# A BRIEF HISTORY OF THE PRECISION MEASUREMENT GROUP AT THE UNIVERSITY OF VIRGINIA

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## OUTLINE

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## I. Introduction

The purpose of this talk is to introduce to the students some of the main experimental techniques that we use in our work at Virginia. Hopefully a historical presentation of these research developments will help to familiarize the students with these techniques and their associated terminology. In this way I hope to make the later talks about the work at Virginia more intelligible to you.

Although this presentation is not a complete history, I hope that it is at least an accurate story and an enjoyable one as well.

## II. The Work of Dr. Jesse W. Beams

The Precision Measurement Group grew out of the laboratory of Dr. Jesse W. Beams. Dr. Beams, a well known American physicist, received his Ph.D. in physics from the University of Virginia in 1926. He was a member of the physics faculty at the University of Virginia from the 1930's until his death in 1977. Of the many honors he received and the distinguished positions that he held, I will only mention one. And that is that he was president of The American Physical Society from 1958 to 1959. His other achievements are too numerous to list here.

Dr. Beams was instrumental in developing the technique of magnetic suspension during the 1930's and 40's. As a general laboratory tool, Dr. Beams used magnetic suspension to pursue research interests in many areas, from biophysics[2] to material science[3] to gravitational physics.[4] I will only mention two areas in which Dr. Beams became well known: isotopic separation of elements by gaseous centrifugation, and ultra-centrifugation of biological solutions.

### a) The Gas Centrifuge

During World War II the United States Army initiated a massive project to build an atomic bomb. In order to build reactors and a bomb an adequate supply of the fissionable isotope U-235 was needed. The concentration of U-235 needed for self-sustaining chain reactor is greater than what is normally found in nature, so a fuel enrichment process was needed in order to achieve the required level of U-235 concentration. Taking advantage of the mass difference between U-235 and the more abundant isotope U-238, it might be possible to separate these two isotopes in a centrifuge. If a gaseous uranium compound is used, and if the gas can be spun fast enough the U-238 compound should move to the outside of the centrifuge and the U-235 compound should stay in the center.

Since the mass difference between U-235 and U-238 is small, large g forces, and hence large centrifuge speeds, are needed to provide an adequate separation of the isotopes. Conventional bearings of that time could never withstand the frictional forces arising from such high speed operation, so a magnetic suspension bearing was used. Such a bearing is frictionless and therefore capable of prolonged high speed operation.

A gas centrifuge of this type was built and operated during the war and Dr. Beams was a principle investigator in this project. Figure 1 shows one of the gas centrifuge rotors. Although isotope separation using this method was successful in the laboratory during the war, it was determined not to be feasible for use on an industrial scale and the gaseous diffusion method was used instead.

Today, however, with improvements of high stress materials and more stable feedback electronics, this method is capable of industrial scale fuel enrichment.

b) The Ultra-centrifuge for Biology

During the 1950's biology began to move from being mostly an observational science to being a more experimental science. To do this new tools were needed, and these were provided by the physicists.

One way to probe a cell was to look at it with "light" of shorter wave length. The development of the electron microscope was a major breakthrough. Another way to probe the cell was to separate the various components of a cell (e.g. the nucleus) and analyze the parts; in particular determining the molecular weight of the parts. Once again the mass differences of the parts are small, so an ultra-high speed centrifuge is needed to affect the separation. The war time gas centrifuge project demonstrated that ultra-high speed centrifuges were possible using magnetic suspension. Although work on ultra-centrifuges had been in progress for twenty to thirty years it only became a standard laboratory tool in the 1950's. Dr. Beams had been actively involved in much of this research.[1,5] Figure 2 shows an ultra-centrifuge rotor and figure 3 shows the electromagnet and vacuum chamber of an early ultra-centrifuge.

In both of these research projects the key technique used was magnetic suspension. Why? Because magnetic suspension provides a nearly frictionless bearing, and this provides many advantages. Suspended objects can be spun at very high speeds. These spinning objects can have very stable speed constancy because there are no fluctuations induced by bearing frictional forces (this is true for high or low speed operation). And one of the most important properties of a rotating system is its frequency; and frequency measurements are one of the most precise measurements that can be made.

Hence, an expertise in magnetic suspension techniques almost inevitably leads to the use of rotating systems, and an exploitation of all the properties unique to precision rotations. Therefore key words

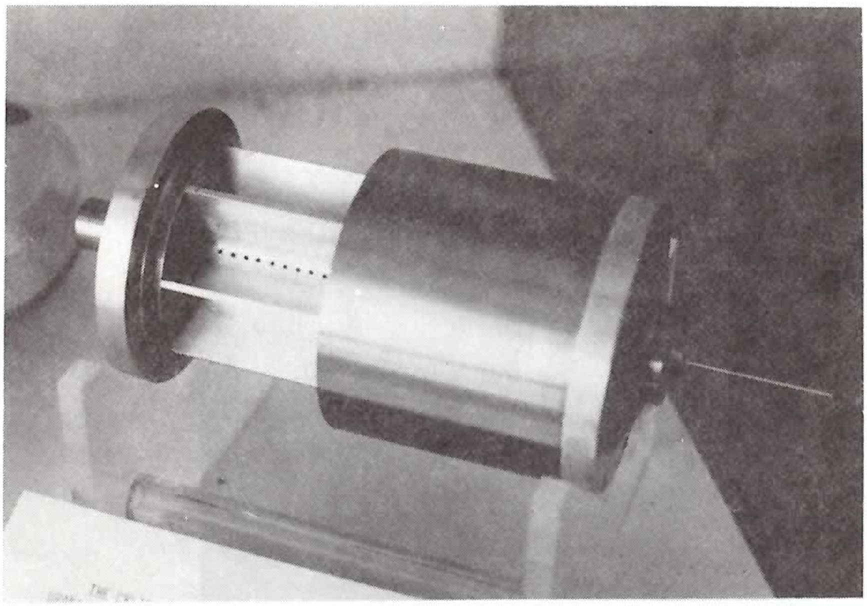

Figure 1. A Gas Centrifuge Rotor - Approximately 10 cm in diameter and 15 cm in length. The rotor is shown with its inner portion partially withdrawn. Fins for helping the gas rotate and the gas extraction holes can be seen.

