................................................................................5-11
  3.3 The Electromagnet .....................................................................................5-11
  3.4 Suspension Servo Mechanism ..................................................................5-11
  3.5 Filament Safety Features ..........................................................................5-17
4. Monitoring the Operation of the Rotor ................................................................. 5-17
5. Damping and Positioning of the Rotor ................................................................. 5-18
6. The Rotor ............................................................................................................. 5-21
  6.1 Shape ........................................................................................................5-21
  6.2 Rotor Material ............................................................................................5-23
  6.3 Machining of the Rotor ..............................................................................5-24
CHAPTER VI  THE AETHER DRIFT EXPERIMENT AND ASSOCIATED MEASUREMENTS

1. Introduction ............................................................................................................ 6-1
2. Preparation of the Mössbauer Source and Absorber .............................................6-2
3. Gamma-ray Detector............................................................................................6-14
   3.1 Proportional Counter Response ................................................................6-18
   3.2 Efficiency of the Proportional Counter .......................................................6-20
4. Counter Electronics and Saturation Effects..........................................................6-21
5. Principle of Operation...........................................................................................6-25
6. Kicksorter Accumulation.......................................................................................6-27
7. Dead Time Effects................................................................................................6-28
8. Alignment and Stability.........................................................................................6-34
9. Data Display.........................................................................................................6-37
10. Running Time.......................................................................................................6-39
11. Data Analysis ......................................................................................................6-40
12. Future Improvements ...........................................................................................6-51
13. Discussion............................................................................................................6-54
14. Emission Theories of Light Propagation...............................................................6-58

REFERENCES
CHAPTER I

INTRODUCTION

1. The Theory of Relativity and the Search for a Preferred Frame of Reference.

Considering the amount of new information obtained in the physical sciences in recent years, it does not appear that we are near exhausting the wealth of nature; in fact, the more accurate and extensive experiments one has conducted, the more one has become aware of the underlying complexities of physical phenomena. The recent discoveries of Quasars and Pulsars have played their part in opening our eyes to the mystery of the world around us.

The special theory of relativity stands in interesting contrast. Its basic postulates have stood unchallenged ever since they were first conceived by Einstein in 1905, and even though they have frequently been questioned, there has been no evidence to suggest a possible limitation of the theory in its given framework.

The theory maintains that all inertial frames of reference are equivalent and that in such frames the velocity of light is a universal constant independent of the velocity of the source or the observer. That such should be the case is a remarkable finding if one considers the theory in its full implication. As Bondi (1962) has pointed out, there is, cosmologically speaking, in contrast to the theory, a preferred frame of reference determined by the "fixed" stars. Travel relative to that frame would be readily detectable by observing the colour of the sky. The stars in the direction of motion would be blue shifted while those behind
would be red shifted, giving a direct indication of the state of motion. It has been pointed out (Isaak, 1965) that it is even possible in principle to detect such motion by measuring the angular dependent energy distribution of the neutrino flux. It would not be possible, in the spirit of an Einstein Gedanken-experiment, to build a completely self-enclosed laboratory by shielding against the neutrino flux, as the mass needed to do so would give rise to spontaneous gravitational collapse.

Hence, when discussing a laboratory experiment, one cannot ignore the influence of the rest of the universe. This is further brought out by considering the nature of gravitational and inertial forces. Newton would have considered inertial forces strictly in terms of an acceleration of the laboratory relative to absolute space. Today, through the efforts of Mach (1904) (Sciama, 1953; Dicke, 1960) one considers such forces in terms of a retarded gravitational interaction with distant matter; i.e., the 'accelerated' distant matter is thought of as generating a gravitational wave which interacts with the laboratory.

From this point of view one could expect the results of experiments carried out in the local frame to be affected by the matter distribution of the universe and to be varying with time and the relative velocity of the earth frame.

Considering then the aether drift experiments, as first conducted by Michelson and Morley, one detects a change in emphasis. Whereas the first experiments tried to resolve the question of the existence of a classical aether, the recent ones have attempted to discover an anisotropic interaction between local and distant matter observable in the local frame. As these experiments are
direct tests of the fundamental postulates of the special theory, they are also the most accurate test of Lorentz invariance.

The aether drift experiments can be divided into two categories, those that measure the light speed over a return path and are sensitive only to second order terms in v/c, and those that are sensitive to first order terms in v/c. The most accurate one of the former type is the experiment conducted by Jaseja, et al. (1964) which put a limit of 1km/sec on the aether drift compared to the classically expected effect of 30 km/sec. The experiment conducted by Cedarholm and Townes (1958, 1959) was of the latter (first order) type and used two ammonia beam masers to establish a limit of 30 m/sec on any observed anisotropies in the light speed.

It was at this time that Mössbauer discovered the effect of recoilless emission and absorption of gamma rays, and in 1960 Ruderfer suggested using this effect with a potential sensitivity four orders of magnitude higher than the ammonia maser in an aether drift experiment. As the effect does involve nuclear and electromagnetic interactions as well as the propagation of electromagnetic radiation, it is potentially a very powerful test for the invariance of these mechanisms, all of which could be affected by a nonuniformity in the distribution of distant matter.

The aim of the aether drift experiment reported in this thesis is to fully exploit the inherent sensitivity of the Mössbauer effect and to try to achieve an experimental accuracy limited mainly by present day technology.
2. **Resonance Fluorescence.**

Resonance fluorescence was first observed in atomic systems by R. W. Wood. As this phenomenon depended on the quantization of the energy levels, a similar effect was expected for nuclear transitions involving gamma rays. Early experiments by Kuhn (1929) and others, however, were not successful in detecting such effects.

The difficulty of observing a gamma ray resonance can be appreciated if one considers the recoil imparted to the radiating system of mass \( M \) during the emission of one quantum of energy \( E_0 \). By conservation of momentum this recoil energy will be

\[
R = \frac{E_0^2}{2Mc^2}
\]

During the absorption of a similar quantum of energy, another recoil will be imparted to the absorbing system, such that the emission and absorption line will be separated by an energy \( 2R \). Whereas this recoil energy is negligible for atomic transitions, it is large enough for nuclear transitions to prevent an effective overlap of the emission and absorption lines.

In a gas or a weakly bound lattice, the lines will also be Doppler broadened because of the thermal motion of the radiators. Assuming a Maxwellian velocity distribution for the unbound atoms, the lines will have a Gaussian shape of width \( D = \frac{E_0}{c} \left( \frac{3kT}{M} \right)^{1/2} \). The full width of the emission and absorption lines will be the sum of the Gaussian component and the Lorentzian width \( \Gamma \), the latter being determined by the mean life \( \tau \) of the state \( \Gamma = \frac{\hbar}{\tau} \).
A number of techniques have been employed to either compensate for the recoil loss or to broaden the lines to increase the effective overlap. Moon (1951) used high speed rotors to Doppler shift the 411 kev gamma ray from $^{198}$Au ($\beta^-$ \rightarrow $^{198}$Hg) toward the absorption line, and was thus able to demonstrate an increase in the resonant scattering cross-section from which the mean life of the excited state could then be deduced.

Other methods include the heating of the source to broaden the emission line (Malmfors (1952)) and the utilization of the recoil from a previous nuclear decay or reaction (Ilakovac and Moon (1954), Metzger (1956)).

A breakthrough in the study of nuclear resonant fluorescence occurred when Mössbauer (1958) showed that under certain conditions gamma rays were emitted with a negligible recoil and the line unbroadened by the thermal motion of the atoms in a crystal. This effect became a useful research tool when it was found in 1959 that at room temperature 70% of the 14.4 kev gamma radiation from $^{57}$Fe occurred without recoil.
CHAPTER II

THE MÖSSBAUER EFFECT

1. Cross-section.

Under general assumptions the energy dependent cross-section for nuclear resonance processes can be expressed by (Breit and Wigner (1936), Kapur and Peierls (1938)).

\[ \sigma(E) = \frac{\sigma_o \Gamma^2}{4(E - E_o)^2 + \Gamma^2} \]

where for the case of gamma ray resonant absorption

\[ \sigma_o = \frac{\lambda^2 (2I_e + 1)}{2\pi (2I_g + 1)} \]

is the maximum absorption cross-section

- \( E_o \) the energy of the excited state
- \( \Gamma \) the natural width of the excited state
- \( I_e, I_g \) the spin of the excited and the ground state
- \( \lambda \) the wavelength of the gamma ray.

Usually the excited state can decay by several modes, the most predominant one for low lying states being the internal conversion process. The total width is then the sum of the partial widths; i.e.,

\[ \Gamma = \Gamma^\gamma + \sum_i \Gamma^\alpha_i = \Gamma^\gamma (1 + a) \]

where \( \Gamma^\gamma \) is the gamma ray partial width and “\( a \)” the internal conversion coefficient.
To get the final cross-section for absorption and scattering experiments \( \sigma(E) \) has to be modified depending on the number of emission processes occurring before final detection of the gamma ray; i.e., (Jackson, 1955)

\[
\sigma_{\text{abs}} = \frac{\Gamma_{\gamma}}{\Gamma} \sigma(E) \\
\sigma_{\text{scatt}} = \left( \frac{\Gamma_{\gamma}}{\Gamma} \right)^2 \sigma(E)
\]

The cross-section has a Lorentzian shape with the full width at half maximum equal to \( \Gamma \). In the case of hyperfine splitting (see Section 2.6, 2.7) each resolved line will exhibit this shape.

Similarly, the normalized source intensity can be expressed by

\[
I(E) = \frac{\Gamma}{2\pi} \frac{I}{(E - E_o)^2 + (\Gamma/2)^2}
\]

which is just the square of the Fourier analyzed time-dependent wave function of the photon.

2. **Lattice Binding.**

The amazing feature about the Mössbauer effect is not only that the emission and absorption of the gamma rays occur without recoil, but also that the line is not Doppler broadened and exhibits, under ideal conditions, the natural line width.

The essential aspect of the recoilless effect is readily explained if one considers the radiating nucleus as strongly bound in a crystal such that the momentum is taken up by the crystal as a whole. If, according to the Einstein
model of a solid, the recoil energy $R$ is small compared to that required to excite the lattice, the gamma ray will be emitted with the full transition energy $E_o$. (See next section.)

Classically (Shapiro (1961)) one obtains the unbroadened line by regarding the source atom as bounded in a harmonic oscillator potential such that during an emission of a quantum of frequency $\omega_o = E_o / \hbar$ the thermal vibrations of the atom in the lattice (of frequency $\Omega$) will modulate the source radiation. The resulting frequency spectrum will consist of the fundamental carrier frequency $\omega_c$ with side frequencies $\omega_c \pm n \Omega$, $n=1, 2, 3,\ldots$. The amplitude of the various components is given by the Bessel function $J_n\left(\frac{x_o \omega_o}{c}\right)$, where $x_o$ is the amplitude of oscillation of the atom. The intensity of the central component, which can be identified with the unshifted Mössbauer line is $f = J_o^2\left(\frac{x_o \omega_o}{c}\right)$ which, if generalized for a large number of lattice vibrations, can be expanded to give

$$f = \exp\left(-\frac{\langle x^2 \rangle}{\lambda^2}\right); \quad \lambda = \frac{c}{\omega_o}$$

$\langle x^2 \rangle$ is the mean square displacement of the nucleus about its equilibrium position. A similar factor is obtained for the absorption mechanism.

The implications of this result have been discussed by Frauenfelder (1962) and Nussbaum (1966) and in more general terms by Lipkin (1960). Even though the classical treatment does account for the unshifted line, it does not account for the shape of the phonon spectrum. In an actual solid the lattice
vibration spectrum is a continuum with the individual oscillators interacting with one another. Furthermore in a lattice containing different atoms, variations of the force constants between neighbouring atoms have to be considered.

3. **Debye-Waller Factor.**

The factor $f$ gives that fraction of the radiation which is emitted and absorbed without recoil. It is very similar to the Debye-Waller factor, known from X-ray diffraction work, which describes the temperature variation of the elastically scattered radiation intensity.

Both factors depend on the mean square displacement of the radiating system. To obtain $\langle x^2 \rangle$ one can assume, to a first approximation, that the crystal obeys the Debye model; i.e., that the frequency spectrum is described by the density function:

$$
\rho(\omega) = \frac{9N\omega^2}{\omega_D^3}
$$

normalized for the $3N$ possible modes of vibration, $N$ being the number of atoms in the crystal. $\omega_D$ is the maximum vibration frequency with the Debye temperature defined by $\Theta_D = \frac{\hbar \omega_D}{k_B}$.

In a harmonic potential each mode of oscillation $\omega_i$ has associated with it an energy

$$
3NM \omega_i^2 \langle x_i^2 \rangle = \hbar \omega_i \left( \frac{1}{e^{\hbar \omega_i / kT} - 1} + \frac{1}{2} \right) = \hbar \omega_i \left( n_i + \frac{1}{2} \right)
$$

Averaging over all of the frequencies one obtains:

Chapter 2-4
\[
\langle x^2 \rangle = \frac{6R}{h\omega_D^3} \int_0^{\omega_D} \left( \frac{1}{2} + n \right) \omega d\omega
\]

\[
= \frac{3R}{2k_b \Theta_D} \left[ 1 + 4 \left( \frac{T}{\Theta_D} \right)^2 \int_0^{\Theta_D/T} u du \right]
\]

This integral can be readily evaluated at the limit of low and high temperature

\[
f = \exp \left( -\frac{3R}{2k\Theta_D} \right) \text{ for } T << \Theta_D \quad \text{... 3.3a.}
\]

\[
f = \exp \left( -\frac{6RT}{k\Theta_D^2} \right) \text{ for } T >> \Theta_D \quad \text{... 3.3b.}
\]

Even though the integral in Equation 2.3.2 accounts for the predominant temperature dependence of \( f \), an additional factor arises because of the volume dependence of \( \Theta_D \) (Boyle, et al., 1961) which, for crystals with cubic symmetry, can be expressed through the Grüneisen constant \( \gamma = -\frac{\partial \ln \Theta_D}{\partial \ln V} \).

The effect of thermal expansion is then given by

\[
\frac{\partial \Theta_D}{\partial T}_P = \Theta_D \left( \frac{\partial \ln \Theta_D}{\partial \ln V} \right) \left( \frac{\partial \ln V}{\partial T} \right) = \Theta_D \gamma^2 KC_Y / V \quad \text{... 3.4.}
\]

where \( C_Y \) is the heat capacity per unit volume and \( K \) is the compressibility of the solid. Preston, et al., (1962) find that increasing the temperature of an iron lattice from room temperature to 1000°C decreases \( \Theta_D \) by about 100°K.

Changing the ambient pressure at the lattice has a similar effect on \( \Theta_D \).

\[
\frac{\partial \Theta_D}{\partial P}_T = \Theta_D \left( \frac{\partial \ln \Theta_D}{\partial \ln V} \right) \left( \frac{\partial \ln V}{\partial P} \right) = \Theta_D \gamma K \quad \text{... 3.5.}
\]
For iron \( \frac{\Delta \Theta_D}{\Theta_D} \sim 1.0 \times 10^{-6} \) per kg/cm\(^2\) and is therefore negligible for most purposes.

In the foregoing discussion, the characteristic lattice temperature has been assumed to be \( \Theta_D \). This is, however, not strictly the case, as can be readily seen by writing the integral for the heat capacity (Kittel, 1957):

\[
C_v = \frac{3h^2}{\omega^3 k_B T^2} \int_0^{\omega_D} \tilde{n}^2 \omega^4 \exp(\frac{\hbar \omega}{kT}) d\omega
\]

A comparison of this equation with Equation 2.3.2 shows that different weighting factors have been used in the two frequency integrals, so that the \( \Theta_D \) obtained from specific heat measurements does not necessarily represent the lattice temperature of interest for evaluating \( f \). Whereas \( C_v \) accentuates the high frequency part of the spectrum, Equation 2.3.2 puts more weight on the low frequency part.

In a realistic model one would also have to consider the effects of the acoustical and the optical vibration modes in a crystal, and, in the case of impurity atoms in a host lattice, the presence of localized modes. The acoustical modes have a broad frequency band that can be well approximated by the Debye model. The frequency spectra of the optical and the localized modes are more peaked and can be better represented by the Einstein model (Wertheim, 1964) for which

\[
f = \exp \left( - \frac{R}{k \Theta_E} \left( 3 - \frac{2\Theta_E}{T} \right) \right) \text{ for } T \ll \Theta_E
\]

Chapter 2-6
\[ = \exp \left( -\frac{2RT}{k\Theta_E^2} \right) \text{ for } T \gg \Theta_E \]

where \( \Theta_E = \frac{\hbar \omega_E}{k_B} \) and \( \omega_E \) is the Einstein frequency.

Comparing Equations 2.3.3 and 2.3.7 for \( \Theta_D = \Theta_E \) one finds that the latter gives a higher value for \( f \), a factor which is enhanced if \( \omega_E > \omega_D \) as would be expected for a lightweight impurity in a heavyweight lattice (Montroll and Potts, 1955).

Accurate measurements of the recoilless fraction have given considerable information about the properties of various crystal lattices. Boyle, et al., (1961) have shown that the temperature variation of \( f \) for the 24 keV radiation from \(^{119}\text{Sn}\) deviates from Equation 2.3.3, which they attribute to anharmonicities in the lattice potential.

The problem of an impurity atom in a host lattice has been treated by many authors and most recently by Mannheim and Simopolous (1968), who have detected the presence of localized vibration modes for iron in a Vanadium lattice. They have calculated and verified experimentally that an increase in the force constant at the impurity site gives rise to an increase in \( f \).

The above discussion is valid only for crystals with cubic symmetry. For lower symmetries one has to consider \( \langle x^2 \rangle \) along the various crystal axes as has been shown for the case of potassium ferrocyanide (Duerdoth 1964) where \( f \) exhibits an angular dependence.
In general, to obtain a high recoilless fraction, a host lattice with a high Debye temperature has to be selected, one in which impurity atoms are strongly bound in a localized position.

4. **Transmission Line Width.**

Ideally it should be possible to obtain an emission and absorption line of natural line width $\Gamma$ with a resulting transmission line width of $2\Gamma$. In practice, however, one needs a finite absorber thickness to obtain a sizeable resonance effect, which will appreciably broaden the transmission line. Also the various hyperfine interactions can produce a shifting or splitting of the line which, when unresolved, can cause additional broadening. These effects are generally well understood and are described below.

5. **Isomeric Shift.**

The isomeric shift was first observed by Kistner and Sunyar (1960) and results from the difference in the chemical environments at the source and absorber nuclei. The nucleus having a finite radius $R$ will interact electrostatically with the electron charge density at the nucleus $e|\psi(0)|^2$. This Coulomb interaction relative to that experienced by a point nucleus is $\frac{2\pi}{5} Z e^2 |\psi(0)|^2 R^2$. If the charge radii $R_{\text{ex}}$, $R_{\text{gr}}$ of the excited and the ground state of the nucleus are different, a change in the gamma ray transition energy will result, which is

$$\delta E = \frac{2\pi}{5} Z e^2 |\psi(0)|^2 \left( R_{\text{ex}}^2 - R_{\text{gr}}^2 \right)$$

Chapter 2-8
A relative shift between the emission and the absorption line will then occur if the chemical environments in the source and the absorber are different; i.e., if the respective electron charge densities at the nucleus \( e|\psi_s(0)|^2 \) and \( e|\psi_a(0)|^2 \) are different. This shift is

\[
\Delta E_{IS} = \delta E_a - \delta E_s = \frac{2\pi}{5} Ze^2 \left( |\psi_a(0)|^2 - |\psi_s(0)|^2 \right) \left( R_{ex}^2 - R_{gr}^2 \right)
\]

and is analogous to the isotope shift observed in atomic transitions (Breit, 1958).

Only this relative shift is directly measurable and has been studied in detail for \( ^{57}\text{Fe}, ^{119}\text{Sn}, \) and \( ^{197}\text{Au} \). For the 14.4 kev level in \( ^{57}\text{Fe} \), it was found (Walker, et al., 1961) that a decrease in the electron charge density produced an increase in the gamma ray transition energy from which it can be concluded that \( R_{gr} \) is larger than \( R_{ex} \).

Table 1 shows the shifts that have been generally observed for iron in the various host lattices. A positive shift corresponds to a decrease (increase) in the source (absorber) transition energy.

No full explanation, which accounts quantitatively for the observed shifts, has as yet been given. Some attempts have, however, been made for the transition metals by correlating the shifts with the filling of the d-shells (Qaim, 1967) taking into consideration the effect of the shielding of the 3s by the 3d electrons (Walker, et al., 1961; Ingalls, 1967).
Table 2.1

<table>
<thead>
<tr>
<th>Source Lattice</th>
<th>Crystal Structure</th>
<th>( f_s ) 1)</th>
<th>( \Theta_D ) 2)</th>
<th>( \Delta E_{IS} ) (mm/sec) 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhodium</td>
<td>f.c.c.</td>
<td>.70</td>
<td>350</td>
<td>-.114</td>
</tr>
<tr>
<td>Copper</td>
<td>&quot;</td>
<td>.61</td>
<td>340</td>
<td>-.226</td>
</tr>
<tr>
<td>Palladium</td>
<td>&quot;</td>
<td>.55</td>
<td>275</td>
<td>-.185</td>
</tr>
<tr>
<td>Platinum</td>
<td>&quot;</td>
<td>.53</td>
<td>230</td>
<td>-.347</td>
</tr>
<tr>
<td>Gold</td>
<td>&quot;</td>
<td>.37</td>
<td>165</td>
<td>-.632</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>b.c.c.</td>
<td>.64</td>
<td>425</td>
<td>-0.60</td>
</tr>
<tr>
<td>Chromium</td>
<td>&quot;</td>
<td>.60</td>
<td>400</td>
<td>+.152</td>
</tr>
<tr>
<td>Tungsten</td>
<td>&quot;</td>
<td>.52</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>Tantalum</td>
<td>&quot;</td>
<td>.52</td>
<td>230</td>
<td>-.033</td>
</tr>
</tbody>
</table>

1) Values obtained by Quaim (1965). For the case of Rh, Pd the values are quoted for the sources used.

