High-Speed ROTATION

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By J. W. Beams

UPON this occasion the speaker usually reviews some scientific or technical subject with which he is or has been associated or he discusses current problems involving the role of physics in human affairs. Although the latter subject certainly is most timely and important, I shall address myself to the former. I will attempt to discuss some applications of high-speed rotation to science with special emphasis upon problems of centrifuging. No effort will be made to review adequately the subject or to emphasize the most important work done in the field. Instead I will discuss some of the work that has interested me personally. Unfortunately time is not available to mention properly all of my collaborators and students to whom should go most of the credit for the work.

In the course of some experiments about thirty years ago in which a number of phenomena which occur in very short intervals of time were being studied by Kerr cells, it became important to determine whether or not the Kerr cells were operating properly. Since sufficiently high-speed oscillographs were not available to us at that time, we set about to develop a rotating mirror with large enough time resolving power to check the operation of the Kerr cells.[1] Fortunately Henriot and Huguenard [2] had just published a most ingenious method of spinning a small cone-shaped rotor to several thousand revolutions per second on a whirling jet of air, so we adapted and modified their method for spinning our mirrors. With this rotating mirror the operation of the Kerr cells was confirmed and several of the previous experiments were repeated using the rotating mirror instead of the Kerr cells.[3, 4] The centrifugal field near the periphery of the rotor in the above experiments reached values of the order of 10^6 times gravity so the question naturally arose as to whether or not this simple, inexpensive air-driven rotor could be used as a centrifuge for producing molecular sedimentation. Professor Svedberg and his students in their great pioneering experiments on the characterization of proteins and other large molecular weight compounds already had shown that molecular sedimentation in a centrifugal field was a most effective way of determining molecular weights.[5] In order to carry out their experiments they had developed an "ultracentrifuge" which spun on a rigid shaft in hydrogen at a pressure of several mm of mercury and was driven by oil turbines. This excellent ultracentrifuge functioned most effectively for the determination of molecular weights. On the other hand it required the greatest care in design, workmanship, and dynamical balance and was not generally available at that time.

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In our first attempts to produce molecular sedimentation with the air-driven, air-supported rotor it was found that the results were invalidated because of convection in the centrifuge. This troublesome remixing was traced to thermal gradients in the rotor produced by cooling of the expanding air jets and heating by air friction on the rotor surface. Thermal gradients are especially effective in generating convection in a centrifuge because the forces which produce convection are proportional both to the temperature gradient and to the centrifugal field. However, in experiments where accurate temperature control is not important and in which a large centrifugal field is essential only over a small radial distance, the above air-driven "top" proved to be a useful centrifuge. For example, H. W. Beams and R. L. King,[6] E. N. Harvey,[7] and many others have used this type of centrifuge in most interesting studies of sedimentation of the components inside of a biological cell. Furthermore with proper rotor design in which the thermal gradients or their effects were eliminated, molecular sedimentation has been carried out successfully.[8, 9]