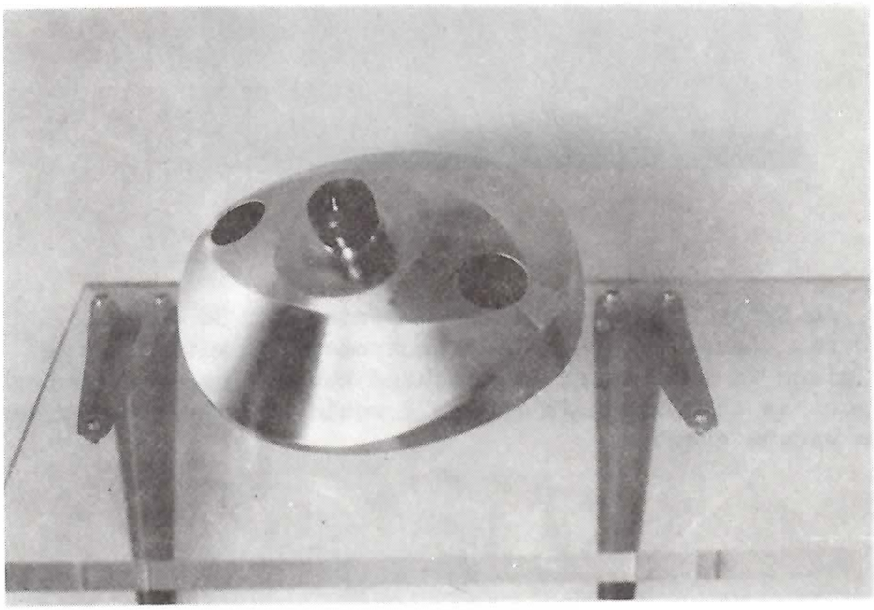

Figure 2. An Ultra-centrifuge Rotor - Diameter ~ 20 cm and height ~ 10 cm. Holes are for holding a sample vial and counterweight. Rotor is ~ 5 kg.

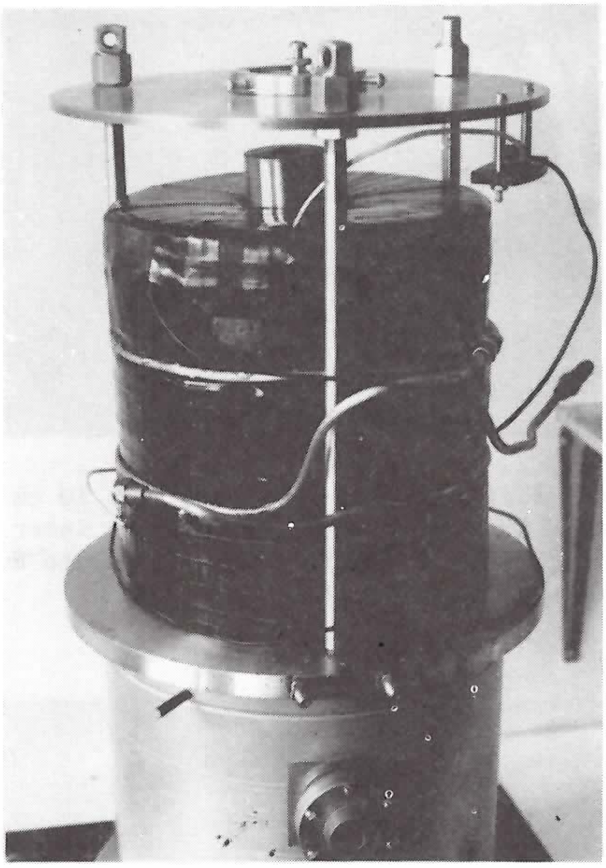

Figure 3. An Early Ultra-centrifuge - Diameter ~ 30 cm and height ~80 cm. Large water cooled electromagnets with a large iron pole piece in the center are located above a vacuum chamber. A rotor, such as that shown in Figure 2 would be magnetically suspended within the vacuum chamber.

to look for in future talks about our research at Virginia are magnetic suspension and precision rotations.

## III. The Later Work of Dr. Beams: 1965-1977

In the later year's of Dr. Beams life he did much of his research in two main areas: gravity experiments, and biophysics experiments. Again, I will only discuss two projects, but note that only one uses magnetic suspension.

### a) A Measurement of the Gravitational Constant, G[4,6]

A precise measurement of Newton's gravitational constant, G, is one of the most difficult measurements a physicist may undertake. Dr. Beams made such a measurement using the Cavendish pendulum technique, but he also employed a novel twist. The pendulum was placed on a turntable and rotated.

The pendulum had a small mass dumbell attached to a quartz fiber. The fiber support was attached to a turntable. Two large masses are then placed on the turntable near the small masses. The small masses would experience the gravitational attraction of the large masses and, therefore, they would twist the fiber. This twist was detected by a photodetection system. The detection system would then drive a motor which would rotate the turntable. This, in turn, would move the large masses away from the smaller masses. In response to the gravitational attraction the small masses would follow the large masses, trying to twist the fiber. However, the feedback detection system would continue to drive the motor of the turntable and thus continue to repeat the process. In this way the turntable motor tries to make the fiber twist go to zero, and the turntable continuously accelerates. A schematic diagram of the apparatus is shown in figure 4.

This experiment explicitly uses the properties of precision rotations. Firstly, by using a rotating platform the mass distribution of the surrounding laboratory is averaged out over many revolutions of the turntable. This is very important for gravity experiments of this type. Secondly, instead of measuring the angular twist of the quartz fiber to determine, G, the twist is used to create an angular acceleration of the turntable. By measuring this acceleration, G can be determined. This involves repeatedly measuring the period of the turntable, and as mentioned before, period measurement can be made with the highest precision.

Although magnetic suspension was not utilized here, all that was learned about rotations from the suspension experiments (e.g. period measurement, drive motors, feedback electronics, etc.) were used to the fullest.