2) Obtained from specific heat measurements (Kittel, 1957).

3) Shift quoted relative to natural iron (Mössbauer Data Index, 1966).


In the previous section the nucleus was assumed to be spherical and the charge distribution uniform. More generally, nuclei that have a spin \( I \neq 0, \frac{1}{2} \) will
exhibit an electric quadrupole moment $eQ$, which, in the presence of a local electric field gradient, will split the line. If this gradient is axially symmetrical about the crystal z-axis, the energy splitting will be given by (Abragam, 1961).

$$\Delta E_q = \frac{e^2 q Q}{4I(2I-1)} \left( 3m_i^2 - I(I+1) \right)$$

where $e_q = \frac{\partial^2 V}{\partial z^2}$ and $I,m$ are the spin quantum numbers of the particular nuclear level. The substates $\pm m_i$ will be degenerate and in fact will remain so even in the presence of an axially non-symmetrical field gradient if $I$ is half integral. In the latter case Equation 2.6.1 will be modified by an asymmetry parameter.

For $^{57}$Fe with $I_{gr} = \frac{I}{2}$ and $I_{ex} = \frac{3}{2}$, the ground state is spherical, and any quadrupole splitting will only be due to the excited state. Because of the double degeneracy of the four substates $\pm \frac{I}{2}, \pm \frac{3}{2}$ a doublet will result.

The electric field gradient will vanish in a lattice of cubic symmetry like that of natural iron and many of the other transition metals. In other substances like FeF$_2$ (Wertheim, 1961) a splitting is observed that can be readily resolved. In the ferro cyanides the quadrupole splitting cannot be resolved and is only deduced from the broadened transmission line. As the intensity of the two components in the doublet varies, depending on the angle $\theta$ between the crystal z-axis and the direction of emission (absorption) of the gamma ray, the unresolved splitting will appear as an angle dependent shift of the transmission line (Evans, 1968). The angular dependence of the intensity of the two components is characterized by
the classical radiation pattern for $\Delta m = 0,1$ and is given by (Wertheim, 1964) (see next section)

$$\frac{3}{2} \left( 1 + \cos^2 \theta \right) \quad \text{for} \ \Delta m = \pm 1$$

$$1 + \frac{3}{2} \sin^2 \theta \quad \text{for} \ \Delta m = 0$$

... 6.2.

The ratio of the two intensities varies from 3 for $\theta = 0^\circ$ to $3/5$ for $\theta = 90^\circ$. For a polycrystal the intensities will be equal unless the recoilless fraction should also be angle dependent as is the case for potassium ferrocyanide.

7. **Magnetic Hyperfine Splitting.**

The interaction between the nuclear magnetic dipole moment $\mu$ and the magnetic field at the nucleus $H$ will produce a splitting of each nuclear level into $2I + 1$ components. Each substate $m_i$, where $m_i$ takes on the values $I, I-1, ..., -I$, will be shifted by an amount

$$\Delta E_{m_i} = -g\mu_n H m_i$$

where $g$ is the nuclear gyromagnetic ratio, and $\mu_n$ the nuclear magneton $\frac{e\hbar}{2m_e c}$ equal to $3.15 \times 10^{-12}$ eV/gauss. As the various components are equally spaced and for ferromagnetic substances like iron easily resolved, it becomes easy to measure the relative transition probabilities between given substates, as calculated by squaring the corresponding Clebsch Gordon coefficients, and the radiation pattern relative to the direction of the magnetic field. For a pure multipole transition the angular dependence of the individual components is given by $\left| X_{Lm} (\theta, \psi) \right|^2$, where $L$ is the angular momentum carried off by the
gamma ray and $\theta$ is the angle between the direction of the magnetic field and that of the emission (absorption) of the gamma rays. $|X_{\ell m}(\theta, \psi)|^2$ is the vector spherical harmonic (Jackson, 1963).

For the MI transition of $^{57}$Fe (14.4 kev) the angular dependent intensity of the various transitions is given by

$$\frac{3}{2}(1 + \cos^2 \theta) \quad \text{for } \pm \frac{3}{2} \rightarrow \pm \frac{1}{2} (\Delta m = \mp 1)$$

$$2 \sin^2 \theta \quad \text{for } \pm \frac{1}{2} \rightarrow \pm \frac{1}{2} (\Delta m = 0)$$

$$\frac{1}{2}(1 + \cos^2 \theta) \quad \text{for } \pm \frac{1}{2} \rightarrow \mp \frac{1}{2} (\Delta m = \mp 1)$$

For an unmagnetized ferromagnetic material, the intensity of the three components will be in the ratio 3:2:1. Often one finds, however, that thin foils are preferentially magnetized in the plane of the foil, which tends to increase the intensity of the $\pm \frac{1}{2} \rightarrow \pm \frac{1}{2}$ transition, while saturation effects, arising from the thickness of the absorber, tend to reduce the outer components.

Given the knowledge of the nuclear magnetic moment of the ground state of, for instance, $^{57}$Fe (0.0902 nm) one can readily deduce the magnetic moment of the excited state (0.155 nm) and the effective field $H_{\text{eff}}$ at the nucleus. The magnetic hyperfine structure has been used extensively for that purpose and also to determine the sign of $H_{\text{eff}}$. For iron at room temperature $H_{\text{eff}}$ is $-330\text{kG}$, and the resulting energy splitting can be used as a convenient standard (Preston, et al., 1962).

Experiments conducted with Co-Pd and Fe-Pd alloys of varying concentrations have indicated (Clogston, et al., 1962) that the palladium atoms
take part in the magnetic coupling so that quite small concentrations of a ferromagnetic metal, like 0.5% of iron, can produce ferromagnetism in the alloy. No such effect has been observed for rhodium alloys.

8. **Thermal Shift.**

Pound and Rebka (1960) and Josephson (1960) have pointed out that gamma rays emitted without recoil are still affected by the mean square velocity \( \langle v_s^2 \rangle \), \( \langle v_a^2 \rangle \) of the nuclei in the source and absorber, respectively, which gives rise to an energy shift

\[
\frac{\Delta E_{ab}}{E} = \frac{1}{2c^2} \left( \langle v_s^2 \rangle - \langle v_a^2 \rangle \right)
\]

This shift can be explained in terms of the relativistic second order Doppler shift or as being due to the resulting change in mass of the nucleus during the emission or absorption of a gamma quantum. Both views appear to be equivalent.

When the source and the absorber are both at the same temperature, the corresponding shifts occurring during the emission and absorption processes will compensate each other. Expressing this shift as a function of the net temperature difference between that of the absorber and the source, one obtains

\[
\frac{1}{E} \frac{\partial E}{\partial T} = -\frac{1}{2c^2} \frac{\partial}{\partial T} \langle v^2 \rangle
\]

which for a monatomic solid with harmonic lattice forces becomes

\[
\frac{1}{E} \frac{\partial E}{\partial T} = -\frac{1}{2Mc^2} \frac{\partial U}{\partial T} = -\frac{C_p}{2c^2}
\]
where $U$ is the lattice energy per atom (of mass $M$) and $C_p$ is the specific heat of the lattice.

For iron at room temperature the total temperature shift observed was $(-2.09 \pm 0.05) \times 10^{-15}$ per °K (Pound, et al., 1961). It consists of the contribution of the second order Doppler shift $(-2.24 \times 10^{-15}$ per °K) and a correction factor due to the temperature dependent contribution of the isomer shift arising from the thermal expansion of the lattice.

The second order Doppler shift has also recently been used to establish the presence of localized vibrational modes for dilute iron impurities in a vanadium lattice and to detect changes in the force constant between the iron and neighbouring atoms (Mannheim and Simopolous, 1968).

9. **Pressure Effects.**

An increase in the ambient pressure at the source and the absorber not only increases the recoilless fraction of both, but it also affects the isomeric and the thermal shifts. Pound, et al., (1961) have given the relative contribution of each as

$$\frac{1}{E} \left( \frac{\partial E}{\partial P} \right)_T = \frac{1}{E} \left( \frac{\partial E_{is}}{\partial \ln V} \right) \left( \frac{\partial \ln V}{\partial P} \right) - \frac{1}{E} \left( \frac{\partial E_{th}}{\partial \ln V} \right) \left( \frac{\partial \ln V}{\partial P} \right)$$

$$= -aK \left( \frac{\partial |\psi(0)|^2}{\partial \ln V} \right)_T - \frac{3}{20} \frac{k_B \Theta_p^2 r K}{Mc^2 T}$$

where $a$ is the proportionality constant relating the isomeric shift with $|\psi(0)|^2$.

The first contribution is the predominant one ($\sim 95\%$) and has been attributed by
the above authors as being due to a change of the 4s electron density $|\psi_{4s}(0)|^2$.

This effect has been examined in more detail for the transition metals (Ingalls, et al., 1967). It was found that the above conclusion by Pound, et al., is not necessarily accurate for some of the metals like Fe, Ti, and Cu, where, most likely, the 3s electron density $|\psi_{3s}(0)|^2$ is affected by the shielding of the outer d electrons giving rise to a small additional volume dependence. The observed pressure induced shifts vary from $1.5 \times 10^{-4}$ mm/sec per kbar pressure for platinum to $6.4 \times 10^{-4}$ mm/sec per kbar for iron and vanadium, with $3.1 \times 10^{-4}$ mm/sec per kbar for palladium. This indicates that the pressures reached with the ultracentrifuge ($\sim 10$ kbar) can be neglected.

10. Relaxation Effects.

So far only time independent hyperfine interactions have been discussed. Generally one would also expect time dependent ones to exist. They may arise from effects associated with the excitation of the Mössbauer level or from others involving electronic relaxations.

Transients, as occur when the nucleus is perturbed by a previous nuclear transition or reaction, can leave the atom in different charge states. If the time needed for the atom to return to its equilibrium charge state is comparable with the nuclear life time, the emission spectrum will exhibit the shifts and/or splittings representative of the various charge states present. This has been observed for $^{57}$Co (E.C.$\rightarrow^{57}$Fe) in Co(NH$_4$SO$_4$)$_2$.6H$_2$O where the emission spectrum could be decomposed into two shifted and quadrupole split lines due to Fe$^{++}$ and Fe$^{+++}$.
(Ingalls and De Pasquali, 1965). It would also be reasonable to expect that the perturbations occurring during the creation of the Mössbauer level could decrease the effective $f_S$. No effect, however, using Pd and Cu lattices has been found (Craig, et al., 1964).

Recently paramagnetic hyperfine interactions have been investigated for a number of substances (Wickman, et al., 1966; Lang and Marshall, 1966) where relaxation effects arise because of spin-spin or spin-lattice interactions. Usually these effects are only substantial at low temperatures when the relaxation times are larger than the Larmor precession period of the nucleus, though for a few special cases, like the Fe-Pd alloys, they might still have to be considered at room temperature.
CHAPTER III
EXPERIMENTAL PARAMETERS OF THE MÖSSBAUER EFFECT

1. Sources and Absorbers.

Even though some of the Mössbauer candidates have a potentially narrower line than $^{57}$Fe, the latter is still the best source for precision experiments as it not only exhibits near natural line widths, but has also a large recoilless fraction at room temperature depending on the host lattice used.

The ideal host lattice would have a cubic symmetry and be diamagnetic with the impurity atoms tightly bound at equivalent lattice sites. This would ensure that there would be no quadrupole or magnetic splitting and that the isomeric shift would be constant.

Even if such materials were available for various Mössbauer nuclei, the practical problem of ensuring uniform conditions throughout the lattice and incorporating the source and absorber at equivalent sites remains. Taking the example of a natural iron foil absorber, which comes nearest to exhibiting a natural line width (Kerler, et al., 1962; Housley, et al., 1964), one can broaden the observed line width by as much as $\Gamma$ by introducing dislocations and imperfections in the absorber foil (Abou-Elnasr, 1968). The line width can then be brought back to its original value by annealing the absorber for several hours in a reducing atmosphere, which would eliminate the strain in the foil and reduce the imperfections.

Using various transition metals as the host lattice for the source and a sodium ferrocyanide absorber, line widths have been obtained that range from
.28 mm/sec to .60 mm/sec (Qaim, 1965) with Pd and Cu giving the narrowest lines. Also the metals with a f.c.c. structure give generally a narrower line than those with a b.c.c. symmetry. This illustrates that the impurity atoms are better incorporated in some metals than in others, even though the crystal structure may be the same. In these studies no recipe has been found for obtaining narrow source and absorber lines. This does not of course preclude the possibility of finding some host material that does give rise to natural line width for the other narrow line Mössbauer sources.

The potential competitors to $^{57}\text{Fe}$ are $^{73}\text{Ge}$ (13.5 keV) and $^{181}\text{Ta}$ (6.25 keV), where both, because of the small transition energy, should have a recoilless fraction comparable to or larger than that of $^{57}\text{Fe}$. The problem with $^{73}\text{Ge}$ is that it has a large internal conversion coefficient, $\alpha \sim 1300$ (Czjzek, et al., 1965) so that no effect has as yet been observed, and in any case, the large internal conversion coefficient would severely limit the practical use of the line in high precision experiments.

$^{181}\text{Ta}$ is a more hopeful possibility. A 5% resonant effect has been observed (Steyert, et al., 1965) but the resultant line width was 1.0 mm/sec instead of the expected .007 mm/sec. This excessive broadening was attributed to quadrupole splitting arising from the very large electric quadrupole moment of the nucleus where the resulting sensitivity to electric field gradients is $\sim 700$ times larger than it is for $^{57}\text{Fe}$.

For the present work $^{57}\text{Fe}$ was used throughout. To obtain the highest sensitivity, the source and absorber had to satisfy several criteria:
(i) large recoilless fraction,
(ii) unsplit line of near natural width,
(iii) optimum shift between source and absorber,
(iv) small electronic absorption,
(v) optimum absorber thickness.

The following sections discuss the problem of measuring and optimizing some of these parameters.

2. Transmission Spectra.

For large resonance effects a transmission geometry is most suitable, as it utilizes most of the source radiation. A transmission spectrum is then obtained by correlating the number of gamma rays detected with the Doppler velocity used to scan the emission line over the absorption line (or vice versa). The resonance will show up as a dip in the transmission spectrum, which is referred to as negative detection.

An alternative method is to detect the associated X-rays or electrons produced by the internal conversion process in $\frac{a}{1+a}$ of the gamma rays absorbed. This is known as positive detection because the counting rate at resonance will be increased. The relative merit of each system depends on the detection geometry, the source strength, and the detector used.

A kick sorter with 128 channels and a double Goodman's vibrator were used to obtain the velocity spectra. The motion device and associated equipment have been described previously (Isaak, 1965). As the vibrator could
be fed with a variety of velocity waveforms, the system allowed for a ready
determination of the resonance dip, line width, shift, and background.

2.1 Background Correction.

Even though the resolution of the detector, in this case usually a
proportional counter, is of the order of 15% the degraded high energy gamma
rays usually still contribute around 20% to the counting rate under the 14.4 keV
peak. This contribution can be accurately determined by measuring the residual
counting rate after interposing a 1/8" aluminum sheet in the source beam, which
effectively eliminates the low energy gamma rays and reduces the high energy
gamma rays by a known amount.

2.2 Resonance Dip.

For an unshifted line the resonance dip $R_m$ is determined by comparing the
counting rates at resonance $\hat{N}(0)$ and off resonance $\hat{N}(\infty)$ corrected for the
background counting rate $\hat{N}_{BG}$.

$$R_m = \frac{\hat{N}(\infty) - \hat{N}(0)}{\hat{N}(\infty) - \hat{N}_{BG}}$$

$\hat{N}(\infty)$ was obtained using a square wave to drive the source at a few mm/sec. In
the presence of a shift, the relative counting rates were most readily determined
from the full transmission spectrum.
2.3 **Transmission Line Width.**

To economize on the accumulation time, the velocity of the vibrator is best adjusted to sweep over ~ 4 transmission line widths. Then correcting the counting rate at the wings to obtain the true off-resonance counting rate, a correction at the 2% level (see Section 3.3), one can directly determine the full line width at half the minimum $\Gamma_{\text{exp}}$.

To calibrate the width, another spectrum is taken with an iron absorber where the inner two lines are split by 1.667 mm/sec.

2.4 **Shift.**

Two methods are available to measure the shift, depending on the desired accuracy. The shift can be deduced from the transmission spectrum knowing the channel corresponding to zero velocity. That channel is found by taking another spectrum in which the velocity of the vibrator has been reversed.

A more accurate measurement of the shift can be made if one concentrates on 3 (or 4) points of the resonance line to improve the statistical accuracy of each. Then if the normalized accumulated counts at velocities $V_1, V_2, V_3$ are $N_1, N_2, N_3$ the shift will be (Wilson, 1966)

\[
\Delta E(\text{mm/sec}) = \frac{1}{2} \left( V_1 + V_2 + \frac{N_1 - N_2}{N_3 - N_2} (V_3 - V_2) \right)
\]

with \( \sigma^2(V) = \frac{(V_3 - V_2)^2}{4(N_3 - N_2)^4} \left[ (N_3 - N_2)^2 \hat{N}_1 + (N_3 - N_1)^2 \hat{N}_2 + (N_1 - N_2)^2 \hat{N}_3 \right] \)
where $V_1$ lies on one side of the steepest part of the resonance and $V_2$ and $V_3$ on the other.

3. **Transmission Intensity.**

A number of authors have investigated the problem of how the absorption line width is affected by the thickness of the source and absorber. Margulies, et al., and more recently Heberle (1968) have studied the case of unbroadened source and absorber lines, and O'Connor (1963) has treated the case of Lorentz broadened lines.

3.1 **Unbroadened Emission and Absorption Lines $\Gamma_s, \Gamma_a$.**

The source radiation consists of a fraction $f_S$ emitted without recoil, which is subject to nuclear and electronic absorption, and the remaining fraction emitted with recoil attenuated only by electronic absorption. For an unsplit thin source; i.e., one that does not exhibit self-absorption, the emitted intensity is:

$$I(E')dE = I_s(E')dE + I_r(E')dE$$

$$= \frac{f_s\Gamma dE}{2\pi \left[ (E' - E_s)^2 + \left( \frac{\Gamma}{2} \right)^2 \right]} + \frac{(1 - f_s)dE}{kT}$$

... 3.1

where $E' = E + S$ and $S$ is the first order Doppler shift $\frac{vE_s}{c}$. The first term represents the unshifted natural line, and the second term is an approximate expression for the thermally broadened line where both contributions are normalized to unity.
The absorption cross-section per unit thickness of absorber will exhibit a similar dependence

\[
\sigma(E) = \frac{\sigma_o n f_a \Gamma^2}{4 \left[ (E - E_o)^2 + \left( \Gamma/2 \right)^2 \right]} + \sigma_e = \sigma_o(E) + \sigma_e
\]  

... 3.2

where \( n \) is the number of resonant nuclei per unit thickness, \( f_a \) is the recoilless fraction of the absorber, \( \sigma_o \) is the peak absorption cross-section, and \( \sigma_e \) denotes the electronic absorption cross-section. The resulting intensity using an unsplit absorber of thickness \( t \) will be:

\[
N(E') = (1 - f_s) e^{-t\sigma_e} + e^{-t\sigma_e} \int_{-\infty}^{\infty} I_{\infty}(E') e^{-t\sigma_o(E')} dE'
\]  

... 3.3

This expression can be correlated with the experimentally determined \( R_m \) value by defining

\[
R(S) = \frac{N(\infty) - N(E')}{N(\infty)} = f_s (1 - \int I_{\infty}(E') e^{-t\sigma_o(E')} dE')
\]  

... 3.4

For \( E' = E_o \), this becomes

\[
R(0, T_a) = f_s (1 - e^{-T_a; j \left( \frac{i T_a}{2} \right)})
\]  

... 3.5

where \( T_a = n f_a \sigma_o = N f_a \sigma_o \)

Expression 3.3.4 has been evaluated numerically assuming that the transmission spectrum is Lorentzian (Boyle and Hall, 1962)

\[
R(S, T_a) = \frac{R(0, T_a)}{1 + (2S/\Gamma)^2} \quad \text{for} \quad 0 < T_a < 5
\]  

... 3.6

where

Chapter 3-7
\[ \Gamma_r(T_a) = 2\Gamma(1 + 0.135T_a) \quad \text{(Visscher 1961)} \]

\( R(S,T_a) \) and \( \Gamma_r(T_a) \) are shown in Figures 3.1 and 3.2, and the resulting slope at the points of inflection \( E = E_a \pm \frac{\Gamma_r}{2\sqrt{3}} \) is shown in Figure 3.3. One can see that the optimum thickness is around \( T_a \sim 4 \), when the slope of the spectrum is steepest, assuming minimum \( \mu_c \) and background.