Since the surface velocity of a rotor increases from zero at the axis to a maximum at the periphery, nonuniform heating and so-called "pumping" occur when it is surrounded by a gas at an appreciable pressure. Because of this limitation E. G. Pickels and I, in 1934, worked out a method of spinning centrifuge rotors in a high vacuum.[10] This so-called vacuum-type centrifuge consisted of a large centrifuge rotor located inside of a vacuum-tight chamber, a small air-driven, air-supported turbine situated above the chamber, and a thin flexible shaft which connects them together and which is coaxial with their common axis of rotation. Fig. 1 shows a diagram of an early air-driven, vacuum-type centrifuge which has proven very suitable for both the purification of substances of large molecular weight and for measuring molecular weights.[11] The centrifuge rotor C inside the vacuum chamber is connected to the air-supported, air-driven turbine T by the vertical flexible steel shaft A. G_1 and G_2 are vacuum-tight oil glands mounted in flexible neoprene rings. The rotating members are supported on an air bearing between B and T and are spun by air impinging upon the turbine T. A similar reverse air drive is usually provided for decelerating the rotor. Since there is no air friction on the rotor and the temperature of the oil gland G_1 is maintained constant by circulating oil at the same temperature as the metal vacuum chamber the thermal gradients in the metal rotor are eliminated. Also the temperature of the rotor can be held at a known constant temperature. The thin (0.1″ o.d.) flexible steel shaft A not only has a small friction in G_1 and G_2 but it allows the large rotor C to seek its own axis of rotation and spin stably without the need for accurate dynamical balancing. In practice the maximum rotational speed is limited only by the mechanical strength of the rotor. This fortunate combination of high centrifugal field, large-size rotor, lack of thermal gradients, and lack of need for painstaking dynamical balance made this centrifuge almost ideal for the purification of biological and other large molecular weight compounds. It became commonplace to centrifuge over 300 cc of liquid in a field of 300 000 times gravity with a rotor having a diameter of 18 cm. The importance of the shaft flexibility can be seen from the fact that if one of the test tubes in the above rotor contained 1 cc more liquid than the others, the unbalancing force would be well over 500 lbs if the shaft were not flexible. Most of the substances of importance in medicine and biology are deactivated by large changes in temperature or strong chemicals so that it has not been possible to purify them by chemical means. Also many of them occur in comparatively dilute solutions. Fortunately they are not appreciably effected by large centrifugal fields. The vacuum-type centrifuge was used by Pickels and his collaborators, Wyckoff, and many others to purify for the first time a large number of substances in appreciable quantities. For example, a number of the viruses actually crystallized out with comparatively small centrifugal fields in the centrifuge. If the rotor C shown in Fig. 1 is replaced by one which carries a centrifuge cell with quartz windows, sedimentation can be observed. From these data the molecular weights of the substances in solution can be determined.

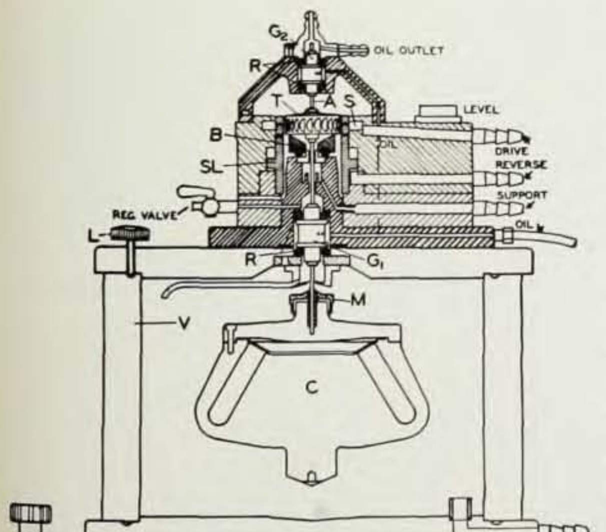

Fig. 1

In some further experiments about 20 years ago with the vacuum-type centrifuge the air-turbine drive was replaced by an electrical motor and the magnetic suspension was introduced to replace the air-cushion support.[12, 13] The drive was a two-phase ac induction motor supplied with 1 kw at 1188 cycles per second. The power input to the rotor was automatically regulated and held the rotor speed at just over 1000 rps with variations of less than 0.5 rps for an experiment of many hours duration.[13] The weight of the rotating system was almost but not quite carried by the lifting action of an iron-sheathed solenoid upon the rotating core. The small remaining weight was borne by a small thrust bearing. Since the magnetic field is axial and symmetrical, no electromagnetic drag is produced on the rotor. Consequently the friction in the thrust bearing can be made small even though the rotating system may be very heavy. I shall return to other applications and variations of the magnetic bearing support later.

The purification of biological and other substances with large molecular weights as well as the determination of their sedimentation constants and/or molecular weights has become of such great importance in recent years that much effort has gone into designing commercial models of the vacuum-type centrifuge. E. G. Pickels, especially, has developed a vacuum-type ultracentrifuge now commercially available which is almost wholly automatic. It practically has become a necessary part of a modern molecular biological laboratory.