### b) Biophysics

Dr. Beams continued his interest in biophysics by designing and building measurement equipment such as densimeters,[2,7] osmometers,[8]

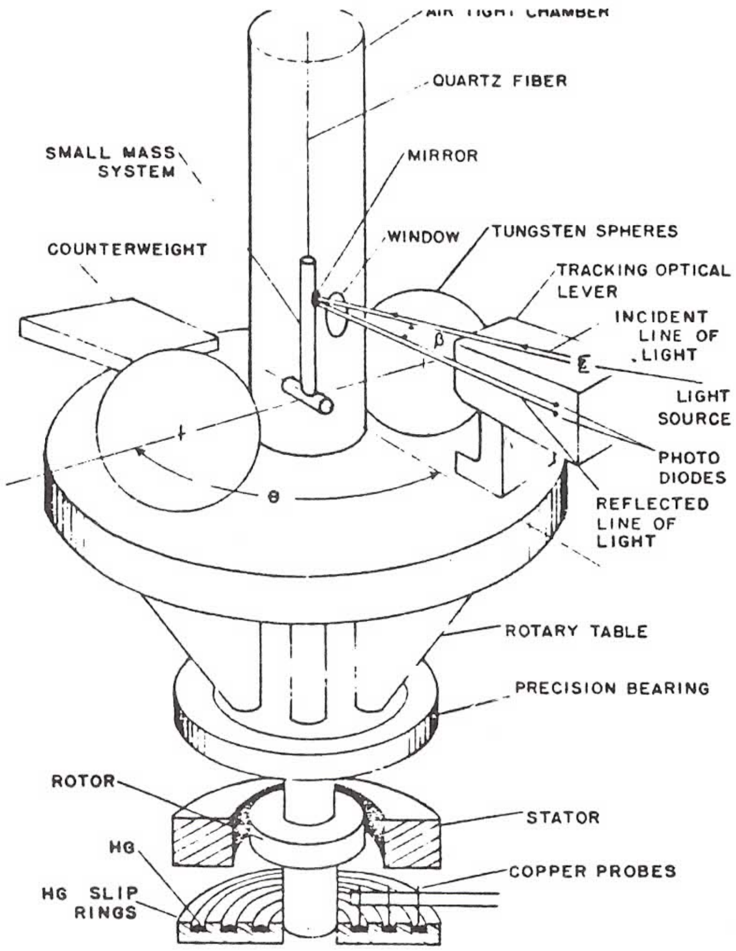


Figure 4. The G Experiment - schematic diagram

and viscometers[9] of very high precision. This equipment could be used in biochemistry research, and was capable of measuring the very small forces involved to the $10^{-6}$ level in some cases. All these machines used the technique of magnetic suspension in some way. I will only describe the workings of a magnetic suspension densimeter as an example.

First, a ferromagnetic object is magnetically suspended while immersed in the fluid whose density is to be determined. As shown in figure 5 three forces are now in equilibrium: gravity, buoyancy, and magnetic. The equilibrium position is determined by the position transducer and the three forces. A measurement of the current in the electromagnet indicates how much magnetic force there is, and hence how much buoyancy force. Since the buoyancy force depends on the density of the fluid, the amount of current also becomes a measure of the fluid density. This density measurement can be made to a high level of precisionif the position transducer is very sensitive and if the current can be measured precisely.

Also, density changes of the fluid, due to a chemical reaction for instance, can easily be detected. The density change causes the forces to lose equilibrium. The suspended "buoy" will try to move, but this motion is detected by the position transducer which causes a change in current (magnetic force) which re-establishes the equilibrium. The current change follows the density change and is easily measured.

Let me note briefly that rotating the buoy in the fluid will create a viscous drag on it. If a constant torque is applied to the buoy the resulting equilibrium angular velocity, $\omega$, is a measure of the fluid viscosity. Dr. Beams built a machine that could simultaneously measure the density and viscosity of a fluid using these techniques.[10]

Both of these later experiments use another important tool of precision measurement. And that is the use of feedback control in the measurement process. Negative feedback explicitly uses the technique of "nulling", i.e. there is a control signal that is being driven to zero. If the parameter you want to measure is the control signal, then instead of measuring it directly, you measure that part of the feedback signal that drives the control signal to zero. For example let $\Delta$ be the control signal, and let A be the parameter of interest. Then the feedback system could use the formula,

$$\Delta = A - B, \ \Delta \to 0 \tag{1}$$

The feedback system should then allow for an easy measurement of B.

Why is this important? Because it is difficult to make an accurate absolute measurement of anything. However, it is easy to accurately measure zero. And a properly designed negative feedback system will measure zero accurately, precisely, automatically, continuously, and "instantaneously". All you have to do to measure A is to measure B, which is one of the feedback parameters. And because B is one of the feedback parameters, it is most likely an electrical