### 3.2 Broadened Lines

In general both the emission and the absorption line will be broadened by amounts differing from one source-absorber combination to another. As the broadening of the source and absorber lines are folded into the transmission spectrum, it is in general very difficult to separate the individual contributions, especially as it is not known a priori if the broadening is of Lorentzian or of Gaussian character or possibly even of some other shape.

The difficulty arises from the fact that the convolution integral of two Lorentzians is different from that for two Gaussian functions. Equation 3.3.4 for \( T_a << 1 \) is essentially such an integral. Calculating the convolution integral using two Lorentzian lines of width \( w_1 \) and \( w_2 \), and similarly, two Gaussian lines of same width, the resulting width will be for the two cases:

\[
\begin{align*}
w_k &= w_1 + w_2 \\
w_G &= (w_1^2 + w_2^2)^{1/2}
\end{align*}
\]
FIGURE 3.1

FIGURE 3.2
i.e., the Gaussian lines will not be broadened to the same extent as the Lorentzian will be. Margulies, et al., (1963) have calculated $R(S, T_a)$ and $\Gamma_r(T_a)$ for the case where both the emission and the absorption lines are pure Gaussian functions (see Figures 3.1, 3.2). The broadening is then much smaller, and the resonance dip, for a given value of absorber thickness, is much larger because of the preferential absorption at the centre of the emission line.

In general of course both these ideal cases are unrealistic, as in a practical situation, one would expect the lines to consist of a Gaussian
distribution of Lorentzians. Such a line profile could be expresses by a Voigt integral (Posener, 1959)

\[
H = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{e^{-u^2}}{1 + (u - x)^2} \, dx
\]

where \( u = \frac{(E - E_0)}{\Gamma/2} \) and \( \frac{1}{a} = \frac{\Gamma_G}{(\ln 2)^{1/2} \Gamma} \) expresses the Gaussian broadening. \( \Gamma_G \) is the width of the Gaussian distribution. The convolution integral of two such integrals gives another Voigt integral, which represents the transmission spectrum for the case of a thin absorber.

Because of the admixture of Lorentzian and Gaussian components, the resulting broadening \( w \) of the line width would be \( w_G \lesssim w \lesssim w_L \) and in practice not enough parameters are available to extract the relative components without some simplifying assumptions.

One approach is to separate the transmission spectrum into its Lorentzian and Gaussian components and then to try to correlate the latter with either the source or the absorber parameters by, for example, increasing the thickness of a given absorber using the same source (Evans, 1968) or changing the source keeping the absorber parameters constant. In some cases one might find that the Gaussian contribution is predominantly due to either source or absorber. One can then subtract the Gaussian contribution and unfold the source-absorber lines in terms of Lorentzian widths.

Intuitively speaking, if the broadening is due to differences in the local environments, one might expect the resulting changes in the shifts and splittings
to exhibit a Gaussian shape and furthermore expect them to be larger for substances where iron has been added as an impurity than for those where iron is chemically bonded, as in the case of the ferrocyanides. This has indeed been found when a 10 mCi $^{57}$Co (Pd) source, one of the rotor sources later to be described, was used in conjunction with a sodium ferrocyanide absorber of varying thickness (Evans, 1968).

3.3 Lorentz Broadened Lines.

O'Connor (1963) has derived the transmission spectrum for the case when the emission and absorption lines are both Lorentz broadened by amounts $1/k_s$ and $1/k_a$, respectively. This approach could be used to treat some of the broadening mechanisms as a first approximation. As the calculation does give the resonance dip $R^i(O, T_a^{-1})$ and the line width $\Gamma_a^{-1}(T_a)$ as a function of $k_s$ and $k_a$, the relationship between the various parameters emerges quite clearly.

Using a Lorentz approximation to expand the exponential in Equation 3.3.4, the resonance dip is given by

$$R^i(0, T_a^{-1}) = \frac{(1 + k)R(0, T_a^{-1})}{1 + k k_a / k_s}$$

where $T_a^{-1} = k_a T_a$ and $k$ is a parameter expressing the broadening due to the absorber thickness. $R^i(0, T_a^{-1})$ is shown in Figure 3.4 for the values $k / k_a = 0.5, 1.0, 1.5$. 

Chapter 3-12
The transmission line width $\Gamma^1$ is found by evaluating the total transmission line shape

$$\Gamma^1 = \Gamma\left(\frac{1}{k_s} + \frac{1}{k_a}\right) + 0.27\Gamma T_a \text{ for } 0 < T_a < 5$$

This result reduces readily to the previous one (Equation 3.3.7) and gives surprisingly the same absorber broadening, even though the emission and the absorption lines have different widths than before.

Using the above two expressions for $R^1$ and $\Gamma^1$, one can readily determine how the slope at the points of inflection of the resonance depends on the broadening of the individual lines. As the slope varies as $R^1/\Gamma^1$, one can keep $\Gamma^1$ constant ($\Gamma^1 = 5\Gamma$) and then plot $R^1(k_s, k_a, T_a)$ as a function of either $k_s$ or $k_a$ as shown in Figure 3.4. The solid lines show those values of $R^1$ where $k_a$ is held constant and the dotted lines show those for constant $k_s$. As one might have expected, the largest value of $R^1$ occurs for $k_s = 1.0$ and decreases appreciably for increased source broadening, i.e., decreasing $k_s$. The resonance dip, however, does not depend very strongly on the broadening of the absorber line. For $k_s = 0.8$ and $k_a$ varying from 1.0 to 0.6 $R^1$ changes only by 2%.

Using these general criteria, one finds that, in order to obtain the largest possible slope, one must maximize $f_s$ and $k_s$ and choose values of $k_a T_a \sim 4$. 

Chapter 3-13
4. **Recoilless Fraction.**

Several methods are available to measure the relative recoilless fraction of the source and absorber. An absolute measurement is more difficult, as it involves measuring a change in the beam intensity. Ideally one would need an absorber with unit absorption efficiency over the whole of the transmission line. An absorber made of a suitable combination of fluoroferrates best satisfies such criteria (Housley, et al., 1964) and gives $f_s$ directly by measuring $R_m$ after applying several corrections. The first accounts for the residual transmission at the centre of the absorption line and can be deduced by measuring the change in
\( R_m \) using a double black absorber. \( \frac{\Delta R_m}{R_m} \) is of the order of 2\%. The second correction compensates for the residual transmission at the wings and is less than 1\% for \( \Gamma_a \sim 20\Gamma \). An alternative correction method involves taking a transmission spectrum for both a single and a double black absorber, where the areas under the absorption peak, normalized to unit off-resonance-transmission, are \( A_1 \) and \( A_2 \), respectively. This gives (Duerdoth, 1965)

\[
f_s = R_m \sqrt{\left[ 1 - (1 - R_m) \frac{A_2}{A_1} \right]}
\]

This correction method is more accurate than the above, because it does not rely upon the knowledge of the line shapes of the source and absorber. It is, however, also more laborious.

Once the absolute value of \( f_s \) for one source is known, that for all others can be directly found by using an identical absorber and determining the areas under the absorption peak, where then;

\[
f_s^1 = f_s \frac{A^1}{A}
\]

Similarly knowing \( f_s \) and \( A \) for a thin absorber, one can determine \( f_o \). The area under the absorption peak is

\[
A = \int \sigma_0 \left( 1 - e^{-\sigma_0(E)} \right) dE
\]

and does not depend on the detailed shape of the emission line. This integral can be simply evaluated for the case of \( Nf_o \sigma_o \ll 1 \) when
\[ A = \frac{\pi}{2} N \sigma_a f_a f_a \Gamma \]

Thus, for this special case, one can immediately obtain \( f_a \). For greater thicknesses one has to evaluate the integral including higher order terms for the expansion of the exponential.

Another method for finding \( f_a \) relies upon the assumptions made in Section 3.3.3. One can then deduce \( f_a \) from the slope of \( \Gamma_r(T_a) \) given by Equation 3.3.9.
1. **Introduction.**

The Mössbauer effect involves the theory of relativity in several ways. The thermal shift (see Section 2.8) has been variously described in terms of the special theory. The gravitational red shift experiment demonstrates the equivalence of mass and energy and involves the general theory of relativity. The rotor experiment described in this thesis is subject to relativistic time dilatation and is a most accurate test of the fundamental postulates of the special theory. As the thermal shift and the time dilatation observed in the rotor experiment can be considered using arguments arising from both the special and the general theory, they also demonstrate the cohesive overlap of the two theories.

2. **The Lorentz Transformation.**

Before Michelson and Morley conducted the first aether drift experiment in 1887, it had generally been assumed that electromagnetic waves propagated with the speed of light $c$ relative to a fundamental aether considered to be at rest in respect to Newtonian absolute space. This view was further substantiated by early experiments on the aberration of star light (Bradley, 1728; Airy, 1871; Lodge, 1892), which demonstrated that the aether was not carried along by the earth. According to the classical concepts, Maxwell's equations were form invariant under a set of Galilean transformations.
The failure to detect the classical aether did produce a dilemma, as it became impossible to unify Maxwell's equations with Newtonian kinematics. Even though Fitzgerald (1890) and Lorentz (1895) could explain the null result of the experiment by postulating that bodies moving with velocity \( v \), relative to the absolute frame, are contracted by 
\[
\left(1 - \frac{v^2}{c^2}\right)^{1/2}
\]
in the direction of motion, the dilemma was not resolved until 1904 when Lorentz showed that under a particular set of transformations, now named after its originator, Maxwell's equations stayed form-invariant. Lorentz did try to interpret the contraction phenomenon physically, but did not realize the underlying significance of the transformations.

It was left to Einstein (1905) to show the fundamental significance of the transformations. Starting from a critical analysis of the measuring process, he was able to derive the transformation properties from the two fundamental postulates:

i. That the laws of physics are the same or invariant in all inertial frames of reference, and

ii. That the speed of light (in vacuum) is a constant independent of the inertial reference system used or the state of motion of the source or the observer.

This approach in conjunction with the work of Poincare and Minkowski provides a most consistent and general framework for relating physical phenomena as observed in different inertial frames of reference. Using the 4-vector notation, the Lorentz transformation from frame \( X \) to \( X^1 \), the latter moving with velocity \( v \) relative to \( X \), is described by
\[ x^1_\mu = \sum_{\lambda=1}^{4} a_{\mu \lambda} x_\lambda \]  

where \( x = (x_1, x_2, x_3, ict) \) are the four coordinates of frame \( X \), and similarly, \( x^1 \) are the coordinates of \( X^1 \). For the case of \( v \) being parallel to \( x_1 \)

\[
a_{\mu \lambda} = \begin{bmatrix}
\gamma & 0 & 0 & \nu \gamma \beta \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
-\nu \gamma \beta & 0 & 0 & \gamma \\
\end{bmatrix} \]

with \( \beta = v/c \) and \( \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2} \)

In accordance then with the first postulate, all laws of physics are covariant under a Lorentz transformation. This means that scalar quantities are Lorentz invariant, 4-vectors transform in accordance with Equation 4.2.1 and tensors like

\[
F^1_{\mu \nu} = \sum_{\lambda, \sigma=1}^{4} a_{\lambda \mu} a_{\nu \sigma} F_{\lambda \sigma}
\]

where in particular \( F_{\lambda \sigma} \) is the electromagnetic field strength tensor and gives the transformation properties of the electric and the magnetic field.

The Lorentz transformation has thus become the basis of all of relativistic mechanics, and it would appear desirable to test its general validity as accurately as is possible today. The Michelson-Morley experiment gave the original impetus for the two postulates, and it can also be regarded as the most direct test of the transformation. Other more indirect experiments test the consequences of the Lorentz transformation and have in recent years most strikingly verified the predictions of the special theory of relativity.
3. **Time Dilatation and the Doppler Effect.**

According to the Lorentz transformation, the time \( t \) measured in a moving frame is slowed down by a factor \( \gamma \) in comparison with the time measured in a stationary frame. A number of experiments have been conducted to compare the life time \( \tau \) of unstable particles, pions and muons, moving at relativistic speeds with the life time of these particles at rest (Rossi, et al., 1941; Durbin, et al., 1952; Frisch and Smith, 1963). They have established the time dilatation factor to within 10%. The most convincing experiment is that by Farley, et al., (1967) in which the decay of muons in a storage ring was directly monitored as a function of time. They found that

\[
\frac{\tau^D}{\tau} = 25.15 \pm 0.03
\]

is in satisfactory agreement with \( \gamma = 26.72 \).

In the above experiments time dilatation is measured directly, whereas in experiments involving the propagation of electromagnetic radiation, the dilatation factor can be deduced from the modified Doppler shift formula. Because of the Lorentz invariance of the phase of an electromagnetic wave, with wave number \( k \) and frequency \( \nu \), the relativistic Doppler shift can be obtained directly by transforming the phase

\[
k_{\mu}x_{\mu} = \sum_{i=1}^{3} k_i x_i - 2\pi \nu t
\]

from the stationary to the moving frame. An observer moving with velocity \( \mathbf{v} \) relative to the source of radiation will then measure a frequency

\[
\nu' = \nu \gamma \left( 1 - \frac{\hat{n} \cdot \mathbf{v}}{c} \right)
\]

where \( \hat{n} \) is the unit vector in the direction of wave propagation. This Doppler shift is in essence the classical Doppler shift modified by the dilatation factor. For
\[ \hat{n} \cdot v = 0 \] the time dilatation factor emerges directly. It has been observed by Ives and Stilwell (1938, 1941) when they measured the frequency of the \( H_\beta \) lines emitted by \( H_2 \) ions moving at relativistic speeds \( (\beta = 0.005) \). An improved version of this experiment (Mandelberg and Witten, 1962) confirmed the expected result to an accuracy of 5%.

A similar effect has been observed using the Mössbauer effect with the source and the absorber mounted on a high-speed rotor. Generalizing Equation 4.2.3 for the case where both the source and the absorber are in motion relative to the laboratory frame, the frequencies \( \nu, \nu' \) of the emitted and the received radiation are related by (Lee and Ma, 1962)

\[
\frac{\nu'}{\nu} = \frac{\gamma_a (1 - \hat{n} \cdot U_a / c)}{\gamma_s (1 - \hat{n} \cdot U_s / c)} = 1 + \frac{(U_a^2 - U_s^2)}{2c^2} \quad \text{for } \hat{n} \cdot (U_a - U_s) = 0
\]

where the energy shift between source and absorber can be expressed by

\[
\frac{\Delta \nu}{\nu} = \frac{\nu_a - \nu_s}{\nu_s} = \frac{\omega^2}{2c^2} (r_s^2 - r_a^2)
\]

\( U_s, U_a \) are the velocities of the source and the absorber relative to the laboratory frame of reference. \( r_s, r_a \) are their respective radial distances from the axes of rotation, and \( \omega \) is the angular velocity of the rotor.

The first experiment of this kind was performed by Hay, et al., (1960) using a \(^{57}\text{Co} \text{(in Fe)} \) source and iron absorber. Later experiments (Hay, 1961; Champeney, et al., 1963) utilized the isomeric shift to verify the sign of the relativistic shift and confirmed its magnitude to within 2%. Kündig (1963) in a
similar experiment Doppler-shifted the source line to observe the whole transmission spectrum and reached an accuracy of 1.1%.

The thermal shift (see Section 2.8) can also be considered in terms of the transverse Doppler shift. As the characteristic frequencies of the atom in the lattice are $10^{12} \text{ sec}^{-1}$, the terms $\hat{n} \cdot \mathbf{U}_x$, $\hat{n} \cdot \mathbf{U}_y$ averaged over the lifetime of the nucleus will be zero so that only the second order shift will remain.

A discussion of time dilatation invariably involves the problem of the clock paradox, which arises when considering the reciprocity of time measured in two different inertial frames of reference. The authoritative approach to time dilatation is to regard it as an absolute phenomenon, i.e., not a consequence of the measuring process, as has been suggested by Essen (1957, 1964) and one that can't be traced back to simpler phenomena (Møller, 1952). The problem of reconciling the one-sided time dilatation with the reciprocity of its observation during an out and return journey is then solved by invoking general relativistic arguments (Born, 1924; Tolman, 1934). This view is contested by Dingle (1961, 1967) who maintains that STR, which refutes the existence of an absolute frame of reference, cannot give rise to absolute effects associated with relative motion. It has been suggested (Lord Halsbury, Bondi, 1957) that the clock paradox can be treated without invoking the aspect of acceleration by using three inertial frames of reference in motion along a straight line and such an analysis does give the same result as that obtained using general relativity.

Sherwin (1960) maintains that the thermal shift observed with the Mössbauer effect does satisfy the conditions of an out and return journey and so
confirms Einstein’s predictions. The shift caused by thermal vibrations of the $^{57}\text{Fe}$ nuclei involves non-uniform motion as well as large accelerations of the order of $10^{16}\text{g}$.

This consistent overlap of the special and the general theory is well brought out by considering the quadratic shift in terms of the scalar gravitational potential at the source and the observer (Pauli, 1958). Two clocks at rest relative to one another but located at different gravitational potentials $\chi_a$, $\chi_s$ are related in frequency by (Møller, 1957)

$$\frac{\nu_a}{\nu_s} = \left(\frac{1 + 2\chi_a / c^2}{1 + 2\chi_s / c^2}\right)^{1/2} = 1 + \frac{\chi_a - \chi_s}{c^2}$$

... 2.5

They will differ in frequency by an amount directly proportional to the difference in their respective gravitational potentials.

The scalar gravitational potential at the surface of the earth produces an energy shift of $1.1 \times 10^{-16}$ per meter difference in the vertical height. This gravitational red shift has been observed by Cranshaw, et al., (1960); Pound and Rebka (1960); Cranshaw and Schiffer (1964); and Pound and Snider (1964) with standard deviations of 50%, 10%, 10%, and 1%, respectively.

By employing the equivalence principle, which states that effects arising from gravitational attraction are locally indistinguishable from those arising from acceleration, one can extend the interpretation of $\chi$ to include potential differences arising from centifugal forces, in which case one obtains
\[
\frac{\Delta v}{v} = \frac{Z_a - Z_s}{c^2} = \frac{\omega^2}{2c^2} \left( r_s^2 - r_a^2 \right)
\]
a result equivalent to Equation 4.2.4.

4. The Aether Drift Experiment.

4.1 Historical Considerations.

Einstein developed his theory in the context of an empty space, devoid of any structure and without the need of an absolute frame of reference. Partly as a result of his later work and that of Mach one regards space today as having a distinct structure determined by the distribution and the relative velocities of matter in the universe. That light is affected by this structure has been established by the gravitational red shift experiments; that it propagates in an inertial frame of reference is seen from the Sagnac experiment (Sagnac, 1913). In the latter experiment two light beams were sent in opposite near circular optical paths and then brought to interference. Upon rotating the whole apparatus with angular velocity \( \omega \), a fringe shift proportional to \( \omega \) was observed, from which one can conclude that light does not partake in the motion of the apparatus. Instead, it propagates in an inertial frame of reference in direct analogy with the Foucault pendulum.

These considerations about the nature of light propagation have recently led a number of authors to reconsider the ideas of Lorentz (Builder, 1958; Janossy, 1962, 1964, 1965; Prokhovnik, 1967). Bondi (1962) has pointed out that, cosmologically speaking, there is a preferred frame of reference and that motion relative to it can be readily determined by measuring the Doppler-shifted spectral...
lines of the stars. The problem of light propagation thus links the special theory of relativity with Cosmology. To understand the nature of light propagation, one must be able to link the two fields by resolving the question of the need for a preferred frame of reference. Does motion relative to the cosmologically preferred frame affect the propagation of light?

This question is unequivocally answered by the special theory, but because the theory does not involve the nature and the effects of the inertial forces experienced by one inertial frame moving relative to another, the question has continued to occupy a number of scientists and still today gives rise to some controversy regarding the interpretation of the special theory of relativity (Prokhovnik, 1967).

Ives (1948) has examined the problem of measuring the velocity of light, in an inertial frame of reference moving with velocity \( V \) relative to the cosmological frame. There are in principle two ways of measuring the light velocity. One is to measure it over a return path (Einstein's method, 1905) which has the advantage of using only one timing clock but the disadvantage that it measures only the average velocity. The other method is to conduct a one-way measurement, which, as Ives shows, does depend on the method used to synchronize the two timing clocks, but is independent of the velocity \( V \). This is because the rods and clocks, which are in essence used to measure the light velocity, are equally affected by the relativistic factor \( \gamma \). He was thus able to show the equivalence of the special theory and the Fitzgerald Lorentz contraction theory in a local frame of reference. Ives' work has been extended by Robertson (1949) and Builder (1958). Robertson
has shown that Einstein's basic postulates can be deduced from the three basic experiments of (i) Michelson and Morley, (ii) Kennedy and Thorndike (see Section 4.3.3), and (iii) Ives and Stilwell and in fact can be replaced by the assumptions that there exists a fundamental frame of reference and that bodies moving relative to such a frame are contracted by the relativistic factor (Builder, 1958). The phenomenon of time dilatation is then deduced using Einstein's measuring conventions (Builder, 1960) and the relativistic predictions are considered as consequences of the Lorentz transformation. The validity of Einstein's basic postulates can then be inferred from experiments where the one-way velocity of light is measured in an inertial frame as a function of the velocity of the source or the observer, and also as a function of $V$, the velocity of the inertial frame relative to the cosmological frame.

These considerations led Ruderfer (1960) to propose the present aether drift experiment, as it essentially represented such a measurement. It was thought that the experiment might be able to distinguish between the two viewpoints (Møller, 1962) but a more careful analysis (Ruderfer, 1961) showed that both theories give rise to the same prediction of a null result.