THE successful use of the vacuum-type centrifuge for the concentration of large molecular weight compounds encouraged us to undertake the separation of isotopes by centrifuging. This latter problem, of course, is many orders of magnitude more difficult than the former, but at that time (1936) there was an urgent need for separated isotopes. The separation of isotopes by centrifuging was first proposed by Lindemann and Aston [14] in 1919. Also, they developed the equilibrium theory for the separation in an ideal gas and in an ideal incompressible liquid. This theory was improved and extended by Mulliken,[15] Chapman,[16] Harkins,[17] and others. Several attempts were made by a number of early workers to obtain the separation of different isotopes in specially constructed centrifuges but each of these attempts [15, 17, 18] was unsuccessful. However, in our first experiments with the vacuum-type centrifuge a definite separation of the isotopes of chlorine in $C\ Cl_4$ was obtained.[19, 20] In further experiments the separation obtained was found to be in quantitative agreement with the theory.[11, 21] In addition to the concentration of the chlorine isotopes in $C\ Cl_4$, the chlorine isotopes were separated in methyl chloride and the bromine isotopes were separated in $C\ Br_4$. Subsequently similar results were obtained by Humphreys [22] for the separation of the bromine isotopes using the same type of centrifuge.

Immediately after the discovery of uranium fission the late Leland B. Snoddy and I undertook the problem of separating the uranium isotopes in uranium hexafluoride by centrifuging. Subsequently we were joined by a number of others,[23] without whose most effective collaboration the work could not have been carried out. The primary purposes of this work were first to find the most useful centrifuge method of separation and second to subject the theory to as rigorous a test as possible rather than to obtain a maximum amount of isotope enrichment.[24]

The first method used was the evaporative centrifuge method originally suggested by Mulliken in 1922. This method consists in partially filling a hollow centrifuge rotor with a liquid compound containing the element whose isotopes are to be separated. The centrifuge is then spun to the desired speed and the vapor is drawn off along the axis. The substance evaporates near the periphery of the spinning rotor, diffuses along the centrifuge radius, and flows out through the hollow shaft. The fraction drawn off along the axis has the lighter isotope enriched while the residue in the rotor has the heavier isotope enriched. The experimental enrichments obtained were in excellent agreement with the Mulliken-Humphrey-Cohen theory.[24]

Although the separations obtained in these experiments were in excellent agreement with the theory for the separation in a radial field, the evaporative centrifuge method is not suited for separating large quantities of material because it is a "batch" and not a continuous method of separation. Also, from elementary theory the quantity of material that can be separated in a given time is proportional to the axial length of the centrifuge. For this reason we undertook the problem of spinning long tubular centrifuges. Our first tubular centrifuges were used to concentrate the chlorine isotopes in methyl chloride.[11] Our later tubular centrifuges were straightforward extrapolations of this machine.[24] For a more detailed description of this tubular-type centrifuge, reference should be made to the original articles. However, it will be noted that it spins about a vertical axis in a chamber which may be evacuated. The shafts are small flexible tubes so that material can be introduced and withdrawn from the centrifuge while it is spinning. The material to be centrifuged is introduced at the top of the spinning tube and the lighter and heavier fractions are withdrawn at the lower end near the axis and near the periphery, respectively, through concentric tubular shafts. In later centrifuges stainless steel shafts were used which were divided along their length so that two independent streams of material could flow through them. When such a tubular rotor speeds up it passes through so-called "critical vibrations", which occur at certain speeds only. In order to prevent the amplitude of these vibrations from becoming too large, dampers were placed on the tubular shafts. It was found that as long as the rotor speed was not near a critical frequency the centrifuge spun very stably and without observable vibration.

Several different methods of using the tubular centrifuge for isotope separation have been proposed. The methods differ primarily in the type of flow pattern of the material used inside the spinning tube. Cohen and his collaborators have worked out the theory for the separation by a number of these methods.[25] Although the experimental results obtained with the flow through or concurrent method described above are in good agreement with Cohen's theory, his analysis showed that it was not so efficient as the counter-current-flow method first suggested to us by H. C. Urey. For this reason I will limit my remarks to the counter-current method.

Fig. 2 shows a counter-current-flow method which turned out to be a very good way of using the centrifuge to obtain high efficiency or large "separative work". Incidentally, this particular flow pattern is not the most efficient use of the counter-flow method but it was chosen because it affords a clear-cut test of the Cohen theory.