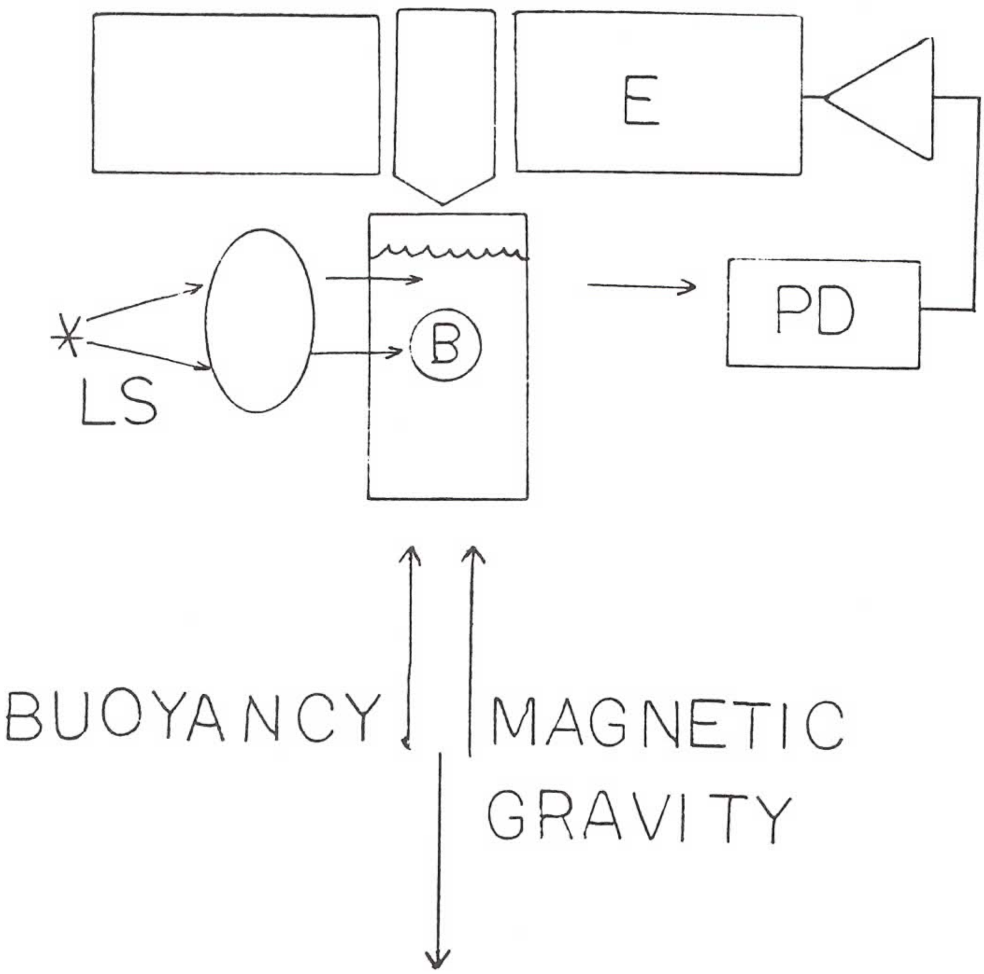


Figure 5. A Magnetic Suspension Densimeter - Depending on the density of the buoy, B, the electromagnet, E, can be located above for pulling up or below for pulling down. Light source, LS, and photodetector, PD.

measurement which is capable of being measured with high precision.

How is this done in the G experiment? Here the parameter of interest is the angular twist of the quartz fiber, but that's hard to measure precisely. So the feedback system "nulls" the fiber twist by accelerating the turntable, and this acceleration becomes the measured parameter, which is easily measured with great precision.

In the densimeter, the buoyancy force is the parameter of interest. The buoyancy force will cause the buoy to float or sink, but the buoy is held in position (position null) by the magnetic force. Hence the current is measured.

Notice that both the acceleration and the current are parameters in the feedback system. Therefore another keywork to look for in later talks is negative feedback control.

## IV. Current Research

The current research of our group stems directly from the research interests and ideas of Dr. Beams at the time of his tragic death. There are three projects: a) the viscodensimeter[11]; b) the determination of spontaneous matter creation[12]; c) the inertial clock.[12] I will only briefly introduce each project to you and I will endeavor to point out how techniques developed in the past are currently being employed, as well as the use of new experimental techniques. The last two projects will be discussed in more detail later in this school and at the symposium.

### a) The Viscodensimeter

This project is an outgrowth of the viscometer and densimeter I have just described to you. However, a new viscosity measuring system is being used. In the old system the suspended buoy was rotated in order to get the viscosity information. In the new system the magnetic suspension is used to get the viscosity information as well as the density information. This is done by using the spring-like properties of the magnetic suspension. That is, the buoy in suspension acts like a mass on a spring. If it experiences a sinusoidal forcing function the equation of motion can be written as,

$$m\ddot{z} + b\dot{z} + kz = F\sin\omega t, \qquad (2)$$

where m is the effective mass of the buoy, b is the viscous and electronic damping coefficient, k is the "spring" constant, F is the amplitude of the external driving force, and z is the vertical position of the buoy with respect to the equilibrium suspension point. The driving force is applied by adding a small ac current to the dc current in the magnetic suspension electromagnet.

Equation (2) can be solved, and the solution is,

$$z = A\sin(\omega t + \beta), \qquad (3)$$

where $\beta$ is a phase lag and A is the amplitude of the motion. The parameters have the form,

$$A = \frac{F}{[m^2(\omega^2-\omega_o^2)^2+b^2\omega^2]^{1/2}}, \tag{4}$$

and,

$$\sin(\beta) = \frac{-b\omega}{[m^2(\omega^2-\omega_o^2)^2+b^2\omega^2]^{1/2}}, \tag{5}$$

where, $\omega_o^2 = \frac{k}{m}$. Using eqns. (4) and (5) will yield,

$$\frac{F\sin(\beta)}{A} = -b\omega, \tag{6}$$

where $b = b(\eta)$ and $\eta$ is the viscosity of the fluid.

Therefore, by measuring the amplitude of motion of the buoy, due to the ac current, and by measuring the phase lag, $\beta$, between the ac current and the motion of the buoy, one can obtain the viscosity information. This method eliminates the need for a magnetic torque and all that extra circuitry and reduces the density and viscosity measurement to that of a dc and an ac electrical measurement respectively. Figure 6 shows the schematic configuration of the viscodensimeter. Notice that A and $\beta$ are parameters derived from the feedback loop.

b) The Determination of Spontaneous Matter Creation

Based on the Dirac Large Numbers Hypothesis[13] (LNH), Dr. Rogers C. Ritter proposed to use a laboratory experiment[14] to look for possible spontaneous matter creation. Briefly, the LNH says that the large number ratio of the observable mass of the universe to the mass of the proton is $N \sim 10^{78}$, and the ratio of the largest distance to the smallest being the radius of the universe to the classical electron radius is $t_o \sim 10^{40}$. Assuming that N and $t_o$ are related through some Machian process, and since $t_o$ is increasing as the universe expands, one can say that $N \sim t_o^2$ and is therefore increasing also. If the mass of the proton is constant then matter must be spontaneously created in the universe. A rate of $\dot{m}/m \sim 1.2 \times 10^{-10}$/yr. is the expected value for this matter creation.

It's not the purpose of this talk to discuss the merits of the LNH or where and how matter would be created, so I will not say anything more about the theory. Instead let me describe the experiment.