It is interesting to note that some of the basic questions regarding the interpretation of the relativistic phenomena still appear not to have been resolved and continue to give rise to controversy. This does demonstrate the need to conduct more accurate experiments that are sensitive to higher-order effects, as is the present experiment.
Prokhovnik (1967) examines the logical consequences of the differing interpretations and comes to the comforting conclusion that it is possible to conceal a physical model for the universe which does accommodate both viewpoints and where in fact both approaches are valid descriptions of different facets of the universe. The approach of the STR does represent the very fundamentality of the relativistic concept in modern physics, and the neo-Lorentzian viewpoint does shed more light on the cosmological problem.

4.2 Theory of the Aether Drift Experiment.

Following the line of argument of classical physics, one would regard light propagation to be isotropic relative to the fundamental aether, which is assumed to be at rest relative to Newtonian absolute space. In a frame moving with velocity \( V \) relative to the fundamental frame, the phase velocity \( c_{p}^{1} \) and the group velocity of light \( c_{g}^{1} \) would then be modified (Møller, 1952, 1957):

\[
\begin{align*}
c_{p}^{1} &= c_{p}^{1\prime} \hat{n}^{1} = c \hat{n} - V \\
c_{g}^{1} &= c_{g}^{1\prime} \hat{\varepsilon}^{1} = c \hat{\varepsilon} - V
\end{align*}
\]

where \( \hat{n} \) and \( \hat{n}^{1} \) are unit vectors in the direction of the wave normal in the two frames; \( \hat{\varepsilon} \) and \( \hat{\varepsilon}^{1} \) are unit vectors in the direction of propagation of the wave energy similarly in the two frames. In the classical theory \( \hat{\varepsilon}^{1} \neq \hat{n}^{1} \), but because the phase velocity does have the same direction in both reference frames

\[
\hat{n}^{1} = \hat{n}
\]

and in the aether frame is equal to the group velocity

Chapter 4-11
\[ \hat{n} = \hat{e} \]

so that
\[ c^1_p = c - \hat{n} \cdot V \]
\[ c^1_x \hat{e}^1 = c \cdot \hat{n} - V \]

and \( \hat{n} \) and \( \hat{e}^1 \) are then related by
\[ \hat{n} = \hat{e}^1 \left( 1 - \frac{V \cdot \hat{e}^1}{c} \right) + \frac{V}{c} \quad \text{for} \quad \frac{V}{c} << 1 \] ... 3.1

Assuming then that a light source and an observer are moving with respective velocities \( V_s, V_o \) relative to the aether, the observer in his frame will measure the frequency of the light source \( \nu_s \) as being
\[ \nu_s = \frac{\nu_s \left( 1 - \hat{n} \cdot V \right)}{c} \] ... 3.2

This Doppler shift, when written in terms of the velocities relative to the laboratory frame, becomes
\[ \frac{\Delta \nu}{\nu} = \frac{\nu_o - \nu_s}{\nu_s} = \left( \hat{e}^1 \cdot U \right) c \left( \hat{e}^1 \cdot U \right) + \frac{V \cdot U}{c^2} \] ... 3.3

where
\[ U_t = V_t - V \]
\[ U_o = V_o - V \]
\[ U = U_t - U_o \]

and

Equation 4.3.3 has been written in terms of the unit vector \( \hat{e}^1 \), because it is the propagation of the wave energy, which is the observable quantity.
One would ideally then like a geometry that would satisfy
\[ \hat{e}^1 \cdot \mathbf{U} = 0 \]
in which case
\[ \frac{\Delta \nu}{\nu} = \frac{V \cdot (\mathbf{U}_v - \mathbf{U}_o)}{c^2} \]  
... 3.4
is the frequency shift one would expect as a first approximation of the classical theory.

In a rotor experiment with a Mössbauer source and absorber mounted rigidly to the rotor as for instance shown in Figure 4.1, the above condition is readily satisfied. In such an experiment the inherent stability of the nuclear transition provides two stable clocks, and the gamma ray a means to compare the rate of both. Hence any effects, arising from the motion of the laboratory frame relative to the cosmological rest frame, producing a local anisotropy in the
propagation of light or the nuclear or electromagnet forces acting during the decay of the nuclear state, would become observable.

A way of relating the two clock rates can also be found by considering the phase of the electromagnetic wave as emitted by S and received by A. (Ruderfer, 1960.) In a geometry, as shown in Figure 4.1, the phase can be expressed as

$$\varphi = \nu_s \left( t - \frac{r}{c + V \cdot \hat{n}} \right)$$

... 3.5

where \( r \) is the radial distance between the source and the absorber and is assumed to be constant. The second term in Equation 4.3.5 arises because, in the presence of an aether, the phase velocity of light in the rotor frame will be modulated by \( V \).

Taking the time derivative of \( \varphi \) to obtain the instantaneous frequency as seen by A, the frequency shift becomes to first order:

$$\frac{\Delta \nu}{\nu} = \frac{V \cdot U}{c^2} \left( 1 + \frac{4V \cdot \hat{\omega}^l}{c} + \ldots \right) = \frac{V \cdot U}{c^2}$$

... 3.6

where

$$\frac{d\theta}{dt} = \omega, \quad \omega \times r = \dot{U} = \ddot{U}_r - \ddot{U}_a$$

with

$$\frac{d\nu_s}{dt} = \frac{dr}{dt} = 0$$

This to first order is the same result as obtained before.

In the contraction theory, in which light is similarly thought to propagate relative to some fundamental frame, the frequency shift, expressed by Equation 4.3.6, is canceled by the shift arising from time dilatation. With the source and the
observer moving with velocities $V_s$, $V_r$ relative to the fundamental frame, the Doppler shift becomes

$$\frac{\Delta \nu}{\nu} = \frac{U_s^2 - U_a^2}{2c^2} - \frac{\mathbf{V} \cdot \mathbf{U}}{c}$$

i.e., the aether dependent shift is cancelled, and only the time dilatation factor remains.

However, for the next higher order term, one has to consider the effect of the contraction of $r$, which will be of order $UV^2/c^3$ and would have to be included in the higher order terms of Equation 4.3.6. An experiment sensitive to the higher order terms thus would test the exact cancellation of the time dilatation and the contraction factor making the one-way propagation of light isotropic relative to an inertial frame of reference. Following this line of argument, one again arrives at Einstein's basic postulates.

4.3 Past Experiments.

The first optical experiment by Michelson-Morley (1887) reached an accuracy of 10 km/sec compared to the expected aether drift of 30 km/sec, the velocity of the earth around the sun. The experiment was repeated by Joos (1931) who set a limit on the aether of 1.5 km/sec, and by Kennedy and Thorndike (1932) whose modified interferometer reached a sensitivity of 15 km/sec. The interferometer used by Kennedy and Thorndike was similar to that used by Michelson but had unequal interferometer arms. Miller (1933) contested these results and claimed to have detected an effect of 10 km/sec. This contradictory result was later attributed to systematic errors (Shankland, et al., 1955). More
recently modern microwave (Essen, 1955) and laser techniques (Jaseja, et al., 1964) have been used placing a limit of 2.5 km/sec and 1.0 km/sec, respectively. All these experiments are only sensitive to first order terms in v/c.

A very substantial increase in accuracy was achieved when methods became available that measure the speed of light on a one-way - not round-trip – basis and are sensitive to the first order term in v/c. The first such experiment was that conducted by Cedarholm, et al. (1958, 1959) who used two ammonia beam masers and set a limit of 30 m/sec. With the advent of the Mössbauer effect and its high inherent stability, a potential increase in sensitivity of four orders of magnitude was envisaged.

Champeney and Moon (1961) and Cranshaw and Hay (1961) set limits of 50 m/sec and 10 m/sec, and later experiments by Champeney, et al. (1963) and Turner and Hill (1964) achieved a sensitivity of 3 m/sec and 16 m/sec, respectively.
1. **Introduction.**

   It was the aim of the present aether drift experiment to achieve as high a potential accuracy as possible. For that reason, a rotor system had to be designed that allowed not only for an optimization but also a variation of the experimental parameters so that the systematic errors could be minimized and their effects established.

   For this experiment it was also essential to position the gamma ray detector at the center of the rotor so that a high efficiency cycle could be obtained and the rotor frequency be used to spatially modulate the \( \mathbf{U} \cdot \mathbf{V} \) term (in Equation 4.3.3) and make any angular dependencies of the counting rate directly apparent.

   To allow for such a geometry the rotor axis had to be stable to within 0.05 mm over periods of several weeks. This requirement eliminated the possibility of spinning the rotor on a glass plate, a technique that has been used previously in this laboratory (Marshall et al., 1948). The operation of such a rotor was found to be unreliable as the ball bearings had to be replaced daily and the position could vary by as much as 1 cm. Similarly a bearing suspension was not satisfactory as
it would have created excessive vibrations and would not have provided the necessary positioning of the rotor.

To obtain the stabilities needed it was thus necessary to build a free magnetic suspension as has been used by Beams (1951). This in turn raised the problem of the acceleration and damping of the rotor. The detector had to be positioned at the lower axis of the rotor so that it was not possible to accelerate the rotor mechanically, as was done by Beams using an air turbine. In order to critically damp the horizontal motion of the rotor and to position it externally a different damping mechanism had also to be built.

Preliminary tests using small rotors showed that the rotor stability was greatly determined by the rigidity of the structure so that this became a major consideration in designing the apparatus.

2. **Rotor Structure.**

In Figure 5.1 and Plate 5.1 the details of the structure are shown. The scale of the assembly was determined by the size of the largest rotor used and the general lay out was designed to make access to the various parts and especially the vacuum chamber easy.

Five levels of instrumentation are supported by the tripod structure, the top part of which can be lifted off by a hoist arrangement. The lower part is further strengthened by four adjustable steel rods and three brass sleeves fitted over the 1” brass rods. The sleeves also act as spacers for three of the platforms.
PLATE 5.1
BASIC ROTOR STRUCTURE

ARRANGEMENT TO LIFT TOP STRUCTURE

MAGNET ASSEMBLY

TRIPOD STRUCTURE OF 1 INCH BRASS RODS

VACUUM CHAMBER

BALL BEARINGS SUPPORTING UPPER STRUCTURE

ROTATING SEAL

DETECTOR HOLDER

ROTATING TABLE

4 STEEL RODS TO STRENGTHEN LOWER STRUCTURE

SPACERS TO GIVE RIGIDITY

INSTRUMENT TABLE

BEARING TO ROTATE WHOLE STRUCTURE

FIGURE 5.1
The various platforms have distinct functions. The top plate supports the electromagnet and a periscope, which allows a remote monitoring of the rotor. Plate 2 positions the vacuum chamber, the optics for the suspension servo-mechanism, and two steel safety barricades. The diffusion pump and cooling baffle are mounted onto plate 3, which also supports the rotating instrumentation table. Plate 4 is mounted onto a large bearing so that the whole structure can be turned remotely. It also positions the motors, which rotate the instrumentation table and the structure as a whole.

Plate 5 is part of the instrumentation table and supports the electronics for the proportional counter, which in turn is clamped to the upper part of the table and is positioned by the rotating seal at the lower part of the vacuum chamber.

The whole structure can also be moved about and leveled using castors and adjustable legs. This general design proved to be very reliable. The structure has no appreciable resonance frequencies to interfere with the rotor operation.

3. **Magnetic Suspension.**

The basic design of the magnetic suspension followed that of Beams and is shown in Figures 5.2, 5.3 and Plate 5.2. The current in the electromagnet is controlled by a servo-loop, the control signal for which is derived from an optical network, which determines the vertical position of the rotor.
3.1 General Considerations.

Because of the complex shape of the rotor it is not possible to calculate exactly the fields necessary to suspend the large rotor (2.7 kg). It is possible, however, to make some general comments, which help one to understand the characteristics of the magnetic suspension.

Let $r$ be the distance between the lower part of the core and the tip of the rotor, and $L$ the length of the core. If $r \ll L$, one can then regard the magnetic...
The dipole moment of the core as consisting of two magnetic monopoles \( \pm Q_m \) (Hallen, 1962) separated by a distance \( L^1 \) and of magnitude

\[
Q_m = \frac{iNS}{L^1}
\]

where \( i \) is the current and \( N \) the number of turns of the electromagnet. \( S \) is the cross section of the core and \( L^1 = L - 2r_1 \), where \( r_1 \) is the distance of \( Q_m \) from the tip of the core. The flux density below the core is then given by

\[
|B(r)| = \frac{\mu_0 Q_m}{4\pi(r_1 + r)^2}
\]

where \( \mu_0 \) is the primary magnetic constant. \( r_1 \) can be found by measuring \( B(r) \) as a function of \( r \) and is 1.7 cm for the particular core geometry used.

Similarly one can think of the magnetic dipole moment of the rotor as consisting of two poles \( \pm Q_m^1 \), one located a distance \( r_2 \) (~1 cm) below the top of the rotor and the other at its rim. This approximation is not as good as before but suffices for the present purpose. The problem of the magnetic suspension is then reduced to one involving a 'simple' pendulum of length \( (r_1 + r_2 + r) \).

To calculate the induced magnetic dipole moment of the rotor, one would have to know how the magnetic flux density becomes altered in the presence of the rotor, and how the permeability of the rotor depends on \( |B(r)| \) and the exact shape of the rotor.

These factors are not easily calculated. However, taking a small volume element \( \Delta \nu \) in the top part of the rotor, one can assume that the permeability
over that region is constant, i.e., \( B = \mu_r \mu H = \mu_r (H + M) \), and that the induced magnetic moment \( \Delta m \) of that volume element does not significantly influence the magnetic flux density \( B(r) \). \( \mu_r \) and \( \mu \) are the absolute and relative permeability respectively. The intensity of magnetization of that volume element is

\[
M(r) = \frac{\Delta m}{\Delta \nu}
\]

and the force on it
\[ f = (M \cdot \nabla)B = (\mu - 1)\mu_r\mu(H \cdot \nabla)H \]

which along the axis of suspension becomes

\[ |f| = \frac{(\mu - 1)\mu_r Q_m^2}{8\pi^2\mu(r_1 + r_2 + r)^5} \quad \ldots \text{... 3.1} \]

As \( Q_m \) is proportional to the current in the electromagnet, one finds that in order to keep the force of attraction constant

\[ i \propto \left(r_1 + r_2 + r\right)^{5/2} \]

This will still hold for the rotor as a whole as long as the range of the vertical displacements \( \Delta r \) considered satisfies

\[ \Delta r \ll \left(r_1 + r_2 + r\right) \]

Equation 5.3.1 indicates that the force of attraction is proportional to \( i^2 \) and does not greatly depend on the relative permeability of the material as long as it is greater than 1. The force can also be increased by decreasing the distances \( r_1 \) and \( r_2 \), i.e., by tapering the core and the top of the rotor as shown in Figure 5.2. This would also improve the suspension characteristics by providing a definite point-to-point suspension.

As the apparent permeability of the core is of the order of 30, the magnetic flux lines are virtually normal to the lower surface of the core. One can thus plot the flux line distribution and find the optimum taper of the core. It is a compromise between the above considerations and achieving the largest magnetic flux density at the rotor.
ELECTROMAGNET ASSEMBLY

TO ADJUST HEIGHT OF CORE

MULTISTRAND FLEXICABLE

TO ADJUST HEIGHT OF ELECTROMAGNET

ELECTROMAGNET ISOLATED FROM REST OF STRUCTURE

6 COILS EACH WOUND WITH 1200 TURNS OF 18 SWG COPPER WIRE AND WATERCOOLED

CORE INTERCHANGEABLE TO MATCH ROTOR

FIGURE 5.3
3.2 **Core Material.**

The core material had to have a small hysteresis and exhibit no magnetic saturation for the field strengths used. These requirements were, however, easily satisfied for $B \sim 500$ gauss, the maximum flux densities needed to suspend the rotor. The material used is sold under the trade name of 'Hellefors Remko magnetic iron', and is generally known as Swedish steel. It is composed of: C (.03%), Si (.01%), Mn (.12%), S (.01%), Cu (.01%) and iron, and has a maximum permeability of 10,850. It is easy to work on and thus satisfied all criteria.

3.3 **The Electromagnet.**

The electromagnet (see Figure 5.3 and Plate 5.2) consists of 6 coils each containing 1200 turns of 18 SWG copper wire, with the various coils not only insulated from one another, but also from the structure as a whole as an added safety measure to prevent a direct short to earth. Each coil is water-cooled and can handle currents of up to 5 amps. Generally, however, only 1 amp is needed to keep the rotor suspended at a distance of $r = 4 \text{ mm}$. Various means of adjustment were incorporated in the design of the magnet to allow a change in the magnet height and the position of the core, so that different cores can be installed depending on the size of the rotor used.

3.4 **Suspension Servo Mechanism.** The main problem then was to build a reliable suspension system, which depended on an accurate position sensor of the rotor and a stable electronic servo system.
Several sensors were considered and prototypes of a capacitive and an optical system with the respective servo systems were built. The capacitive sensor did measure the rotor position accurately, but it was also very sensitive to the general noise level of the laboratory, whereas the light-photocell sensor was comparatively insensitive to noise as the gain of the amplifier was smaller.

Plate 5.3 shows the design of the optical system. Two 1" prisms deflect the light from the lamp across the top of the rotor to the photocell. Both the light bulb and the photocell are mounted inside brass sleeves, which in turn are rigidly fastened to the brass plate supporting the vacuum chamber. This way the
filament of the lamp is shielded from the rotating magnetic field used to accelerate the rotor, and the noise pick-up at the photocell is kept to a minimum. The collimating lenses and the prisms can be adjusted so as to keep the vertical position of the rotor constant over a range of horizontal displacements (~1cm). Also the height of the light bulb and the photocell can be adjusted to ensure a smooth lifting action of the rotor and a linear control over its height.

For these reasons the optical system was superior to the capacitive position sensor, even though the former was potentially less reliable, as it depended on the finite lifetime of the lamp filament (see next section).

The schematic of the suspension servo system is shown in Figure 5.4. The output of the photocell is amplified by a high gain integrated operational amplifier (type $\mu$A 709, supplied by the courtesy of Fairchild Inc., U.S.A.), which has an open loop gain of 65,000 and a temperature coefficient of $3.0 \, \mu V/\circ C$.

The output of the amplifier drives the power amplifier of an emitter follower type. A voltage feedback signal via resistor $R_4$ decreases the signal noise on the output current by a factor of 30 to less than 10 mV.

The output of the power amplifier drives the electromagnet $L$, which is protected by diode $D$ against sudden voltage surges. The power for the suspension system is supplied by two stabilized 12-volt power supplies, which in turn are powered by two 18-volt accumulators to make the suspension system independent of the Midland Electricity Board. The accumulators were
continuously trickle charged and in case of an electricity failure they would have provided enough power for 15 hours. Before installing the 2 voltage stabilizing networks, the ripple on the supply voltage was about 300 mV and the voltage depended strongly on the charging rate of the accumulators. The stabilizing networks reduced the ripple to 5 mV and made the output supply voltage constant over a 2 volt range of the accumulator voltages.

The most difficult problem in designing the suspension servo loop was to find the correct feedback values to critically damp the vertical motion of the rotor. These had to be found empirically, as it was not possible to obtain a Nyquist
diagram (the transfer function between input and output signal) until the rotor was suspended, as it was an integral part of the feedback system. To suspend the rotor, however, one had to know the transfer function. In retrospect it should be said that it would have been helpful to measure the transfer function even without the rotor in order to determine the frequency response of the suspension system. Figure 5.5 is the Nyquist diagram of the system with the final feedback values. It shows that the maximum gain of 7,750 occurs for a frequency of 245 cps and that the cut-off frequency is around 10,000 cps with a negligible amount of positive feedback at 150,000 cps.

A damping of the vertical motion of the rotor was achieved by adding capacitor \( C_1 \) in parallel with the input resistor \( R_1 \) (100 kOhm). Critical damping was obtained by choosing \( C_1 = 0.25 \, \mu F \), but a slightly higher value was used (0.35 \, \mu F) to make the system less sensitive to transients.

Resistor \( R_2 \) determines the gain of the amplifier, and components \( C_3, R_5, \) and \( C_2 \) limit the input and the output frequency range. Increasing \( C_3 \) from .001 \, \mu F to .005 \, \mu F decreased the response of the circuit at 2.5 kcs by a factor of 5 and made it less sensitive to noise pick-up. Varying \( C_2 \) had generally little effect on the characteristics of the suspension.
The lifting action of the circuit is controlled by the 100 kΩ helipot $R_6$. To suspend the rotor, one merely has to increase the current in the electromagnet until the rotor is attracted, at which point the servo loop takes over. After the circuit has become temperature stabilized, it gives a remarkably constant current output, limited mainly by the fluctuations in the supply voltage and the light output from the lamp. The rotor has been run constantly for periods of over two weeks without major adjustments.
3.5 Filament Safety Features.

The lamp filament is the weakest link in the suspension system as its lifetime was rated at a 1000 hours. This, however, was effectively increased by a factor of 10 by reducing the supply voltage from the rated 24 volts to 21 volts (Specifications for W filaments, Menzel and Brandau, W. Germany). In addition, the lamp was regularly replaced every 1000 hours and then every new bulb was run in for 50 hours before accelerating the rotor to guard against a mechanical failure of the filament.