When equilibrium is established in the system, uranium hexafluoride from the source at a measured rate of L mg/sec enters the spinning centrifuge tube

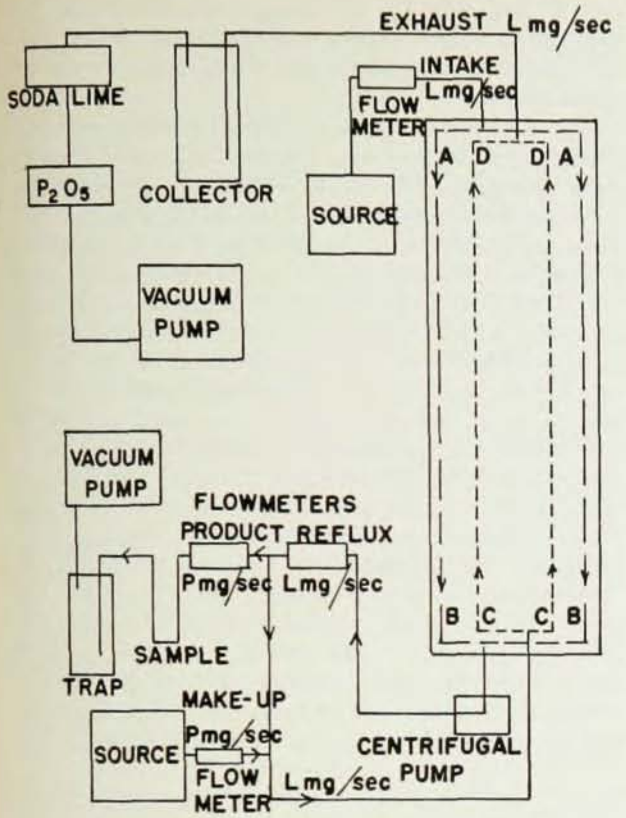

Fig. 2

through one axial channel of a divided stainless steel shaft and is directed downward near the periphery at *A A* in a thin cylindrical stream. At *B B* the cylindrical stream emerges through the end cap, one axial channel of the divided shaft, and into a centrifugal pump attached to the centrifuge shaft. It next passes through a flow meter and is divided into two streams. One stream is collected as product *P* mg/sec in a cold trap. An equal amount (*P* mg/sec) of ordinary uranium hexafluoride (called the make-up) is then introduced into the second stream which is returned to the centrifuge through the other axial channel of the divided shaft. The lower end cap directs it upward in a thin concentric cylindrical stream *C C* to *D D* where it passes out of the upper end cap, the divided shaft, and is collected in a cold trap. The flows were regulated by orifice valves. Because of the centrifugal field (or centrifugal potential) transport occurs between the two counter-current streams. The peripheral stream has the heavier isotope enriched while the inner stream is enriched with the lighter isotope. It will be noted that this type of operation concentrates the uranium-238 rather than the uranium-235 in the product. This "stripper" arrangement was used in these test experiments rather than the "enricher" arrangement because of the slightly greater reliability with which the flow *L* and product *P* could be determined under the experimental conditions. It can be shown that if the operational data are available for the stripper, the performance of the enricher can be determined with reliability.

At first sight it might seem that the two streams would not flow down the length of the tube in thin cylindrical streams as indicated in Fig. 2. However, a little consideration will show that the gas stream will resist radial flow in a hollow spinning centrifuge and hence will flow axially. For example, if the gas from the outer stream moves inward along the radius, first it is cooled as a result of its expansion and, second, its angular velocity is increased because of conservation of angular momentum. Both of these effects are comparatively large and cause the stream to move back outward, i.e., stabilize it.

Two different Duralumin rotors were used in the experiments of Fig. 2. One of these tubes was 7.62 cm i.d. and 81.3 cm long, and the other was 18.66 cm i.d., 21.2 cm o.d., and 345.5 cm long. Both centrifuges could be operated up to their bursting speeds; however, since the purpose of these early experiments was to test the theory of separation rather than produce a large isotope separation, rotational speeds were selected well below those which would explode the rotors. The 81.3-cm tube was operated at 1020 ± 0.3 rps. Originally it was planned to operate the 345.5-cm centrifuge tube between 450 and 470 rps, but flaws were found in the Duralumin and it became necessary to limit the operating speed of the tube to 350 ± 0.3 rps, although it was tested up to 420 rps.