If one has a spinning rotor and matter is created within it, and this matter does not have any angular momentum, but the rotor angular momentum is conserved, then the rotor must slow down in order to conserve

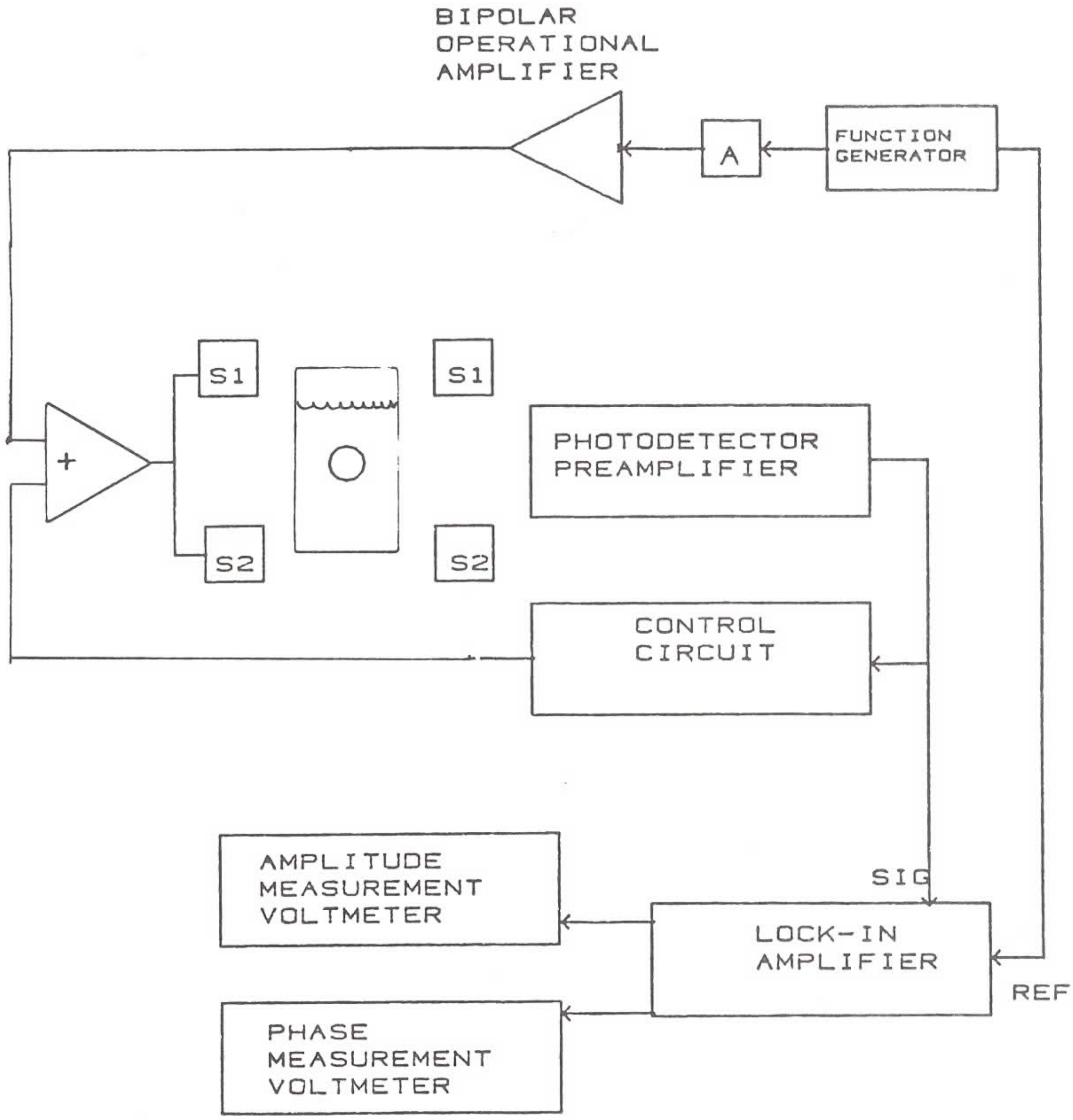


Figure 6. The Electronic Configuration of the Viscometer - The light source (not shown) shines across the sphere to the photodetector. The motion of the sphere creates a signal going from the photodetector preamplifier to the control circuit, and to the lock-in amplifier. The function generator applies a sinusoidal voltage to the drive solenoid, and a reference signal for the lock-in amplifier. $S_1$ and $S_2$ are the support coils; A is a 4-position attenuator.

angular momentum. A simple way to express this is,

$$\dot{m}/m = \mathring{I}/I = \mathring{\omega}/\omega \sim 1.2 \times 10^{-10}/yr. \quad (7)$$

Hence, the rotor's natural spin down due to a variety of energy loss mechanisms must be ~ $10^{-18}$/sec, i.e. $\tau^* = -\omega/\mathring{\omega} > 10^{18}$ sec., where $\tau^*$ is the decay time constant, in order to see matter creation.

A freely spinning rotor has an equation of motion,

$$I\mathring{\omega} + b\omega = 0, \quad (8)$$

where I is the moment of inertia and b is an energy loss drag coefficient producing a drag torque proportional to the angular velocity, $\omega$. The solution to Eq. (8) is,

$$\omega = \omega_o e^{-I/b\ t} \quad (9)$$

and

$$\mathring{\omega}/\omega = -I/b = -1/\tau^*. \quad (10)$$

The two largest drag mechanismson the rotor are gas drag and bearing drag. Bearing drag, as I've mentioned in the past, can be virtually eliminated by using a magnetic suspension bearing To eliminate gas drag a subtle trick can be used. First let me say that even the best vacuum possible would not be able to reduce the gas drag to an acceptable level for this experiment. A $\tau^*$ of $10^{18}$ sec. would require vacuum pressures of $10^{-16}$ torr or less. However, if the gas pressure is reduced to the molecular flow regime, $10^{-5}$ torr or less, an effective pressure of $10^{-18}$ torr can be achieved by corotating the residual gas along with the spinning rotor.

Let me explain this in more detail. The test rotor is allowed to rotate in a vacuum chamber, but the vacuum chamber also rotates along with the rotor. The residual gas in the chamber therefore is not moving with respect to the rotor and hence the gas drag is substantially reduced.

In this experiment the vacuum chamber is on a turntable which is driven at a very constant speed by a magnetic averaging motor locked to an atomic clock time base. Initially the rotor and chamber rotate together, but as matter is created in the rotor it slows down and a lag angle developes between the rotor and the chamber. This lag can be detected and a laser pulsing system then "pushes" the rotor to keep up with the chamber. The feedback signal to the laser is a measure of the amount of matter creation. Figure 7 shows a schematic diagram of the experiment. Figure 8 is a picture of one of the test rotors and figure 9 shows the experimental hardware.