This, of course, did not eliminate the ever-present threat of a filament failure. So, as to reduce the likelihood of a breakdown, a relay (RL) was built into the lamp power supply (see Figures 5.4 and 5.6), which in case of a filament failure adjusted the current in the electromagnet so that 90% of the weight of the rotor was 'suspended.' The rotor then would hopefully continue to spin on an agate plate at the top of the proportional counter (see Figure 5.2). Fortunately, we never had to use this facility, so the author is unable to report on its reliability.

The finite resistance of the lamp contacts also made the suspension system less reliable, but this problem was overcome by actually soldering the lamp into the socket.


As the rotor structure was enclosed in a cubicle, separate from the main laboratory, the operation of the rotor had to be remotely monitored. This was done visually by a periscope and a system of mirrors. It was generally found,
however, that the meters, monitoring various aspects of the suspension system, and the oscilloscope trace of the control voltage $V_{OP}$ (see Fig. 5.4) were more effective in displaying any irregularities in the rotor suspension.

At the control console the following parameters can be monitored:

i) the voltage across the electromagnet $V_m$,

ii) the current supplied to the magnet $I_m$,

iii) the voltage supplied to the suspension lamp $V_L$,

iv) the current supplied to the suspension lamp $I_{LI}$,

v) the current supplied to the gating lamp (see section 6.5) $I_{L2}$,

vi) the supply voltage to the suspension system $V_s$,

vii) the charging rate and the accumulator voltage $V_A$.

The currents needed to suspend the rotor ranged from 1.8 amps to 3.2 amps, and in the later part of the experiment $I_m$ was measured more accurately by using a voltage to frequency converter and a frequency counter.

5. **Damping and Positioning of the Rotor.**

In the aether drift experiment the vertical axis of the rotor had to be positioned to within .1 mm and held constant to better than .05 mm (see Fig. 5.2). The vertical motion of the rotor was also restricted to ± 1 mm, so that it became essential to not only position the rotor accurately but also damp its motion effectively.
The vertical motion could be damped electronically by choosing appropriate feed back values in the servo loop. The horizontal damping presented a more difficult problem, as it had to be done mechanically. As the rotor was accelerated it went through several resonances caused by the pendulum motion of the magnet core about its point of support, the pendulum motion of the rotor about its suspension point and the resultant action of this compound pendulum. Also, at 100 cps, a resonance was observed which was caused by the coupling of the horizontal and the vertical motion.
To damp these motions a central oil dash-pot damping of the core was found to be insufficient and the system, shown in Figure 5.7, was developed. This provided a strong damping and could also be used to position the core and the rotor. It had the advantage of allowing a number of extra parameters for the adjustment of the damping constants. The leaf springs were made of phosphor bronze. A thickness of 18 gauge made the springs weak enough to follow the motion of the rotor, yet strong enough to position it accurately.
Various damping fluids were tried but epoxy resin (without hardener) was found to be the most effective. It gave a damping constant of 3 sec compared to 8 sec in air.

The tension and the position of the springs could be adjusted by locking nuts and two of the spring assemblies were movable so that the position of the rotor could be varied during a medium high speed run without disturbing the rotor.

6. The Rotor.

As the sensitivity of the aether drift experiment is directly proportional to the tip speed \( (V_s - V_a) \) of the rotor, it became essential to optimize the shape of the rotor, while at the same time incorporating a number of features to allow for the mounting of the source and the absorber.

6.1 Shape.

The necessity of having a central detector eliminated the possibility of a hollow-rod-type rotor as it would not have had sufficient overall strength. For this and other reasons, the alternative of a disc-shaped rotor was preferable, as it can be directly machined on a profile lathe and is also less sensitive to imbalances. Figure 5.8 shows the final design.
Marshall et al. (1948) have shown that in order to obtain an equal stress throughout the rotor, its profile would have to conform to a Gaussian error function with the thickness as a function of radius expressed by

$$t(r) = t_o \exp\left(-\omega^2 r^2 / 2S\right)$$

where $t_o$ is the thickness at the center of the rotor, $S$ the tensile strength and $\rho$ the density of the rotor material.

Figure 5.8 shows the ideal shape for various tip speeds, assuming a tensile strength of 125 tsi at .2% proof stress. Only the top surface could be approximated to this shape. The lower surface had to be made virtually flat, so that most of the radiation coming from the source, mounted at the rim of the
rotor, could reach the detector. Towards the rim the angle of both surfaces was equal to produce as much of a uniform stress in that part of the rotor as possible. Two recesses were machined in the lower surface to hold the source and the absorber skirt. In the course of the experiment two different skirts were used. One consisted of a steel tube with a wall thickness of 2.5 mm and windows cut at opposite sides. This allowed the radiation to penetrate through the absorber foil, which was held in place by a .016" thick beryllium disc. The other skirt consisted of a beryllium tube of 2 mm wall thickness. The skirt was reamed into the inner recess of the rotor and then araldited into place.

The top of the rotor was determined by previous considerations (see section 5.3.1). A point at the lower axis of the rotor allowed it to spin on an agate plate in case of a filament failure. In order to test this rotor design a wax model was built and spun to breaking point. It showed, as was expected, that the rim of the rotor was the weakest point.

6.2 **Rotor Material.**

The material had to satisfy several criteria. It had to be ferromagnetic for the magnetic suspension. It had to have as high a ratio of \( \frac{\text{tensile strength}}{\text{density}} \) as possible and at the same time it had to be soft enough to make machining possible.
These conditions were best satisfied by maraging steel, a relatively new steel-nickel-cobalt-molybdenum alloy*. The material exhibits a tensile strength (at .2% proof stress) of between 90 and 133 t.s.i., depending on the relative composition. The material differs most strikingly from other high strength steel alloys in that it is hardened by a low temperature heat treatment, which 'marages' the martensite by causing a precipitation of intermetallic compounds. This treatment causes negligible distortion so that the rotor can be machined before hardening it.

In the unhardened condition the steel has a hardness of around 300 Brinell, which makes machining readily possible. The particular type of steel used goes by the trade name of maraging steel 648C (Firth Brown Ltd.) and has a tensile strength (at .2% proof stress) of 125 t.s.i. It consists of Ni (18%), Co (9%), Mo (5%), Ti (0.6%), Al (0.1%), Si (.05%) and C (0.2%). The full strength of the material was developed by keeping it for 4 hours in an inert atmosphere at 460°C.

6.3 Machining of the Rotor.

The rotor was machined in two stages. After eliminating the bulk of the material on a conventional lathe, the top surface and the rim were shaped on a profile lathe using a pattern made of bakelite. The negative of the surface was also put into a brass disc, which then served as a tool to hold the rotor while the lower surface was shaped. A set of grooves had been cut into the brass disc so

* The help received from the Vacuum Melting Dept. Of Firth Brown Ltd., who put several slabs of the material at our disposal, is gratefully acknowledged.
that the rotor could be araldited into position during the machining process and later removed again. The brass block also served conveniently to hold the rotor while the absorber skirt was ream-fitted.

The finished rotor was tested ultrasonically for structural weaknesses. This was done by submerging it into a tank of water to couple it with the ultrasonic antenna and receiver. No marked change in the echo times could be detected.


Accelerating the rotor turned out to be a major problem. It was not possible to accelerate it mechanically as the axis of the rotor was not accessible, so that the only alternative was to accelerate the rotor using an externally rotating magnetic field. Unfortunately, the acceleration rate with the big rotor was very small (4 cps per minute) and was also limited by the eddy current heating, so that it became necessary to optimize a number of parameters.

7.1 General Considerations.

The basic acceleration mechanism resulting from the rotating magnetic field can be understood by considering a conducting ferromagnetic body regular in shape, like for instance a sphere, so that the magnetic flux density in the body is approximately uniform. A torque in the direction of the rotating field will then result, because of the interaction between the induced eddy currents in the body and the applied field.
Choosing a set of Cartesian coordinates, as shown in Figure 5.9, with the z-axis parallel to the axis of rotation of the magnetic field and \( \omega_b \) the angular velocity thereof, we have

\[
\mathbf{B} = \hat{i}B_x + \hat{j}B_y = \hat{i}B\cos \omega_b t + \hat{j}B\sin \omega_b t
\]

and

\[
\dot{\mathbf{B}} = -\hat{i}\omega B_x + \hat{j}\omega B_y
\]

Applying Faraday's law,

\[
V \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
\]

one finds then that the induced electro-motive forces will be in the plane parallel to both \( \mathbf{B} \) and \( \omega_b \). In fact, considering an annular ring in the plane parallel to \( \mathbf{B} \) and rotating with the magnetic field, the electric field will be given by

\[
\mathbf{E} = \frac{1}{2}\omega B \left( -\hat{k} + \hat{x} \right) = \rho \mathbf{J}
\]

where \( \rho \) is the resistivity of the material and \( \mathbf{J} \) the current density in the annulus.

The resulting torque on a small element in this annular ring will be

\[
\tau_{EC} = \mathbf{r} \times (i\mathbf{d} \times \mathbf{B})
\]

so that

\[
|\tau_{EC}| \propto \omega B^2
\]
This torque will act on the element so as to accelerate it in the direction of the rotating field. In fact, it has been shown that the torque acting on the element when the magnetic field is stationary but the body rotating with angular velocity
\( \omega_r = -\omega_B \) is the same as above, and in general depends on the difference of the two frequencies (Jonas, 1960).

Above considerations hold only when the magnetic flux density is uniform throughout the conducting body. For high frequencies this is not the case as the magnetic field will only penetrate a finite depth given by

\[
\delta = \left( \frac{2\rho}{\mu \mu_0 (\omega_B - \omega_r)} \right)^{1/2}
\]

so that when \( \delta \) is smaller than the 'average' radius \( r \) of the body the eddy current torque will be effective only over the skin layer and the total torque will be

\[
T_{EC} \propto (\omega_B - \omega_r) B^2 \text{ for } \delta \gtrsim r
\]

\[
T_{EC} \propto (\omega_B - \omega_r)^{1/2} B^2 \text{ for } \delta \lesssim r
\]

Figure 5.10 shows that for maraging steel the penetration depth is quite small, for \( (\omega_B - \omega_r)/2\pi = 100 \text{ cps} \) it is 3.5 mm so that the \( (\omega_B - \omega_r)^{1/2} \) dependence will dominate throughout the frequency range.

For a ferromagnetic material an additional torque will act on the body arising from the rotational hysteresis, as the induced magnetization in the material lags behind the applied rotational field. When the applied field is constant and the magnetic properties of the material isotropic the hysteresis
torque per unit volume can be described by (Bozorth, 1951; Jonas, 1960)

\[ \tau_{ji} \propto B^2 \sin \theta \]

where \( \theta \) is the hysteresis angle between the field strength and the intensity of magnetization. For the frequencies we are concerned with \( \theta \) will stay relatively constant (Evershed and Vignoies Ltd., London, Data sheet 5A section 3) and for low flux densities, as used here, will be negligible.
7.2 Experimental Considerations.

Rotating magnetic fields have been employed in this laboratory to accelerate smaller rotors (Marshall et al., 1948) and the same basic set-up is used in the present experiment. Two generators rated at 500 watts each and adjusted to be in quadrature supplied the power to two sets of coils. Each set of coils (see Plate 5.4) consisted of 2 oppositely mounted coils, each with 200 turns of 18 SWG copper wire; the first series of 4 coils was built to investigate the
acceleration rates for the big rotor. The rates were disappointingly small but were, as expected, proportional to \( B^2 \) at constant \( (\omega_B - \omega_R) \) (see Figure 5.11).

During an actual rotor run, however, it was found that the acceleration rate decreased much more quickly than could be accounted for by the above arguments. Figure 5.12 shows the expected rate and that found with the first series of coils. The decrease in the acceleration rate was so marked that in fact one could not have accelerated beyond 400 cps using a driving frequency \( f_B = 950 \) cps or beyond about 600 cps using \( f_B = 2500 \) cps.

![Figure 5.12](image)
This rapid decrease in the torque is explained by the nonuniformity of the rotating magnetic field. If one considers two coils of radius $a$ in a Helmholtz geometry with distance of separation $2b$, then the magnetic field $B_m$ halfway between the two coils will be as shown in Figure 5.13. Separating the coils decreases $B_m$ rapidly relative to the field $B_0$ at the center of one of the coils. The ratio $B_m/B_0$ gives essentially the fraction of the field penetrating both coils, i.e., the 'uniform field.' Only this uniform component of the field will contribute to the rotating field, whereas the non-uniform component $B_n$ will appear as stationary in the laboratory frame. It will hence set up a braking torque

$$ T_{EB} \propto \omega_R B_n^2 $$

Chapter 5 - 32
which is directed opposite to $\omega_R$ and increases with $\omega_R^{\frac{3}{2}}$. That this explanation does account for the discrepancy in the acceleration rate has been verified by measuring the braking torque for various rotor frequencies by disconnecting one set of coils to eliminate the rotating magnetic field. The curve marked $T_{EB}$ (in Figure 5.12) has been obtained by extrapolating the low frequency dependence to higher frequencies, which does account for the limiting of the acceleration rate at $f_R = 400$ cps.

In order to obtain a more uniform magnetic field, another more ideal set of coils was built (see Plate 5.5) that was also matched to the generators to obtain maximum power output. The power generators had an internal impedance of $Z_G = 25$ at 950 cps and a power output of $I_g = 4.4$ amps (RMS) at $V_g = 110$ volts (RMS). The new set of coils, with a geometry as shown in figure 5.13, were wound with 520 turns of 18 SWG copper wire and used in a series resonance circuit. This turned out to be an unfortunate choice as the voltage across the coils was $\sim 900$ volts, which the coils could not withstand for long. A faint smell of ozone detected during the acceleration substantiated this view.

Current amplification, using a parallel resonance circuit with low impedance coils was found to be preferable. The optimum impedance of the coils is given by $Z_c = \frac{R_1 + j\omega L_1}{2} = \frac{Z_g}{Q}$ where $R_1$ and $L_1$ are the resistance and the inductance of the individual coils connected in parallel. The quality factor $Q$ of the above coils was found to be 8.2 for $f_B = 950$ cps. It was measured with a Wayne Kerr Universal Bridge so as to include the eddy current losses in the coils. As the quality factor can be considered to be constant for coils having the
same geometry and volume of copper, the values of $R_1$ and $L_1$ for a parallel resonance circuit can be readily found.

PLATE 5.5. Vacuum chamber with damping assembly and big accelerating coils.

The final coils were wound with 72 turns of .2" x .08" copper strips giving an inductance of .26 mh.

After installing the coils, the quality factor actually decreased to 5 because of losses in the supply cables and the steel safety barricades around the coils. These losses could not be reduced because the supply cables had
already been made as short as possible and the inner of the two steel barricades removed.

The acceleration rate using the new coils did follow the expected theoretical curve and improved the overall efficiency of the acceleration system even though initially the acceleration rate was not larger than before. It took about 12 hours to accelerate the rotor to 700 cps compared with the 24 hours it took to reach 450 cps when using the small coils.

7.3 Eddy Current Heating.

The acceleration rate was then not so much limited by the power output of the generators as by the eddy current heating in the rotor. The absorber material, sodium ferrocyanide in araldite, would have decomposed at 130°C and this set the limit on the allowable rotor temperatures.

The power dissipated in the rotor can be found by

\[ P = T_{EC} |(\omega_R - \omega_b)| \]

assuming that no higher harmonics in frequency are present.

The heating of the rotor is given by

\[ H_R = \frac{I \alpha |(\omega_b - \omega_R)|}{CM} \]

\[ = 0.96^\circ C/\text{min} \quad \text{for } \omega_R = 0 \]

Where:

- \( I \) is the rotational inertia of the rotor (1.07 x 10^{-2} \text{ kg.m}^2),
- \( \alpha \) is the \( \omega_R \) dependent rate of acceleration (3.6 cps/min at \( \omega_R =0 \)).
the mass of the rotor (2.7 kg) and \( C \) is the specific heat of iron equal to \( 1.2 \times 10^2 \) cal/kg °C.

The figure agrees well with the experimentally determined value of 1°C/min for \( f_B = 950 \) cps.

In order to keep the temperature of the rotor below the tolerable limit, alternate cycles of acceleration and cooling had to be used. Figure 5.14 shows the rate of cooling for two different pressures from which the relative length of each cycle can be deduced.
For $f_r$ equal to 0, 200, 500, and 700 cps, the cooling cycle has to be 1.7, 1.2, .56, and .23 times the acceleration cycle respectively, so that the total acceleration time would be increased very little by increasing the acceleration rate.

Unfortunately no direct method was available to measure the rotor temperature. Usually a deterioration of the vacuum gave a rough indication of the rotor temperature, but as the vacuum improved toward the end of a long run, even this method was not very reliable.
8. **Slowing-down Rate of the Rotor.**

Before the rotor was tested at high speed, the main fear was that it might exhibit some resonances at higher velocities, which could make it unstable. As the slowing down rate of the rotor in a vacuum did give a good indication of the stability of the suspension system and the general vibration level, it was monitored over the whole frequency range. The slowing down rate is shown in Figure 5.15 as a function of rotor frequency and vacuum pressure.

The resonances at 2, 7 and 10 cps can be explained by the action of the damped pendulum. The lower resonance is caused by the motion of the rotor about its point of suspension. The length of this effective pendulum, deduced from the period, is 6.2 cm corresponding to the distance between the center of mass of the rotor and the suspension point at the core. The two higher resonances are representative of the vibrational frequencies of the leaf springs along the two axes, and the resonance at 100 cps caused by the interaction of the vertical and the horizontal motion of the rotor, was eliminated by the stabilized power supply. No other large resonances were observed, even though some effect was expected at half synchronous speed.

Two features are brought out by Figure 5.15:

i) the slowing down rate \( R_{sd} (P) \) is proportional to the residual vacuum pressure \( P \), and

ii) \( R_{sd} (\omega_r) \propto \omega_r^{\frac{1}{5}} \) for constant \( P \), as given by the slope of \( R_{sd} (\omega_r) \).

The remnant slowing down rate decreased with increasing rotor speed and can be attributed to an imbalance in the rotor. While monitoring the control
signal of the suspension current, a ripple was observed, which had the same frequency as that of the rotor. This also indicated that the rotor was not running true, i.e., that the center of mass of the rotor did not fall on the axis of rotation. It can be assumed, however, for the later analysis, that the center of mass of the rotor does prescribe a circular motion about the axis of rotation and that the radius of this circular path decreases with increasing rotor frequency.

**PLATE 5.6.** Rotor as suspended.

Some attempts were made to obtain a vacuum of around $10^{-6}$ torr limited only by the pumping rate of the diffusion pump (150 l/sec), but the best vacuum
actually achieved was $1.6 \times 10^{-5}$ torr. This was probably caused by the outgassing of the perspex parts of the vacuum chamber; polishing the perspex and covering it with Apiezon grease did not improve the vacuum. It was found, however, that the slowing down rates were quite acceptable and required only the occasional accelerating burst every 90 minutes to keep the rotor at speed.

9. **Safety Devices.**

Several safety features had to be incorporated to protect against a high speed rotor crash, and to dissipate the kinetic energy of the rotor of $\sim 10^5$ joules. A system of concentric steel barriers guarded against fragments from a disintegrating rotor and also served to take up some of the angular momentum. For that reason the inner steel barrier, which was 7" high and had a wall thickness of 1¼", was mounted on ball bearings and also lined with plasticene to soften the impact.

The outer steel barrier was 8½" high and consisted of two ¾" concentric steel cylinders that were bonded together by a lead filling as an added radiation shield. Both steel barriers could be demounted by a hoist to allow more working space.

A wooden barricade surrounded the whole structure to a height of six feet and provided further protection. It was constructed of 5" x 10" railway sleepers and consisted of two movable L-shaped sections. The whole assembly was kept in an enclosure separate from the rest of the laboratory with the rotor operation controlled remotely.
Additional safety features guarded against an overheating of the diffusion pump and protected it against a failure of the backing pump.
CHAPTER VI

THE AETHER DRIFT EXPERIMENT AND ASSOCIATED MEASUREMENTS

1. Introduction.

The sensitivity of the present aether drift experiment was greatly increased over previous tests by optimizing the slope of the resonance, the counting rate, the duty cycle and the speed of the rotor. The inherent stability of the magnetic suspension also made it possible to have long continuous experimental runs thereby simplifying the analysis of the data.

In the present experiment the source was mounted at the rim of the rotor and the absorber on the skirt near the center of the rotor (see Figure 5.2). This allowed data to be collected with an almost continuous duty cycle. The distance between the source and the absorber is 7.8 cm; the resulting energy shift from time dilatation is shown in Figure 6.1. Knowing the ultimately achievable tip speed of the rotor one could then select the most appropriate source-absorber combination.
Preparation of the Mössbauer Source and Absorber.

Table 6.1 shows the Mössbauer parameters for $^{57}$Fe. As discussed in section 3.3.3, one would like to find a source with highest recoilless fraction and narrowest line width. The values shown in Table 6.2 indicate that the line widths for the four source lattices with the highest $f_s$ are nearly the same. The small differences in the line width are probably a result of the different techniques employed to produce the sources. For an identical Na$_4$Fe(CN)$_6$ absorber with $T_a$~1 the resultant line widths are typically .29 - .31 mm/sec. For natural line widths the expected width would be .22 mm/sec.
In the course of the experiment two sources were used. The first was a \( ^{57} \text{Co} \) in palladium source (10 mCi) with the active area measuring 1.3 x 9 mm. It exhibited an excessive line width of .56 mm/sec for a P.F.C. absorber with \( T_a = 2 \). In order to reduce the line width the source was reannealed at 1000\(^{\circ}\)C (nominal) in a hydrogen atmosphere, and the radioactive surface was scraped to remove any surface impurities. This did not significantly improve the transmission line width. The excess line width can be partly attributed to the fact that the source, originally 116 mCi strong, exhibits an appreciable amount of self absorption (\( T_s \sim .8 \)) which would broaden the emission line by \( \sim .03 \) mm/sec. A more general
study (Evans, 1968) has also indicated that old sources can be broadened by as much as $\Gamma$ which would explain the excess line width.