Table I gives typical equilibrium values obtained with the 345-cm centrifuge tube. The first column shows the flow rate, the second the product rate, the third the theoretical value computed from the Cohen theory for N_0/N_z and the last column the experimental values for the same ratio, where N_0 is the mole fraction of U_{235} in the feed material and N_z is the mole fraction of U_{235} in the product *P*. It will be observed that the experimental results are in substantial agreement with the values predicted by theory. This is especially true when consideration is given

Table I

L mg/sec	*P* mg/sec	N_0/N_z theoretical	N_0/N_z experimental
80.7	25.65	1.039	1.039
79.5	19.52	1.048	1.048
79.3	15.06	1.057	1.054
79.7	10.64	1.071	1.060
79.6	5.35	1.101	1.073
64.3	19.80	1.042	1.047
65.4	14.90	1.053	1.053
65.2	9.70	1.072	1.070
64.9	24.83	1.035	1.041
65.2	15.11	1.053	1.053
65.2	10.26	1.069	1.067
50.0	19.72	1.036	1.043
49.8	15.03	1.044	1.051
50.3	10.12	1.063	1.066

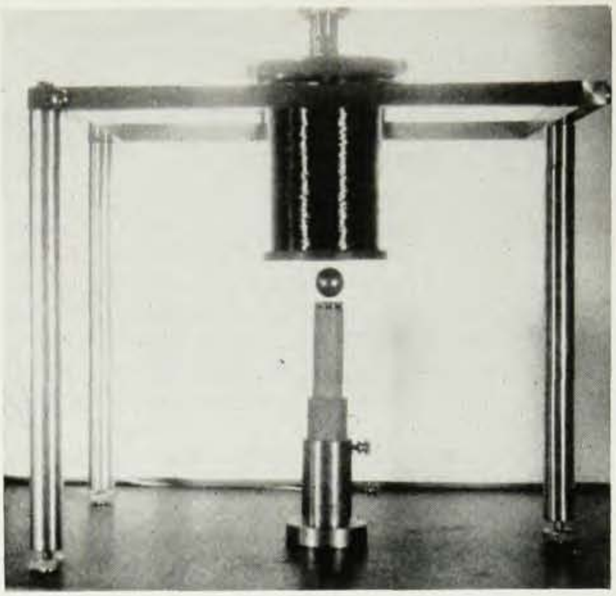

Fig. 3

to the fact that the theory is highly idealized, i.e., extremely thin flow streams were assumed, etc. However, similar agreement with the theory also was obtained with the other centrifuge tube 81.3 cm long, 7.62 cm i.d., spinning at various rotor speeds. Furthermore the inside peripheral speed of the 345-cm tube was less than normally would be used, and both experiment and theory indicate that as the inside peripheral velocity is increased the flow streams become more stable. Consequently the experiments indicate that the theory may be used for estimating the isotope separation or so-called separative work in a centrifuge with considerable reliability.

At this point I would like to describe briefly some more recent experiments. At about the same time Snoddy, Skarstrom, and I began using magnetic suspensions for partially supporting our heavy centrifuge rotors,[12, 13] F. T. Holmes at Virginia developed a magnetic suspension which would support a rotor freely.[26] With this suspension Holmes and I succeeded in spinning a small steel rod up to 1000 rps in a vacuum and observed that it was remarkedly free of friction.[27] Because of the urgency of other work at that time both Holmes and I were forced to drop the problem but C. S. Smith [28] and L. E. MacHattie [29] in our laboratory were able to carry it on. They confirmed the previous observations and MacHattie succeeded in spinning a steel sphere up to its bursting point in a vacuum. After the war we returned to the problem and found that by means of an improved servo-mechanism technique the magnetic support could be greatly stabilized.[30, 31] Subsequently, rotors from 0.005 cm to 30 cm in diameter and with weights from 10^{-6} gm to 10^{5} gm have been freely suspended. In all cases the rotor speeds attainable by this method are limited only by the strength of the rotors. For example, we have spun a 0.029-cm rotor to well over 10^{6} rps which produced a centrifugal field of over 10^{9} times gravity.