I hope you noticed in this experiment the advantageous use of magnetic suspension and the use of the feedback signal as a measurement

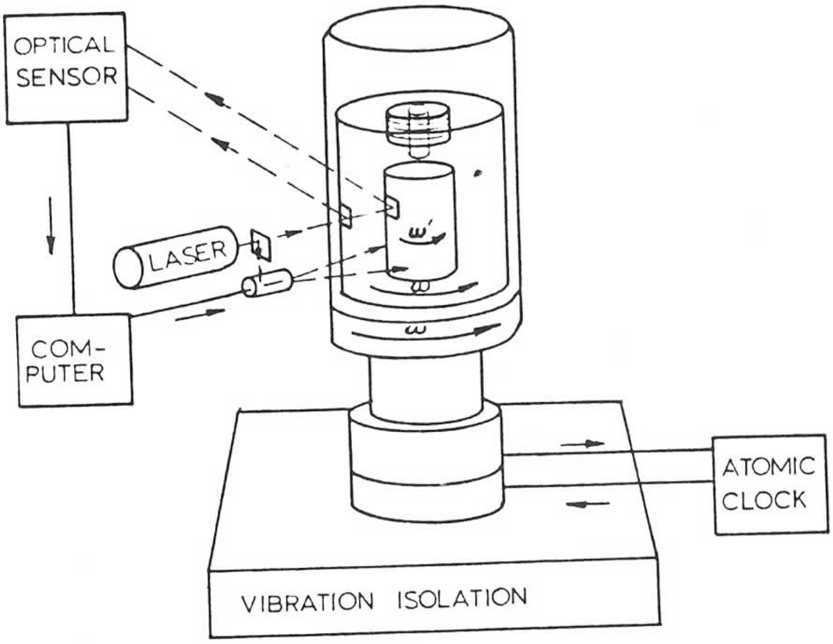


Figure 7. The Matter Creation Experiment - schematic diagram.

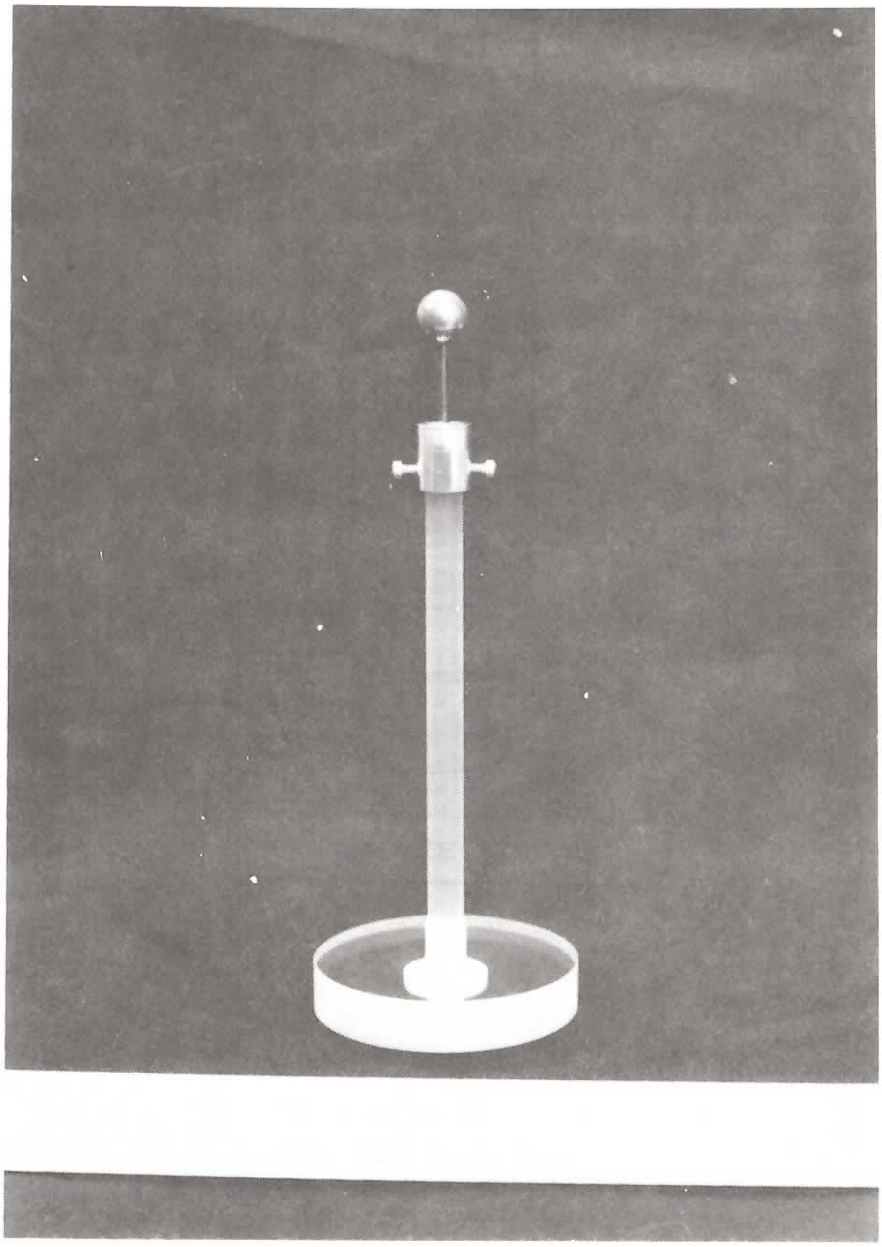

Figure 8. Test Rotor - A zerodur (glass) test rotor for use in the matter creation experiment.