Table 6.2

<table>
<thead>
<tr>
<th>Source lattice</th>
<th>$\Delta E_{IS}$ (mm/sec)</th>
<th>$\Gamma_{exp}$ (mm/sec)</th>
<th>Absorber Used</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rh</td>
<td>-.114</td>
<td>0.29</td>
<td>S.F.C. $^1$ (Ta=1)</td>
<td>Qaim et al. (1967)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.34</td>
<td>S.F.C. (Ta=1.2)</td>
<td>Present experiment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.32</td>
<td>nat. iron (Ta=1)</td>
<td>Present experiment</td>
</tr>
<tr>
<td>Pd</td>
<td>-.185</td>
<td>0.31</td>
<td>S.F.C. (Ta=1)</td>
<td>Qaim et al. (1967)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.53</td>
<td>S.F.C. (Ta=1)</td>
<td>Present experiment</td>
</tr>
<tr>
<td>Cu</td>
<td>-.226</td>
<td>0.29</td>
<td>S.F.C. (Ta=1)</td>
<td>Qaim et al. (1967)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.29</td>
<td>P.F.C. $^2$</td>
<td>Taylor et al. (1964)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.23</td>
<td>nat. iron</td>
<td>Taylor et al. (1964)</td>
</tr>
<tr>
<td>Mo</td>
<td>-.060</td>
<td>0.30</td>
<td>S.F.C. (Ta=1)</td>
<td>Qaim et al. (1967)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.28</td>
<td>nat. iron (Ta=0.28)</td>
<td>Qaim et al. (1967)</td>
</tr>
</tbody>
</table>

1) S.F.C. = Na$_4$Fe (CN)$_6$

2) P.F.C. = K$_4$Fe (CN)$_6$

Chapter 6 - 4
The other source used consisted of $^{57}$Co in rhodium with an initial source strength of 50 mCi and a radioactive area of 1.3 x 11 mm. This source was also reannealed, at 1200°C, and then cut to size to fit the rim of the rotor.

The final parameters of the two sources relative to a $(T_a = 2)$ S.F.C. absorber are given in Table 6.3.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Gamma_{exp}$ (mm/sec)</th>
<th>$E_{IS}$ (mm/sec)</th>
<th>$R_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{57}$Co(Pd)</td>
<td>0.535 ± 0.015</td>
<td>-0.229 ± 0.005</td>
<td>0.55 ± 0.015</td>
</tr>
<tr>
<td>$^{57}$Co(Rh)</td>
<td>0.350 ± 0.008</td>
<td>-0.155 ± 0.005</td>
<td>0.70 ± 0.020</td>
</tr>
</tbody>
</table>

The negative sign of the energy shift implies that the transition energy of the source is larger than that of the absorber, so that the shift resulting from the time dilatation factor would sweep the emission line over the absorption line.

This means that a $^{57}$Co(Pd) source used with a S.F.C. absorber is an ideal combination for rotor frequencies up to 450 cps, while a $^{57}$Co(Rh) source with a S.F.C. absorber is ideal for frequencies above 625 cps. The rotor frequency corresponding to the optimum slope depended on the characteristics of the individual absorbers.

Three different absorbers were used all made from S.F.C. enriched to 91% in $^{57}$Fe. To make the absorbers more stable under high temperatures the crystals of Na$_4$Fe(CN)$_6$.10H$_2$O were dehydrated and then cast in araldite. The
dehydration occurred in several stages by heating the crystals to 130°C until a constant weight was obtained. The weight difference accounted for 95% of the water of hydration, which suggested that the crystals had already been partially dehydrated. The S.F.C. was then ground to a fine powder, mixed with araldite in the ratio of 1:7 and allowed to harden between two sheets of polythene, which were spaced to give the desirable thickness of $T_a = 4$. The absorbers prepared in this way were mechanically very strong and could withstand temperatures of up to 130°C.

**Figure 6.2**
The first two absorbers made had an $^{57}$Fe concentration of .84 mg/cm$^2$ and .395 mg/cm$^2$ respectively. Because of the high concentration of $^{57}$Fe only a small amount of S.F.C. was needed to give the desirable absorber thickness. This turned out to be a disadvantage as the absorbers ended up being not very uniform and exhibited a grainy texture. This resulted in a smaller $R_m$ value than expected. For that reason the thinner absorber, which had an effective area of 25.6 cm$^2$, was cut in half and doubled in thickness. All three of these absorbers were used during the experiment and will be denoted as absorbers 1, 2, 3.

Absorber 1 was used with the palladium source and the steel absorber skirt. It was mounted onto two .008" thick beryllium discs and then fitted into the recessed window of the steel skirt. Absorbers 2 and 3 were used with the rhodium source and the beryllium skirt. They were directly glued to the inside of the skirt so as to cover all of the detector area as seen by the source. Outside of the tantalum collimator, which shielded the lower unused portion of the counter, no collimation was used.

Because of the non-uniformity of the absorber and the resonant absorption in the beryllium skirt (see Figure 6.5) it was not possible to obtain accurate line width measurements until the absorber was finally mounted on the rotor. This produced other difficulties as the geometry using the rotor and the central proportional counter was not as well defined as in a bench experiment. The higher vibration level of the rotor structure, used to support the counting equipment, added additional uncertainty to the results. Hence for the final accurate evaluation of the data the slope of the resonance at the operating
speeds of the rotor was determined directly from the change in the counting rates observed during the acceleration of the rotor, (see Section 6.10) after allowing it to cool.

Figures 6.2, 6.3 and 6.4 show the transmission spectra for the three source-absorber combinations. The spectra were taken with the absorber mounted as during an actual experiment. The source was attached to the vibrator, which was inclined to approximate the position of the source as when it is mounted on the rotor. The central proportional counter was shielded against the source radiation, which did not penetrate the absorber. Figure 6.2 shows the excessive line width of the $^{57}$Co (Pd) source. The slope of the resonance is maximum at rotor frequencies of 300 and 800 cps and zero at 600 cps. Figures 6.3 and 6.4 show that the transmission line width is not broadened very much by doubling the thickness of the absorber, which further indicates the non-uniformity of the absorber. The $R_m$ value, however, was almost doubled. The slope is maximum for frequencies of 225 and 670 cps and minimum at 495 cps. In the final series of runs the rotor was run at 650 and 701 cps from which the slope at the inflection point was found as being $2.28 \times 10^{11}$.

In order to determine the iron content in the beryllium another spectrum was taken using beryllium tubing 4 mm thick (see Figure 6.5). The spectrum shows that even though the beryllium is 99.9% pure it contains enough iron to produce a $\sim 1\%$ resonance dip for every 1 mm thickness of beryllium. The transmission line is quadrupole split and very broad (.83 mm/sec) so that the
resulting transmission line width, when using the S.F.C. absorber and the 2 mm thick beryllium skirt, would be slightly increased.

To establish the effect of the graininess of the absorbers another series of spectra was taken using the $^{57}$Co(Rh) source and a set of unenriched S.F.C. absorbers (supplied by M. J. Evans). The absorbers were quite uniform and ranged in thickness from .05 to .47 mg/cm$^2$ of $^{57}$Fe. The line widths and $R_m$ values obtained are shown in Figures 6.6 and 6.7. Figure 6.6 is plotted as a
function of $N\sigma_a$, where $N$ is the number of resonant nuclei per cm$^2$, such that the slope is equal to 0.27 $f_a$. As drawn $f_a = 0.40 \pm 0.05$. Superimposed on the graph are the line widths obtained using the same source and natural iron foil absorbers. Extrapolating the line widths data to zero absorber thickness it appears that the iron foil absorbers give a line width narrower by 0.02 mm/sec than those obtained for the S.F.C. absorber. If one assumes that the absorption line of iron is natural one obtains for the $^{57}$Co (Rh) source a width $\Gamma_c = 2.1\Gamma'$ or $k_s = 0.5$ (see § 3.3.3). This means that the slope of the resonance using an unenriched S.F.C. absorber with $T_a = 4$ is 0.48 of the slope obtained with unbroadened lines. In Figure 6.7, the experimental $R_m$ values are compared with the theoretically expected values assuming $f_s = 0.7$.

The effective thickness of the three absorbers can then be deduced by comparing the observed transmission spectra, using the same $^{57}$Co (Rh) source, with the values of the unenriched absorbers. The parameters of the three absorbers are shown in Table 6.4.

<table>
<thead>
<tr>
<th>Absorber</th>
<th>mg/cm$^2$ of $^{57}$Fe</th>
<th>nominal $T_a$</th>
<th>$\Gamma$ exp mm/sec</th>
<th>$R_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.84 mg/cm$^2$</td>
<td>8.3</td>
<td>.424</td>
<td>.209</td>
</tr>
<tr>
<td>2</td>
<td>.395 mg/cm$^2$</td>
<td>3.9</td>
<td>.410</td>
<td>.110</td>
</tr>
<tr>
<td>3</td>
<td>.79 mg/cm$^2$</td>
<td>7.8</td>
<td>.416</td>
<td>.214</td>
</tr>
</tbody>
</table>
The values of $\Gamma_{\text{exp}}$ and $R_m$ for absorbers 1 and 3 have been superimposed on Figure 6.6 and 6.7. This shows that even though the two absorbers have a nominal thickness of $T_a = 8.3$ and 7.8 respectively, the observed line widths are rather narrower than expected and in fact are representative of $T_a = 3.5$ and 3.2 respectively. Similarly, the observed $R_m$ values are smaller and give $T_a$ values of 1.75 and 1.8. This means that the slopes obtained with absorbers 1 and 3 are .32 and .33 of the slope for the ideal case. This was still considered tolerable as the electronic absorption for these absorbers is also smaller than for the unenriched absorbers.

In order to correlate the spectra obtained using the linear Doppler shift with those obtained with the time dilatation shift, the background counting rates had to be known accurately. For the rotor experiment the background was measured, while the rotor was not suspended by interposing two 1/16" thick aluminum sheets between the skirt and the detector. Because this geometry is not identical to the one when the rotor is actually suspended, the measurement is not very accurate, so that the experiment cannot be considered to be a very sensitive test of time dilatation.

The temperature dependence of the counting rate, with the source and the absorber both mounted on the rotor, was measured by using the rotating magnetic field to heat the stationary rotor to a temperature of 120°C. With the rotor kept in the vacuum the temperature was monitored with a copper-constantan thermocouple. The increase in the counting rate resulting from the
decrease in $f_s$ and $f_a$ amounted to (.15 ± .01)% per °C and served as a rough indication of the rotor temperature.
3. **Gamma Ray Detector.**

Several methods of detection were considered including

i) scintillation counter,

ii) ionization chamber, and

iii) proportional counter.
The detector had to have a high resolution to resolve the 14.4 keV gamma ray peak and a high detection efficiency (for that peak) to reduce the background counting rate. It had to have a fast response time and be insensitive to stray magnetic fields. It also had to be strong enough to support the rotor.

i) A scintillation counter was ruled out because it failed to satisfy most of the criteria, even though it had a potentially unit detection efficiency for the 14.4 keV peak. In order to make the detector insensitive to the high-energy gamma radiation it would have had to be a thin annular ring (~1 mm wall thickness), which would have made the counter structurally very weak. The resolution of a scintillation crystal (NaI) - even under best conditions - is poorer than that of a proportional counter with typical resolutions of 30% and 15% respectively for 14.4 keV radiation. The need of a photo-multiplier makes such a detection system very sensitive to stray magnetic fields.

ii) An ionization chamber has been suggested for the use in conjunction with strong sources (Isaak, 1965) as it measures currents rather than individual pulses. Filling the chamber with a krypton-methane gas mixture would result in a high detection efficiency for the 14.4 keV radiation, because the K-absorption edge of krypton is at 14.3 keV. This means that the high-energy gamma rays (136 keV and 122 keV) would be rejected in a ratio of 350:1. As the ionization chamber does not discriminate against the pulses this rejection ratio and a suitable absorber material could reduce the background level to less than half of the total signal level. The technical problem in the present situation, however, is that the ammeter measuring
the ionization current would have had to have a 1 ms response time to cope with the fast rotor modulation, and no such instrument is as yet available.

iii) For these reasons a proportional counter was the most promising choice, even though several problems had first to be solved. The counter had to have a small volume to fit inside the absorber skirt and at the same time had to retain a high counting efficiency constant to within 1% over a full revolution of the rotor.

Figure 6.8 shows the final design of the counter. Several have been built incorporating a beryllium tube of 1” diameter and a 1 mm (or 2mm) wall thickness to minimize electronic absorption. The glass to metal seals were selected to have a resistance of greater than $10^{11}$ ohm to keep the noise level of the counter to a minimum. The beryllium was etched and the system assembled using araldite.

A ¼” copper tubing was used to evacuate the chamber over a period of a few weeks, while the walls were heated to a temperature of 100°C to increase the rate of outgassing. The counter was then flushed out several times using the 90% krypton / 10% methane mixture with which the counter was finally filled to a pressure of 2-3 atmospheres.

Two 'O'-rings in the detector holder provided an effective vacuum seal and also, with three Allen screws, positioned the proportional counter. This assembly was inserted into the rotating vacuum seal at the center of the lower vacuum plate (see Figure 5.1) and a tapered groove in the detector holder prevented the proportional counter from slipping into the vacuum chamber. An agate disc was
araldited to the top of the counter to support the rotor when not suspended and in case of emergency.

**PROPORTIONAL COUNTER**

[Diagram of a proportional counter with labels for each component:
- Glass plate
- Glass-metal seal
- Beryllium tubing
- Fine .002" wire
- Krypton-methane mixture at 3 atm. pressure
- Aluminium insert
- Copper tubing to evacuate the chamber
- O-ring seals
- Detector holder
- E.H.T. connection
- Nylon spacer
- Taper to prevent detector from slipping into rotor]

**FIGURE 6.8**
3.1 Proportional Counter Response.

This design proved to be very satisfactory. The resolution of various segments of the counter is shown in Figure 6.9. The pulse height spectrum 1 was taken with a circular collimator of 1 cm diameter restricting the beam to the central portion of the detector. The resolution for the 14.4 kev peak is 16%. Spectra 2 and 3 were taken with the collimator moved towards the top of the detector and, as expected, they indicate the presence of end effects, which distort the spectra. This was tolerable, however, as the detection efficiency decreased as well.

Spectra 4 and 5 exhibit the detector response with the collimator moved to the side of the counter. The peaks are still in the same position but the detection efficiency has decreased. The overall resolution using no collimator is 20%, which is good enough to resolve the 14.4 keV peak during the high speed run when the beryllium skirt is used.

The dependence of the counting rate on the horizontal position of the rotor, with the system as finally assembled, was measured by displacing the rotor along the two axes of the damping springs. The change in the counting rate amounted to (.96 ± .08)% per 1 mm displacement of the rotor and was the same within experimental error for both of the absorber skirts. Later measurements indicated that the horizontal position of the rotor was stable to within .02 mm over a period of one week.
Figure 6.9

Proportional Counter

Useful Volume

Collimator with 1 cm circular aperture

Fe K\textsubscript{α} - 16% Resolution

Channel Number
The counting rate dependence on height was measured by varying the vertical position of the rotor over a range of ~2 mm, i.e., by changing the supply current by .5 amp. This caused a change in the counting rate of .105% per .1 amp change in the supply current. The counting rate also depended to some extent on the position of the tantalum collimator, which was used to shield the lower half of the proportional counter from the source radiation. As the angular asymmetry of the counting rate could be expected to depend on the height of the rotor, the suspension current was kept constant to within .02 amp over 24 hours.

3.2 Efficiency of the Proportional Counter.

The efficiency of the first detector made was 24%, and was measured by comparing its counting rate with that of a scintillation counter assumed to have a 100% efficiency. This low efficiency is partially caused by the electronic absorption in the 2 mm thick beryllium tubing (19%) and the finite absorption in the krypton-methane gas mixture (53%) for the relatively low gas pressures (1-2 atm) used in the first counter. The exact gas pressure could not be accurately assessed as it depended on the adsorption and leakage of the gas in the counter, which were not known. It was also found that only 50% of the radiation absorbed by the counter did appear under the 14.4 keV peak which was attributed to the escape of the 12.6 keV krypton K X-ray. This was substantiated by the size of the escape peak at 1.8 keV, which was of comparable magnitude to the 14.4 keV peak (see Figure 6.11).
In the later counters a thinner beryllium tubing (1 mm thick) and higher gas pressures (2-3 atmospheres) were used, which increased the detection efficiency to ~35%.

4. **Counter Electronics and Saturation Effects**

Even though the response of the various proportional counters was very similar, the voltages needed to give a satisfactory resolution varied from 1550 to 1700 volts and also depended partially on the noise level of the preamplifier (Nuclear Enterprises N.E. 5282), which was adjusted to have a gain of 18. The output of the preamplifier was further amplified and shaped by an Ortec 410 linear amplifier and then analyzed by a Hamner pulse height analyzer model NC-14A.

To determine the effect of high counting rates the resolution of the whole detection system was measured, as a function of the distance r between the uncollimated source and the detector, using the PHA of the 128 channel RCL kicksorter. The spectra shown in Figure 6.10 were taken with the 50 mCi strong $^{57}\text{Co}$ (Rh) source. They indicate a definite deterioration in the resolution for r<8 cm. This shows that there would be no saturation for the source-detector distance of 10 cm actually used in the rotor experiment. As part of the distortion in the spectra can be attributed to the kicksorter another set of measurements was taken using the Hamner PHA with the energy window set on the 14.4 keV peak. The ratio of the direct counting rate $\dot{N}_1$ and that $\dot{N}_2$ after interposing a .03 cm thick aluminum sheet, which halved the counting rate, was measured as a function of $\dot{N}_1$. 
Figure 6.10

$r = \text{DISTANCE BETWEEN THE UNCOLLIMATED SOURCE AND COUNTER}$
It was found that $\dot{N}_1 / \dot{N}_2$ stayed constant up to $\dot{N}_1 = 60,000$ cts/sec, which indicates that for smaller counting rates the electronics can be assumed to have a linear counting rate response.

It would have been interesting to examine if this saturation is a result of the detector or of the electronics, but this could not be easily done without faster electronics and a random pulse generator, which were not available. The specifications of the amplifier suggest, however, that it is due to the amplifier becoming saturated at these counting rates.

The Ortec amplifier was used in the double-delay-line shaping mode, which considerably improved the resolution compared with the single-delay-line and RC shaping modes (see Figure 6.11). The gain of the amplifier was adjusted to make the peak-to-valley ratio $P_1/V_1$ comparable with $P_2/V_2$, where $P_1$ and $P_2$ are the 14.4 keV peak and that caused by the limiting of the amplifier respectively. The levels of the PHA were set according to the criterion $\dot{N}_1 V_1 = \dot{N}_2 V_2$, so that small gain shifts would not appreciably change the counting rate. $\dot{N}_1$ and $\dot{N}_2$ are here the counting rates at $V_1$ and $V_2$. Furthermore, the EHT supply to the detector was adjusted to give, for the final setting of the PHA, a maximum counting rate. The overall stability of the counting rate during an actual rotor run was then found to be remarkably constant. Figure 6.12 shows the counts accumulated during a four day rotor run at 701 cps, each point representing a 85 min. measurement. The slope represents the
.257% decay of the source per day. The larger initial counting rate is a result of the rotor heating during acceleration.
5. **Principle of Operation.**

Figure 6.13 is a diagram of the principal layout of the electronics. The light beam $S$ reflected off a polished strip at the lower surface of the rotor was detected by a photomultiplier tube, the output of which was shaped to give a 12-volt 2 µsec long pulse $ST$. This served as a starting signal for the kicksorter sweep and, in conjunction with a 5245 HP electronic counter, as an accurate monitor of the rotor speed.

The output of the PHA went directly into the kicksorter or, as in the last stage of the experiment, via a by-4 dividing network. The kicksorter had been modified to run on a 16 channel sweep with the time spent per channel determined by an external multi-vibrator which could be adjusted so that $(16 + \varepsilon)$ channels corresponded to one revolution of the rotor. $\varepsilon$ amounted to ~7% of the sweep cycle, which was needed to allow the kicksorter to recover for a new starting pulse.

The kicksorter starting pulse $KST$ was derived from a logic circuit, which required the simultaneous presence of the $ST$ pulse, the OVERFLOW and the OPERATE bias levels from the kicksorter. These levels indicated when the kicksorter had truly come to the end of its sweep.

To allow for a double check of the total counts accumulated a scaler with 1 µsec response time was used to count the PHA output. This scaler as well as the kicksorter and two other scalers, the function of which will be discussed below,
were gated by a manually controlled starting switch. A time scaler, counting at 10 cps, determined the total time spent per run.

The following parameters were also continuously monitored throughout the experiment: the ± 24 volt and ± 12 volt bias supplies, the temperatures of the rotor structure, the PHA, and the kicksorter. They were measured by converting the DC levels into frequencies which could be directly monitored by the HP frequency
counter. At the later stages of the experiment the suspension current was also monitored because the visual display was not sufficiently accurate. These efforts proved to be worthwhile, as a number of anomalies in the counting rate could be readily traced to faulty bias supplies and be repaired without decelerating the rotor. The temperature measurements helped in the attempts to minimize electronic drifts, and an accurate monitoring of the suspension current was needed to eliminate the prime cause of a changing counting rate, i.e., a change in the rotor height. The resulting stability of the counting system was as shown in Figure 6.12.

6. **Kicksorter Accumulation.**

Even though 16 channels were used in the kicksorter only 14 could actually be used in the analysis. The first channel was the clock channel for other modes of operation and could not be easily altered to accept PHA pulses.

The second channel was lost because the channel advance multivibrator (CAM) was not synchronized with the rotor with the result that the slowing down of the rotor to the extent of .1% per run was not adjusted for. Also, the arrival of a CAM pulse during an accumulation cycle would delay the channel advance by a few microseconds, which produced a channel jitter. To avoid missing a KST pulse the CAM rate had to be adjusted so that there was on average a time delay of 7% (of total sweep time) between sweeps.
Attempts were made to synchronize the CAM rate with the rotor frequency but these were not successful because the channel jitter made it impossible to obtain a useful correction signal.

To determine accurately what fraction of the sweep cycle was missed two scalers counting 10 cps clock pulses were gated by the OVERFLOW and the OPERATE levels respectively (see Figure 6.13).

The kicksorter had provisions to count a number of clock pulses before advancing one channel. In our system every CAM pulse advanced the channel and so this provision of a comparator network produced only unnecessary dead time in the kicksorter. Eliminating this logic circuit reduced the time needed to advance one channel from 20 to 13 µsec, i.e., reduced the dead time at a rotor frequency of 700 cps from 21% to 13.6% (see Figure 6.14).

7. **Dead Time Effects.**

For the later analysis of the data it is essential that one understands the effect of the dead times occurring at the various stages of the accumulation cycle as large counting rates can give rise to saturation effects producing a non-linear response to changes in the counting rate.
DEAD TIME OF CHANNEL ADVANCE

CORRECTED FOR \( \epsilon \)

AT 700 CPS

FIGURE 6.14
Using the strong $^{57}$Co (Rh) source and a thin walled proportional counter the counting rates were in the region of 40,000 cts/sec subject to the decay of the source, the position of the rotor, and the window of the PHA. The investigation of the detector amplifier response indicates that there are no dead time effects up to a counting rate of 60,000 cts/sec. The PHA, with a response time of 1 µsec, will introduce a 4% dead time and the grand total scaler with a similar response time should not give rise to an additional dead time and can thus be taken to give a faithful account of the PHA output pulses.

The largest dead times will thus occur in the kicker sorter as it takes 14 µsec to accumulate one pulse. Assuming then that this dead time is not extended, i.e. that pulses arriving during an accumulation cycle do not further extend the dead time, one can write the accumulation rate $\dot{n}$ as (Rainwater and Wu, 1947).

$$\dot{n} = \frac{\dot{N}}{1 + \dot{N}\tau}$$  \hspace{1cm} ...7.1

where $\tau$ is the time of accumulation and $\dot{N}$ the number of PHA pulses per second.

Hence

$$\frac{\dot{N}}{\dot{n}} \frac{d\dot{n}}{dN} = 1/(1 + \dot{N}\tau)$$  \hspace{1cm} ...7.2

which means that for $\dot{N}\tau \ll 1$ the slope is constant and the response to a change in the counting rate linear. For large counting rates the accumulation rate will asymptote to $1/\tau$ and the slope $\frac{\dot{N}}{\dot{n}} \frac{d\dot{n}}{dN}$ will become zero. Considering this decrease in the slope with the statistical gain, which is proportional to $N^{1/2}$ one finds
that the overall sensitivity is maximum for 35,000 cts/sec. This sensitivity $S_1$ is shown in Figure 6.15 and the arrow denotes the point of operation during the high speed run with the $^{57}$Co (Rh) source.

To overcome this severe limitation a divider circuit can be incorporated between the PHA and the kicksorter, which would not only decrease the number of the pulses but also regularize their arrival. Using a by-m-divider network the probability for the occurrence of a pulse during a time interval $dt$ and a time $t$ after the arrival of a previous pulse is given by the Poisson distribution

$$P(t) = \frac{\hat{N}^m t^{m-1}}{(m-1)!} e^{-\hat{N}t}$$

from which the slope $\frac{\hat{N}}{\hat{n}} \frac{d\hat{n}}{dN}$ and the resultant sensitivity can be calculated (Elmore, 1950) as shown in Figure 6.15 for $m = 2, 4$ and 16. The increase in the sensitivity is quite appreciable.

The choice of $m$ is, however, limited by the rotor frequency. Taking $\hat{N}$ equal to 40,000 cts/sec and a rotor frequency of 700 cps, there will be on average 3.2 counts falling in each channel, which limits the scale of the dividing circuit to 4, if one does not want to average the angular dependent counting rate over more than 1.3 channels. Such a circuit has now been installed but new data are not yet available to be included in this thesis.

It would be possible to further increase the sensitivity if one could store the pulses occurring during the channel advance time. Such a logic circuit demanding
the simultaneous presence of a pulse and the OPERATE level was considered. The increase in the sensitivity for $m = 4$ and $16$ is also shown in Figure 6.15.
8. **Alignment and Stability.**

The aim of the experiment was to accurately monitor the angular and time dependent counting rate in \( n(\theta, t) \). To do this it was desirable to make all instrumental asymmetries as small as possible and ensure stable rotor running conditions. The instrumental effects, which could produce angular dependencies, consisted of the electronic asymmetry due to a non-equivalence of the 14 channels used, ii) the asymmetry of the detector response, and iii) the dependency of the counting rate on the rotor position.

Effect i) was found to produce an asymmetry of less than .05% and was thus negligible compared to the other two. Effect ii), upon rotation of the detector through 180°, produced a sinusoidal asymmetry of about 2.5%, which was probably the result of a misalignment between the axis of rotation of the detector and that of the rotor. The asymmetry also depended sensitively on the alignment of the tantalum collimator used to shield the lower portion of the counter. Once the detector had been positioned in the vacuum chamber, it was not possible to readjust it so that the position of the rotor was varied as a final parameter until the angular asymmetries in the counting rate were smaller than .2%. The adjustment was made at low rotor speed by moving the two adjustable damping assemblies.

As it was not thought that the angular dependent detector response would be as uniform as it turned out to be, provisions were made which allowed for a continuous rotation of the detector to average over the asymmetries. This meant rotating the whole table supporting the proportional counter, the EHT supply and the
amplifiers. Fortunately, this was not necessary, even though it was still desirable to rotate the detector at certain stages of the experiment to assess the effect of systematics on the error analysis of the data.

Once the system had been adjusted, it exhibited a remarkable long term stability. Figure 6.16 shows the total counts (~10^8) accumulated in each of the 14 channels during one day, i.e. 22 hours and 40 minutes of actual accumulation time, for 5 consecutive days. The asymmetry is .26% and is constant to within .02%. The 'short' term stability is shown in the second graph of Figure 6.16. It was obtained by dividing the day into four equal parts and displaying the counts accumulated in each during four consecutive days. This shows that the asymmetry is constant to within .015%, which suggests that there were no observable diurnal variations in the counting rate.

During the experiment it was found, however, that the angular asymmetry was not constant for different rotor speeds (see Section 6.11). In order to find if this was a physical or an instrumental effect, attempts were made to monitor the rotor position. Such a measurement has to be sensitive to changes in the rotor position of .05 mm or less and it is not easy to obtain such an accuracy by conventional means. One system built consisted of an oscillator which measured the rotor position capacitatively. The frequency of the oscillator changed by ~1% for a 1 mm change in the rotor position, but the system was not very stable, the temperature coefficient being .02% per °C and the voltage coefficient .05% per 1% change in the supply voltage. As the oscillator was installed in the vacuum system, several other
problems arose, caused by the mercury contacts used to connect the oscillator to the external power supplies and amplifier which made the measurement impracticable.
Another measuring device is presently installed, which detects a change in the core position to a potential accuracy of .01 mm, but as this does not measure the rotor position nor the imbalance of the rotor motion directly, the measurement is not very reliable.

9. **Data Display.**

Because of the high stability of the suspension system a simple program of data acquisition could be used. 16 runs each lasting 85 minutes were taken over a 24 hour period. The resulting 16 x 16 data points were arranged in a matrix and separately analyzed for each day. Because only 14 channels were used zeroes were substituted for the remaining two channels.

As one would classically expect a diurnally varying counting rate one can sum along the diagonals in the matrix (see Figure 6.17) so as to average out the instrumental asymmetries while superimposing the effects of an aether drift.

In order to give each row, i.e. each run, of the matrix equal weight the elements $a_{ij}$ were multiplied by $16 \sum_{j=1}^{16} a_{ij} / \sum_{i,j=1}^{16} a_{ij}$. This correction amounted usually to less than .05%, determined mostly by the decay rate of the source of .257%/day.

The sums $C_j$ of the elements along the 16 columns then give directly the instrumental asymmetries previously displayed in Figure 6.16. By summing the elements along the two diagonals one transforms the data into two frames of reference, one stationary in respect to the fixed stars and the other rotating at twice
the angular velocity of the earth, the sums for the respective frames denoted by $x_k$ and $y_n$. Fitting these values to a sine-function one can analyze their statistical behavior knowing that only the $x_k$ values would exhibit aether drift effects, while both would be equally affected by systematics.

![Figure 6.17](image)

**Figure 6.17**
A computer was used to calculate

\[ X^m(A, \varphi) = \frac{1}{15} \sum_{k=1}^{16} \left( x_k - A \sin \left( \frac{2\pi k}{16} + \varphi \right) \right)^2 \]  

...9.1.

\[ Y^m(B, \delta) = \frac{1}{15} \sum_{n=1}^{16} \left( y_n - B \sin \left( \frac{2\pi n}{16} + \delta \right) \right)^2 \]  

...9.2.

for the \( m \) different run series, where \( A \) and \( B \) were varied in 16 incremental steps to a maximum value of about \( 3 \times 10^{-4} \) \( x_k \) depending on the total counts accumulated. Similarly the phases of \( \varphi \) and \( \delta \) were varied in 16 steps making up \( 2\pi \). From the resulting 16 x 16 array the values \( A_0, \varphi_0 \) and \( B_0, \delta_0 \) could be found, which minimized \( X^m(A, \varphi) \) and \( Y^m(B, \delta) \). The associated errors could also be readily found after applying a dead time correction.

10. **Running Time.**

In total 40 run series each lasting 24 hours were taken. The run series were well spread over the whole year with five major ones taken in July, August, October, April and May. Table 6.5 shows the number of run series taken with the corresponding source-absorber combinations. The slopes shown are deduced from the actual changes in the counting rate observed during the rotor runs.
### Table 6.5.

<table>
<thead>
<tr>
<th>Number of run series</th>
<th>Number of runs</th>
<th>Rotor frequency</th>
<th>Source</th>
<th>Absorber</th>
<th>Slope $\left( \frac{\nu}{N} \frac{dN}{d\nu} \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>66</td>
<td>60</td>
<td>$^{57}$Co(Pd)</td>
<td>S.F.C. ($T_a = 8$)</td>
<td>$1.22 \times 10^{11}$</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>200</td>
<td></td>
<td></td>
<td>$1.35 \times 10^{11}$</td>
</tr>
<tr>
<td>19</td>
<td>328</td>
<td>425</td>
<td></td>
<td></td>
<td>$1.15 \times 10^{11}$</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>250</td>
<td>$^{57}$Co(Rh)</td>
<td>S.F.C. ($T_a = 4$)</td>
<td>$1.16 \times 10^{11}$</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>495</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>676</td>
<td></td>
<td></td>
<td>$1.30 \times 10^{11}$</td>
</tr>
<tr>
<td>1</td>
<td>19</td>
<td>250</td>
<td>$^{57}$Co(Rh)</td>
<td>S.F.C. ($T_a = 8$)</td>
<td>$1.96 \times 10^{11}$</td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>650</td>
<td></td>
<td></td>
<td>$1.75 \times 10^{11}$</td>
</tr>
<tr>
<td>9</td>
<td>151</td>
<td>701</td>
<td></td>
<td></td>
<td>$2.18 \times 10^{11}$</td>
</tr>
</tbody>
</table>

11. **Data Analysis.**

Assuming the presence of an aether drift in a westerly direction and a clockwise rotor motion, the energy of the source when pointing North, as seen by the absorber, will be increased. This would produce a decrease in the counting rate when operating at the lower point of inflection and an increase at the higher point of
inflection. One then obtains the following normalized angular dependent counting rates (see Section 4.3).

\[
\dot{n}(\theta) = 1 + \frac{U V}{c^2} \left(1 + \delta \left(\frac{V}{c}\right)\right) \sin \theta
\]

\[
= 1 + A_o^m \left(\frac{N}{\nu} \frac{d\nu}{dN}\right) \left(\frac{\dot{n}}{\bar{N}} \frac{d\bar{N}}{d\bar{n}}\right) \sin \varphi
\]

...11.1 a

...11.1 b

where \(\left(\frac{\nu}{N} \frac{dN}{d\nu}\right)\) is the slope of the resonance at the operating rotor velocity and \(R_m\) is the corrected sum of the row elements for run series \(m\). The factor \(\frac{\dot{n}}{\bar{N}} \frac{d\bar{N}}{d\bar{n}}\) corrects for the decrease in the counting rate response of the kicksorter and amounts to \((1 + \bar{N} \tau)\).

The aether drift is then simply to first order

\[
V^m = \frac{A_o^m}{R_m^m} \left(\frac{N}{\nu} \frac{d\nu}{dN}\right) \left(1 + \bar{N} \tau\right) \frac{c^2}{U}
\]

...11.2.

The parameters that can be extracted from the data are \(V^m\) and \(\varphi^m\), the phase angle between \(V\) and \(V^m\), and analogously \(I^m\) and \(\delta^m\) which are the instrumental effects as deduced from equation 6.11.2 by substituting \(B_o^m\) for \(A_o^m\). By comparing \(V^m\) with \(I^m\) one can differentiate between real and instrumental effects and determine the statistical significance of any fluctuations observed.

Even though a total of 40 run series were taken, only those results will be discussed that were obtained with the \(^{57}\text{Co}(\text{Rh})\) source as the accuracy of one run series taken with the stronger source was comparable to the combined result of all
the runs taken with the weaker source. The latter result was \( V < (2.1 \pm 16) \text{ cm/sec} \) and is displayed with the more accurate data. In table 6.6 the result of the 11 high speed run series is shown. The asterisk denotes the run that was taken with the thin absorber (\( T_a = 4 \)).

### Table 6.6

<table>
<thead>
<tr>
<th>Run series</th>
<th>Rotor frequency</th>
<th>( V^m ) (cm/sec)</th>
<th>( \phi^m_0 ) (0° = N)</th>
<th>( I^m ) (cm/sec)</th>
<th>( \delta^m_0 ) (0° = N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25*</td>
<td>678</td>
<td>19.0</td>
<td>350</td>
<td>9.8</td>
<td>230</td>
</tr>
<tr>
<td>27</td>
<td>650</td>
<td>5.6</td>
<td>250</td>
<td>13.6</td>
<td>350</td>
</tr>
<tr>
<td>28</td>
<td>650</td>
<td>9.3</td>
<td>45</td>
<td>9.85</td>
<td>180</td>
</tr>
<tr>
<td>29</td>
<td>701</td>
<td>7.75</td>
<td>155</td>
<td>3.4</td>
<td>225</td>
</tr>
<tr>
<td>30</td>
<td>701</td>
<td>9.75</td>
<td>190</td>
<td>8.75</td>
<td>45</td>
</tr>
<tr>
<td>31</td>
<td>701</td>
<td>16.2</td>
<td>30</td>
<td>3.0</td>
<td>215</td>
</tr>
<tr>
<td>32</td>
<td>701</td>
<td>5.45</td>
<td>20</td>
<td>2.0</td>
<td>190</td>
</tr>
<tr>
<td>33</td>
<td>701</td>
<td>15.5</td>
<td>315</td>
<td>3.6</td>
<td>270</td>
</tr>
<tr>
<td>35</td>
<td>701</td>
<td>3.4</td>
<td>250</td>
<td>5.0</td>
<td>340</td>
</tr>
<tr>
<td>36</td>
<td>701</td>
<td>9.35</td>
<td>190</td>
<td>3.0</td>
<td>0</td>
</tr>
<tr>
<td>37</td>
<td>701</td>
<td>6.95</td>
<td>215</td>
<td>7.15</td>
<td>90</td>
</tr>
</tbody>
</table>

\( V_{AVE}^m = 9.82 \text{ cm/sec} \) \( I_{AVE}^m = 6.28 \text{ cm/sec} \)

Averaging the magnitudes of \( I^m \) and \( I^m \) one finds that the former exhibit a larger fluctuation than those values representing the pure instrumental effects. This is further brought out by displaying the results in polar diagrams. Figure 6.18 shows the \( V^m \) values relative to north, the direction in which one would classically expect a larger counting rate. Several runs do indeed show a larger fluctuation in that
direction unlike the results of $I^m$ shown in Figure 6.19 which are more evenly weighted in all directions. In the error analysis given below one finds, however, that the results are well within statistics and that the experiment is not sensitive enough to distinguish between real and instrumental effects. Adding vectorially the results for the 11 run series at high speed and the 19 at low speed one obtains $\nu < (2.0 \pm 5.2) \text{ cm/sec}$ compared to $\nu < (0.7 \pm 5.2) \text{ cm/sec}$.

**Table 6.7**

<table>
<thead>
<tr>
<th>Run Series</th>
<th>Rotor Speed</th>
<th>$R^a$</th>
<th>$R^b$</th>
<th>$\lambda^a(0)$</th>
<th>$\lambda^b(0)$</th>
<th>$\lambda^a(A_{0})$</th>
<th>$\lambda^b(B_{0})$</th>
<th>$\lambda^a(X_1)$</th>
<th>$\lambda^b(Y_1)$</th>
<th>$\lambda^a(X_2)$</th>
<th>$\lambda^b(Y_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>CPS</td>
<td>$x10^6$</td>
<td>$x10^6$</td>
<td>$x10^6$</td>
<td>$x10^6$</td>
<td>$x10^6$</td>
<td>$x10^6$</td>
<td>$x10^6$</td>
<td>$x10^6$</td>
<td>$x10^6$</td>
<td>$x10^6$</td>
</tr>
<tr>
<td>22+</td>
<td>250</td>
<td>94.68</td>
<td>42.9</td>
<td>56.6</td>
<td>40.0</td>
<td>21.0</td>
<td>25.8</td>
<td>19.8</td>
<td>14.0</td>
<td>7.4</td>
<td>9.1</td>
</tr>
<tr>
<td>23+</td>
<td>250</td>
<td>92.46</td>
<td>41.8</td>
<td>221.8</td>
<td>173.5</td>
<td>187.2</td>
<td>140.8</td>
<td>79.5</td>
<td>62.0</td>
<td>66.8</td>
<td>50.5</td>
</tr>
<tr>
<td>26</td>
<td>250</td>
<td>82.43</td>
<td>42.8</td>
<td>165.4</td>
<td>99.0</td>
<td>51.0</td>
<td>35.0</td>
<td>59.4</td>
<td>35.5</td>
<td>18.3</td>
<td>12.5</td>
</tr>
<tr>
<td>AVE.:</td>
<td></td>
<td>89.86</td>
<td>42.5</td>
<td>148.0</td>
<td>104.2</td>
<td>86.4</td>
<td>67.2</td>
<td>52.9</td>
<td>37.1</td>
<td>30.8</td>
<td>24.0</td>
</tr>
<tr>
<td>24+</td>
<td>495</td>
<td>84.21</td>
<td>39.2</td>
<td>63.8</td>
<td>106.4</td>
<td>40.2</td>
<td>67.8</td>
<td>24.4</td>
<td>33.9</td>
<td>15.4</td>
<td>25.9</td>
</tr>
<tr>
<td>34</td>
<td>701</td>
<td>87.28</td>
<td>36.7</td>
<td>197.5</td>
<td>165.7</td>
<td>24.1</td>
<td>35.5</td>
<td>82.0</td>
<td>68.5</td>
<td>10.0</td>
<td>14.7</td>
</tr>
<tr>
<td>25+</td>
<td>678</td>
<td>79.60</td>
<td>36.3</td>
<td>25.0</td>
<td>23.6</td>
<td>10.6</td>
<td>19.7</td>
<td>10.4</td>
<td>9.8</td>
<td>4.4</td>
<td>8.2</td>
</tr>
<tr>
<td>27</td>
<td>650</td>
<td>87.69</td>
<td>37.2</td>
<td>17.4</td>
<td>43.3</td>
<td>15.0</td>
<td>29.4</td>
<td>7.0</td>
<td>17.5</td>
<td>6.1</td>
<td>11.9</td>
</tr>
<tr>
<td>28</td>
<td>650</td>
<td>87.76</td>
<td>37.3</td>
<td>39.4</td>
<td>32.3</td>
<td>32.9</td>
<td>25.0</td>
<td>15.9</td>
<td>13.0</td>
<td>13.2</td>
<td>10.0</td>
</tr>
<tr>
<td>29</td>
<td>701</td>
<td>87.40</td>
<td>36.1</td>
<td>23.3</td>
<td>28.4</td>
<td>15.2</td>
<td>27.0</td>
<td>9.6</td>
<td>11.8</td>
<td>6.3</td>
<td>11.2</td>
</tr>
<tr>
<td>30</td>
<td>701</td>
<td>87.44</td>
<td>36.1</td>
<td>39.7</td>
<td>46.5</td>
<td>26.9</td>
<td>36.3</td>
<td>16.4</td>
<td>19.3</td>
<td>11.1</td>
<td>15.0</td>
</tr>
<tr>
<td>31</td>
<td>701</td>
<td>87.39</td>
<td>36.4</td>
<td>82.9</td>
<td>24.7</td>
<td>47.2</td>
<td>23.8</td>
<td>34.3</td>
<td>10.3</td>
<td>19.5</td>
<td>9.9</td>
</tr>
<tr>
<td>32</td>
<td>701</td>
<td>87.31</td>
<td>36.5</td>
<td>42.1</td>
<td>30.1</td>
<td>37.8</td>
<td>29.5</td>
<td>17.5</td>
<td>12.5</td>
<td>15.7</td>
<td>12.2</td>
</tr>
<tr>
<td>33</td>
<td>701</td>
<td>87.28</td>
<td>36.5</td>
<td>55.6</td>
<td>25.0</td>
<td>23.3</td>
<td>23.3</td>
<td>23.0</td>
<td>10.4</td>
<td>9.7</td>
<td>9.7</td>
</tr>
<tr>
<td>35</td>
<td>701</td>
<td>87.64</td>
<td>36.8</td>
<td>27.8</td>
<td>39.3</td>
<td>26.4</td>
<td>36.1</td>
<td>11.5</td>
<td>16.2</td>
<td>10.9</td>
<td>14.9</td>
</tr>
<tr>
<td>36</td>
<td>701</td>
<td>86.78</td>
<td>36.7</td>
<td>60.7</td>
<td>40.6</td>
<td>48.8</td>
<td>39.5</td>
<td>25.1</td>
<td>16.8</td>
<td>20.1</td>
<td>16.3</td>
</tr>
<tr>
<td>37</td>
<td>701</td>
<td>87.18</td>
<td>36.8</td>
<td>32.1</td>
<td>41.3</td>
<td>25.7</td>
<td>34.3</td>
<td>13.2</td>
<td>16.9</td>
<td>10.5</td>
<td>14.1</td>
</tr>
<tr>
<td>AVE.:</td>
<td></td>
<td>86.72</td>
<td>36.6</td>
<td>40.5</td>
<td>34.1</td>
<td>28.1</td>
<td>29.4</td>
<td>16.4</td>
<td>13.7</td>
<td>11.4</td>
<td>11.8</td>
</tr>
</tbody>
</table>

The real difficulty in the analysis arises when trying to assess the statistical and systematical errors. To do this accurately one would have to know the
exact behavior of the kicksorter under high counting rates. In the above analysis it was assumed that the kicksorter (type RCL) has a non-extended dead time and no buffer storage. While the first assumption is realistic the second assumption could not be verified without fully understanding the logic circuitry used in the kicksorter. Empirically it was found that the counts accumulated in the kicksorter did approximately follow the dependence expressed by equation 6.7.1, which substantiated the two assumptions made.