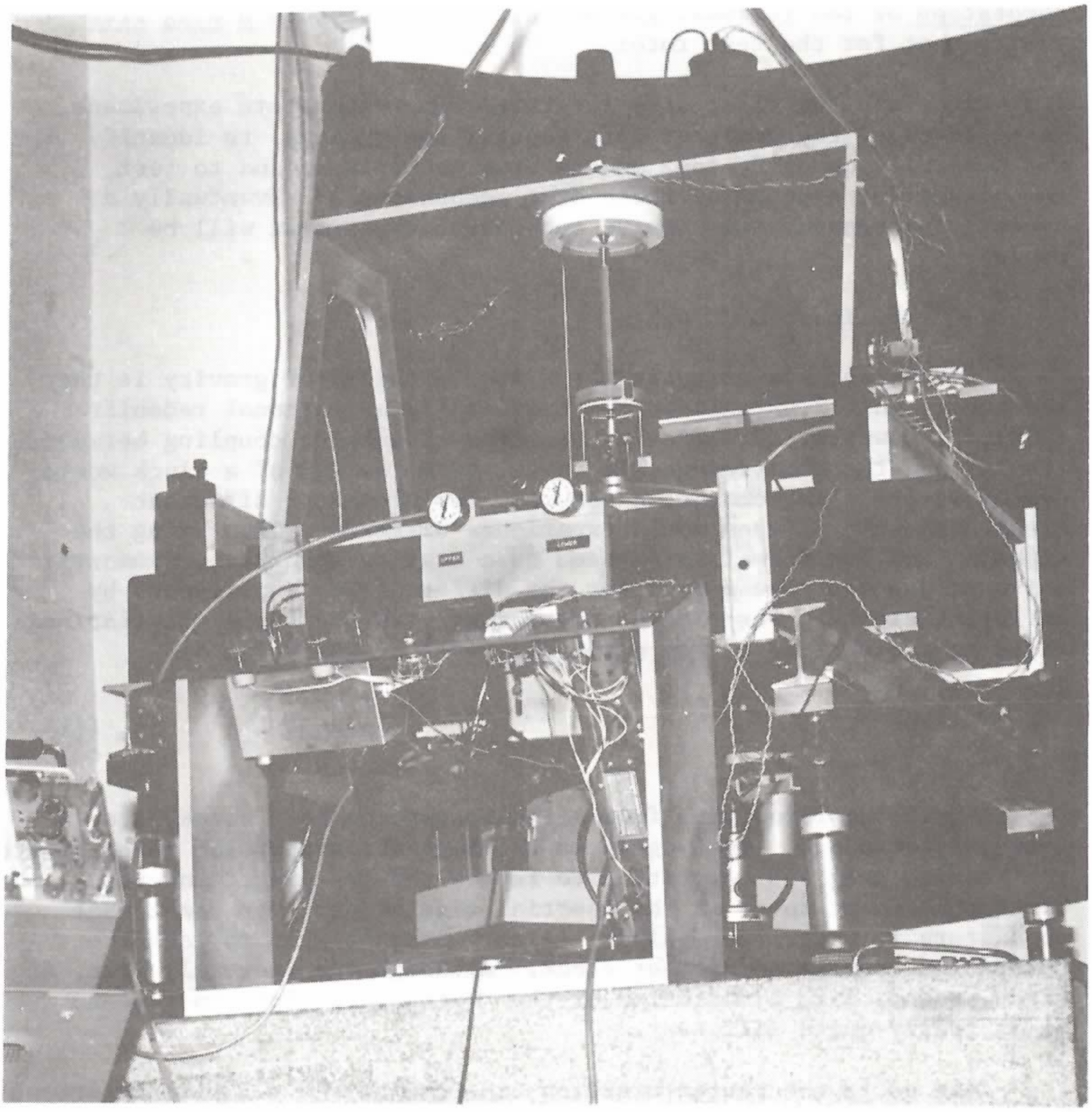

Figure 9 - The Matter Creation Experiment

This photograph shows an overall view of the mechanical part of the experiment emphasizing the vibration isolation system. The first of the two passive stages is the large granite block seen resting on sandwich-stacked Weber isolators. The floor surrounding these isolators has been partially cut as is visible around the base of the photo. The smaller granite stone is supported by pneumatic springs which set on the top of the larger stone. The magnetic suspension system framework and the inner and outer cylinders are seen on top of the smaller stone.

parameter. Also let me point out another keyword. And that is corotation of the residual gas which helps to produce a drag free environment for the test rotor.

Right now the first step for this room temperature experiment, is to develop the computer data acquisition systems, to identify and hopefully quantify some of the drag mechanisms, and to test techniques for overcoming these drag mechanisms.[15] Eventually a cooled, superconducting passive suspension experiment will be needed.

c) The Inertial Clock

One of the criteria for a viable theory of gravity is that the theory must substantiate the universal gravitational redshift (UGR).[16] However, if there is some type of unknown coupling between gravity and the electromagnetic force, then the UGR of a clock would depend on its electromagnetic nature. Two clocks of different electromagnetic natures would experience different UGR. Using the Lightman and Lee formalism[17] based on a static, spherical, symmetrized universe one can give a form for the different UGR experienced by different clocks. For clocks interacting with the sun's gravitational field on the surface of the earth the level of UGR would be,

$$\frac{\dot{\omega}}{\omega} \sim 10^{-13}. \tag{11}$$

A spinning rotor free from all disturbances is a clock, i.e. a frequency standard. Once again we use magnetic suspension to eliminate the bearing drag and corotation to reduce the gas drag. However, because the test rotor is the inertial time keeper, you don't want to disturb it with laser pulses. Also you don't want to lock the corotating chamber to another clock. Although the inertial clock, at first, sounds like a variation of the matter creation experiment, it is really quite different.

Just as in the matter creation experiment, the relative position of the corotating chamber to the test rotor is monitored. Only this time if there is any change in position, the corotating chamber is sped up or slowed down to keep it at the same angular velocity as the inner test rotor. In this case the feedback signal is not used as the measurement parameter. The pure frequency of the inertial test rotor is the measured quantity of interest.

This corotation is maintained by a microcomputer that commands an eddy current drive motor that drives the corotating shroud chamber. In order to have a sensitive motor control for the feedback system, an air bearing turntable could not be used. Instead the shroud chamber is magnetically suspended within a stationary vacuum chamber, and the test rotor is magnetically suspended from within the shroud chamber. This double magnetic suspension, although difficult to achieve, is currently operating at Virginia.[18]

By using feedback control of the shroud chamber the gas drag on the test rotor is significantly reduced and a test rotor $\tau^*$ of $10^{15}$ seconds is our goal. This level of $\tau^*$ would give the inertial clock a stability comparable to a hydrogen maser or a superconducting cavity stabilized oscillator. Hence, these clocks could be used for a UGR experiment.

Figure 10 shows a schematic diagram of the experiment. Figure 11 shows a schematic cut-away of the experiment, while Figure 12 is a picture of the vacuum chamber which is opened to show the shroud and test rotors.