In that case one can calculate the expected variance under high counting rates (Feller, 1948) given by

\[ \sigma^2 = \frac{n}{(1 + N \tau)^2} \]  

...11.3.

Where \( \sigma \) is the standard deviation of \( n \) counts accumulated. Table 6.7 gives, for the individual run series, the average of the total counts accumulated in the 16 effective channels \( x_k \) and \( y_n \) (equal to \( R^m \)) and the expected variance \( R^m / (1 + N \tau)^2 \) denoted by \( R^m \). The actually determined sample deviations

\[ X^m(0) = \frac{1}{15} \sum_{k=1}^{16} (x_k - \bar{x})^2 \]  

...11.3a

\[ Y^m(0) = \frac{1}{15} \sum_{n=1}^{16} (y_n - \bar{y})^2 \]  

...11.3b

can then be directly compared with the expected variance to determine the
FIGURE 6.18

$V \leq 2.0 \pm 5.2 \text{ cm/sec}$
FIGURE 6.19

\[ I < 0.7 \pm 0.2 \text{ cm/sec} \]
consistency of the results. $X^m(0)$ and $Y^m(0)$ are also shown in table 6.7, as well as the fitted values $X^m(A_o, \varphi_o)$ and $Y^m(B_o, \delta_o)$. Considering the run series taken at high speed ($m = 25, 27-33, 35-37$), one finds that the sample deviations agree well with the expected variances with a suggestion that the $X^m(0)$ values are larger than the $Y^m(0)$ values. To analyze these figures more quantitatively the values of $X^2$ have been calculated, where

$$X^2_{15}(X^m(0)) = \frac{\sum_{k=1}^{16}(x_k - \bar{x})^2}{R_c^m} = \frac{15X^m(0)}{R_c^m}$$  \hspace{1cm} \text{...11.4a}

$$X^2_{15}(Y^m(0)) = \frac{15Y^m(0)}{R_c^m}$$  \hspace{1cm} \text{...11.4b}

$$X^2_{13}(X^m(A_o, \varphi_o)) = \frac{15X^m(A_o, \varphi_o)}{R_c^m}$$  \hspace{1cm} \text{11.4c}

$$X^2_{13}(Y^m(B_o, \delta_o)) = \frac{15Y^m(B_o, \delta_o)}{R_c^m}$$  \hspace{1cm} \text{11.4d}

The subscripts of $X^2$ denote the number of degrees of freedom of the respective experimental values.

The expected values are $X^2_{15} = 14.3^{+5.9}_{-4.5}$ and $X^2_{13} = 12.3^{+5.4}_{-4.1}$. Considering again the high speed run series ($m = 25, 27-33$ and $35-37$), one finds that the average values of equation 6.11 fall well within the expected $X^2$ intervals, but that $X^2(X^m(0))_{AVE}$ is somewhat larger than $X^2(Y^m(0))_{AVE}$. This fact is further brought out by considering the individual values. Whereas all the values of $X^2_{15}(Y^m(0))$ and $X^2_{13}(Y^m(B_o, \delta_o))$ fall
within the expected interval, five values of each $X_{15}^2(X(0))$ and $X_{15}^2(X(A_i,\phi))$ fall outside the interval indicating that the $X^n$ values have a significantly higher fluctuation, i.e. those terms that are sensitive to aether drift effects show a larger deviation.

One might argue, however, that in an experiment of the present type, where one compares the data taken over a 24 hour period, one would inevitably expect some excess fluctuations to occur. In fact, the results are so consistent with $X^2$ and some values even smaller than expected, that one might be skeptical if there isn't some additional smoothing effect that averages the data during accumulation. Such an effect cannot be ruled out on our present knowledge of the operation of the kicksorter. Certainly if the fluctuations are as low as indicated above then the method of analysis used here is well justified and added confidence is given to the results.

That the analysis does indeed show up instrumental effects is brought out by run series 34 where a deliberate asymmetry of 2.5% was introduced by rotating the proportional counter. The values of $X_{15}^2(X^{34}(0))$ and $X_{15}^2(Y^{34}(0))$ fall well outside the interval, whereas the fitted values do agree satisfactorily suggesting that the asymmetry could be well represented by a sine-function.
## Table 6.8

<table>
<thead>
<tr>
<th>Run Series</th>
<th>( I^m ) (cm/sec)</th>
<th>( \phi^m_o ) (0° = North)</th>
<th>( J^m ) (cm/sec)</th>
<th>( \delta^m_o ) (0° = North)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25+</td>
<td>19.0 ± 30.1</td>
<td>350 ± 110</td>
<td>9.8 ± 30.3</td>
<td>230 ± large</td>
</tr>
<tr>
<td>27</td>
<td>5.6 ± 22.1</td>
<td>250 ± large</td>
<td>13.6 ± 22.6</td>
<td>350 ± 110</td>
</tr>
<tr>
<td>28</td>
<td>9.3 ± 21.5</td>
<td>54 ± large</td>
<td>9.85 ± 21.5</td>
<td>180 ± large</td>
</tr>
<tr>
<td>29</td>
<td>7.75 ± 15.9</td>
<td>155 ± large</td>
<td>3.4 ± 16.3</td>
<td>225 ± large</td>
</tr>
<tr>
<td>30</td>
<td>9.75 ± 16.3</td>
<td>190 ± 110</td>
<td>8.75 ± 16.3</td>
<td>45 ± 170</td>
</tr>
<tr>
<td>31</td>
<td>16.2 ± 16.2</td>
<td>30 ± 60</td>
<td>3.0 ± 16.2</td>
<td>215 ± large</td>
</tr>
<tr>
<td>32</td>
<td>5.45 ± 16.7</td>
<td>20 ± large</td>
<td>2.0 ± 16.5</td>
<td>190 ± large</td>
</tr>
<tr>
<td>33</td>
<td>15.5 ± 16.3</td>
<td>315 ± 60</td>
<td>3.6 ± 16.5</td>
<td>270 ± large</td>
</tr>
<tr>
<td>35</td>
<td>3.4 ± 16.5</td>
<td>250 ± large</td>
<td>5.0 ± 16.5</td>
<td>340 ± large</td>
</tr>
<tr>
<td>36</td>
<td>9.35 ± 16.5</td>
<td>190 ± 120</td>
<td>3.0 ± 16.5</td>
<td>0 ± large</td>
</tr>
<tr>
<td>37</td>
<td>6.95 ± 16.5</td>
<td>215 ± large</td>
<td>7.15 ± 16.5</td>
<td>90 ± large</td>
</tr>
<tr>
<td>8-21</td>
<td>2.1 ± 16.0</td>
<td>340 ± large</td>
<td>.5 ± 16.0</td>
<td>120 ± large</td>
</tr>
</tbody>
</table>

The results of the other runs \( (m = 22, 23, 26) \) further show that the analysis is affected by instrumental effects. During those runs the +12 volt supply line was observed to fluctuate by .2 volt causing a .6% change in the counting rate, and also during these short run series the system did not have time to come to an equilibrium. These factors are brought out by the excess fluctuations observed for these run series.
In order to determine the errors associated with the values of $V_m^m$, $\varphi_o^m$ and $I^m$, $\delta_o^m$ quoted previously, the 16 x 16 arrays of $X^m(A, \varphi)$ and $Y^m(B, \delta)$ were analyzed to find those values of $A_1$ and $B_1$ that would increase $X^m(A_o, \varphi_o)$ and $Y^m(B_o, \delta_o)$ by $R_m^c$, i.e. by one standard deviation. The errors for the two phases $\varphi_o^m$ and $\delta_o^m$ were found similarly; however, for some of the run series the dependence of phase was not very strong so that no definite error could be assigned to them. The final values and associated errors are shown in Table 6.8.

As discussed before, the values for $V_m$ fall within statistics. The limit set by the present experiment on effects arising from the translational motion of the earth is $(2.0 \pm 5.2) \text{ cm/sec}$ with $\varphi_o = 340^\circ \pm$ large.

In the above analysis only that component of $V$ arising from the translational velocity of the earth has been considered. To put a limit on effects arising from the rotation of the earth, which would appear as a time independent asymmetry in $\dot{n}(0)$ at a given rotor speed, one would have to analyze $\dot{n}(0)$ for two different velocities, preferably at points located at opposite sides of the resonance curve. This was done for rotor frequencies of 250, 495 and 676 cps. The angular asymmetries measured at these speeds are shown in Figure 6.20. As the experiment is insensitive to the aether drift at 495 cps, one can determine the net changes in the asymmetry for the run series taken at 250 cps and 676 cps, which are shown in Figure 6.21. The results indicate that $\dot{n}(0)$ has changed appreciably even though none of the other experimental parameters has been altered. The 'aether drift'
deduced from the high speed run is 3.6 m/sec. As, however, the asymmetry observed for the low speed run is comparable with that at 676 cps and not smaller, as one would expect because of the lower sensitivity at low speeds one can conclude that the observed asymmetry is caused by instrumental effects. To establish this more conclusively, one has to monitor the position of the rotor as a function of its velocity. The difficulties inherent in such a measurement have been discussed previously, but nevertheless a system is presently installed to measure the position of the core from which the time averaged position of the rotor can be deduced.

12. Future Improvements.

In order to investigate some of the problems discussed in this chapter, it is planned to have another series of runs lasting several weeks. Even though the source has decayed since the last run series by .7 of one half life, it should still be possible, with a number of improvements, to achieve a higher sensitivity than before. Assuming that the efficiency of the present counter has not changed, so that, with the present source, one would obtain a counting rate of 25,000 cts/sec, the sensitivity would be increased by a factor of 1.7 by introducing the by-4 divider network between the PHA and the kicksorter. Furthermore, a more uniform S.F.C. absorber would increase the sensitivity by another factor of 1.4, which would give an overall increase in sensitivity of 2.4. This should be a sufficient increase to
investigate in more detail the fluctuations observed at high speed, and would also reduce the limit to the 2 cm/sec level.
The ultimate sensitivity of the experiment is limited by the saturation effects observed with the present counting electronics and the maximum tip speed of the rotor. Assuming one could get a ~60 mCi source one would obtain the optimum counting rate, which would improve the sensitivity by a factor of 2.6. As shown in Figure 5.8 the top part of the rotor is designed for a tip velocity of 700 m/sec, which is more than twice the velocity used in the experiment. As the maximum speed does, however, depend on the strength of the rim and the bond between the rotor and the absorber skirt, both of which cannot be directly calculated, it is questionable if the speed can be much increased. The practical limit is 950 cps for a copper source and a chromium absorber, which would increase the sensitivity by 1.35 and the total sensitivity using maximum counting rates by about 5 over that achieved with the present experiment. This, however, would only improve upon the result obtainable with the present source by a factor of 2, which does not really warrant the expense of a new source. It appears thus that the experiment has reasonably well exhausted the potential accuracy of the equipment.

13. **Discussion.**

Figure 6.22 shows the result of the present experiment in relation to the ones previously conducted. The limit set on the existence of a preferred frame of reference is about six orders of magnitude smaller than that due to the motion of the earth around the sun.
In the spirit of the analysis given by Robertson, one would distinguish between the two frames of reference $X$ and $X'$, one at rest and the other in motion relative to the 'fixed stars.' In a four dimensional Euclidian space the four coordinates are then related by

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2 dt^2$$

where rods and clocks are used to measure space-like and time-like intervals. In the second coordinate frame moving along the x-axis with velocity $v$ relative to the rest frame

$$ds^2 = g_{x^2} dx^2 + g_{y^2} (dy^2 + dz^2) - g_{t^2} c^2 dt^2$$

where the coordinates are measured in the moving frame and are given by the Lorentz transformation expressed by equation 4.2.1. The quantities $g_{0}, g_{1}, g_{2}$ are given by

$$g_{0} = a_{0}^{x} / \gamma$$

$$g_{1} = a_{1}^{x} / \gamma$$

$$g_{2} = a_{2}^{x}$$

where $a_{1}^{x}$ is the transformation coefficient between $dx$ and $dx'$, $a_{2}^{x}$ that between the other spatial coordinates and $a_{0}^{x}$ that between $dt$ and $dt'$. Because of the Lorentz invariance of $ds^2$ the special theory of relativity fully determines the three quantities $g_{1} = g_{2} = g_{0} = 1$. In general to check the equivalence between the two frames of reference $X$ and $X'$, one would have to experimentally determine the set of three quantities.
**Figure 6.22**

- Earth's translational velocity
- Kennedy + Thorndike - Optical
- Michelson + Morley - Optical
- Essen - Microwave
- Joos - Optical
- Jaseja et al. - Laser

---

- Champeney + Moon - ME
- Cedarholm et al. - Ammonia maser
- Cranshaw + Hay - ME
- Turner + Hill - ME
- Champeney et al. - ME

---

- Present experiment
According to Robertson the experiments of Michelson and Morley, Kennedy and Thorndike, and Ives and Stilwell measure the respective quantities \( g_1/g_2, \ g_0/g_1, \) and \( g_0 \) and so fully determine the transformation properties between frames \( X \) and \( X' \). Accurate measurements of these quantities then would not only serve as a test of the fundamental postulates of the special theory and the Lorentz transformation but also as a sensitive method to detect any anisotropies in the propagation of light.

Taking the translational velocity of the earth around the sun as the relevant velocity parameter, the above experiments establish the g- coefficients to the following accuracies:

i) the most accurate optical experiment by Joos (1938) established \( g_1/g_2 \) to within 1 part in 400,

ii) the Kennedy and Thorndike experiment determines \( g_0/g_1 \) to within 1 part in 4 and the experiment by Jaseja et al. (1964) improves this to 1 part in \( 10^3 \),

iii) the result obtained by Mandelberg and Witten establishes \( g_0 \) to within 1 part in 20, and the more accurate experiments conducted using the Mössbauer effect improve this result by a factor of 4.5.

Considering the present experiment in this context, one finds that it is sensitive to both \( g_0 \) and \( g_0/g_1 \) (see section 4.3). It establishes \( g_0 \) to within 3 parts in \( 10^{12} \). As the experiment is sensitive to the second order terms (in equation 4.3.6), which are affected by the Lorentz-Fitzgerald contraction, it determines \( g_0/g_1 \) to an accuracy of 3 parts in \( 10^4 \).
In the above analysis the earth’s translational velocity was taken as the relevant parameter. In order to establish the true local rest frame in the cosmological sense one would not only have to know the mass-velocity distribution of the universe but also the detailed interaction between local and distant matter. One approach to the latter problem is given by the theory of inertia as developed by Sciama (1953). According to this theory the contribution of matter to local inertia falls off with the inverse of the distance, so that the relative contributions of the earth, sun, and our galaxy to local inertia are $10^{-9}$, $10^{-8}$ and $10^{-7}$ respectively, i.e. are negligible compared to the contribution of the universe as a whole. Thus, if one takes the inertial forces as a criterion for determining the local rest frame one might well find that the relevant velocities for the aether drift experiment are much larger than those considered here, as they would be determined by the velocity distribution of distant matter, which could be large indeed. In this context the present experimental results would then establish the principle of relativity to an even higher accuracy.


It has recently been suggested (Fox, 1962, 1965) that the emission theories of light, which stand in contradiction to the special theory of relativity, have not been as thoroughly disproven as had generally been thought. As in these theories light is considered to be emitted with velocity $c$ relative to the source, the outcome of the present experiment would become self evident. Hence it is desirable at this point to
briefly review the main experiments conducted recently, that have now provided the evidence against such theories.

Before 1962 the main evidence came from the observation of binary stars, but as Fox pointed out this evidence was not conclusive as the effect of the extinction and reemission of light in interstellar matter had not been considered. According to Ewald and Oseen, primary radiation (of wavelength \( \lambda \)) when entering a medium with index of refraction \( n \), is extinguished in a distance \( d = \frac{\lambda}{2\pi(n-1)} \) and is replaced by secondary radiation (of same frequency but different propagating velocity), which is emitted by the forced oscillations of the radiating dipoles in the medium.

Experiments designed to test the emission hypothesis must thus be entirely free of extinction effects in order to give a conclusive result. Kantor (1962), who performed the first optical experiment in which this condition was met, did obtain a result consistent with the emission hypothesis. Later, more carefully conducted experiments (Babcock and Bergman, 1964; Beckman and Mandice, 1964), did give results consistent with the special theory of relativity.

The more convincing experiments are those conducted with high energy gamma rays, even though they are subject to some extinction effects in the target material. The most accurate experiment and one in which the extinction length between source and absorber was the smallest so far reported, less than .03 d, was performed by Alvager et al. (1964), who measured the time of flight of gamma rays produced by the decay of 6 GeV \( \pi^o \) mesons and found it to be consistent with \( c \) to an accuracy of 2 parts in \( 10^4 \).
This result was also verified by the present author, in an experiment suggested by A.M. Khan, by using the $^{57}$Co(Rh) source and a stainless steel absorber. The geometry of the experiment was as shown in Figure 6.23, where the source was mounted on a motion device outside of the vacuum chamber and a Mylar window allowed the radiation to penetrate through the chamber walls. The radiation passing through the collimators was dragged by the beryllium skirt of the rotor, which was spinning at approximately 10 cps. If the propagating velocity of the 14.4 kev radiation had been modified by the motion of the beryllium skirt, which had an extinction length of about $1.5 \times 10^3 d$, then the resonance dip with the .0001" thick stainless steel absorber (with an extinction length smaller than 3d) should have been markedly decreased. Instead the $R_m$ observed with the spinning rotor was consistent to better than 3.5\% with the $R_m$ determined for the case of no rotor, which is in satisfactory agreement with expectations.

These experiments do indicate that the propagation of light is unaffected by the motion of the source and, in conjunction with the aether drift experiment, represents a most accurate verification of the fundamental postulates of the special theory of relativity.
REFERENCES


Bondi, H. (1957), Discovery 18, 505.

Bondi, H. (1962) Observatory 82, 133.

Bondi, H. see also Moeller (1962).


Essen, L. (1955) Nature 175, 793.

Evans, M.J. (1968) private communication and unpublished data.


Fitzgerald, G.F. (1890) see Phil. Trans Roy. Soc. A 184, 749 (1893).


Janossy, L. (1962) unpublished manuscript


Joos, G. (1931) Natureviss, 38, 784.


Lodge, O.J. (1893) Phil. Trans. 184, 727.


Malmfors, K.G. (1952) Arkiv F. Fysik, 6, 49.


Miller, D.C. (1933) Rev. Mod. Phys. 5, 203.


Wilson, A.J.C. (1966) lecture notes

Visscher, W.M. (1961) see Margulies and Ehrman (1961)