Needless to say, the experience of operating the computer feedback system of the inertial clock will help immensely when the laser feedback system is built for the matter creation experiment. Similarly, the spin down and corotation experiments of the matter creation project have helped in the design and building of the inertial clock.

V. Conclusion

I hope that I have familiarized you with our work at Virginia. And that you now have an understanding of the technique of magnetic suspension and some of the advantages of precision rotations and negative feedback control. Also, I hope that I have shown how these older techniques along with new tricks, like corotation, can be used in some rather interesting and fundamentally important physics experiments. And finally, I hope I've shown that precision measurement techniques can be used in many different fields from gravity physics to biophysics.

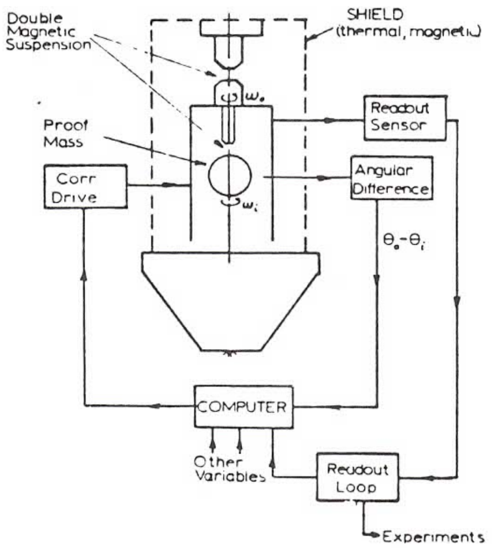


Figure 10. The Inertial Clock - schematic diagram of the experiment.

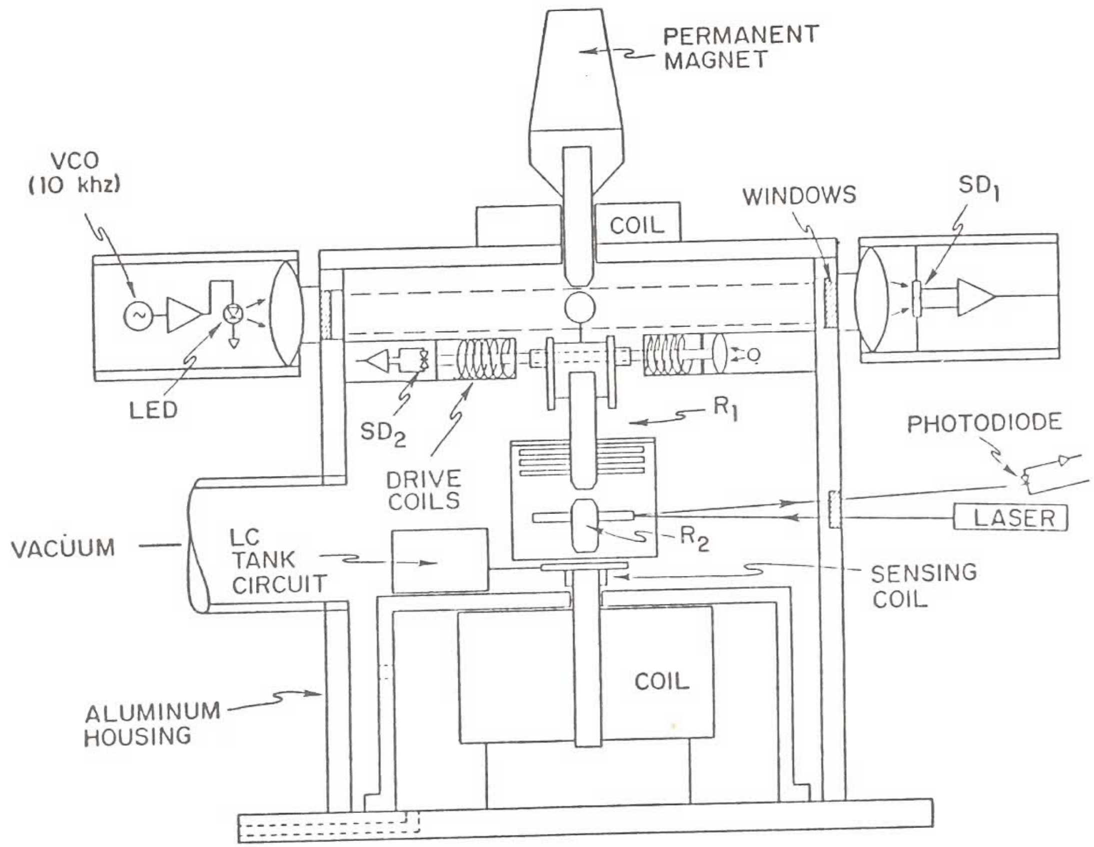


Figure 11. The Inertial Clock - a cut-away diagram of the vacuum chamber. R1 is the shroud rotor and R2 is the test rotor. Notice that R2 is magnetically suspended from within R1.

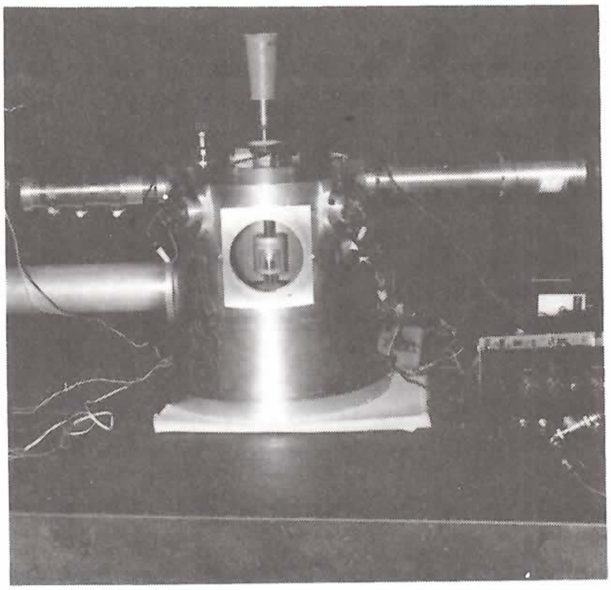

Figure 12. The Inertial Clock - The picture shows the vacuum chamber open with the shroud and test rotors inside.

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