Fig. 3 shows a photograph of a one-inch steel ball freely supported and Fig. 4 gives a schematic diagram of a typical suspension. In Fig. 4 the ferromagnetic rotor is freely suspended inside of a glass vacuum chamber by the axial magnetic field of the solenoid. The upward force on the rotor is approximately equal to $M(dH/dz)$ when M is the magnetic moment of the rotor and dH/dz is the vertical gradient of the magnetic field. The rotor is maintained at the desired vertical position by an automatic regulation of the current in the solenoid while its horizontal position is determined by the geometry of the axial magnetic field. The impedence of a small "pick-up" coil mounted below (or above) the glass vacuum chamber is changed by any vertical motion of the rotor. This produces a signal which automatically regulates the current in the solenoid in such a manner as to maintain the rotor at the desired vertical position. At the same time the rotor seeks the strongest part of the field which is on the axis. However, if it is disturbed it will oscillate around the axis so that some means is usually required to damp this type of motion. In Fig.

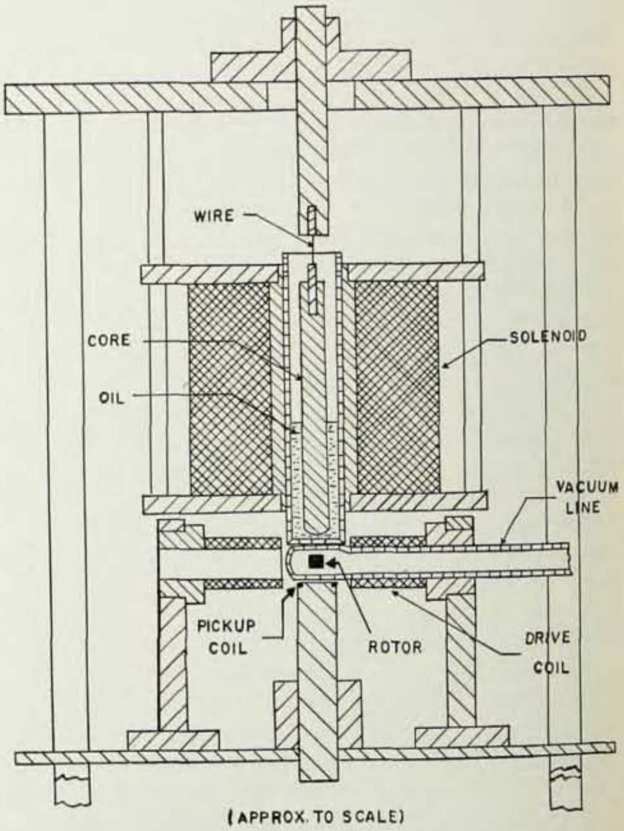

Fig. 4

4 the core of the solenoid is hung by a fine wire as a pendulum in an oil dash pot. If the rotor moves horizontally the core will follow and damp out the motion. For rotors less than 0.1 cm in diameter a small steel damping needle is placed in a tube of liquid just below the vacuum chamber. When properly adjusted no movement of the rotor, either horizontal or vertical, can be observed with a 100-power microscope. For the smallest rotors no horizontal damping is required. In some experiments it is preferable to replace the "pick-up coil" sensing system of Fig. 4 with a system actuated by light or other radiation which may be scattered, reflected, or absorbed by the rotors.

The rotors are spun by a rotating magnetic field in a manner similar to that of the armature of an induction or synchronous motor. If the temperature rise of the rotor is not important the induction motor type of drive is usually preferable but if the temperature of the rotor must be kept uniform and constant the synchronous or some other type of drive should be used.

The speed of the rotor is measured by reflecting (or scattering) light off of the rotor into a photomultiplier tube. Due to irregularities of the reflection from the rotor surface, the output of the photomultiplier is periodic with a repetition rate equal to the speed of the rotor. This signal is amplified and compared with that of a known frequency oscillator by means of an oscilloscope.

The above type of magnetic suspension is very useful for certain types of experiments because first the rotor is freely suspended and no shaft is required. This allows the rotor to be completely surrounded by a glass or metal vacuum chamber which can be baked out and sealed off from the pumping system if necessary. Second the friction associated with the suspension can be made exceedingly minute. This low friction results from the fact that no eddy currents are induced in a ferromagnetic rotor spinning around a vertical axis along the axial field of a solenoid. In practice it has been found that the friction caused by the suspension is negligible in comparison to the air friction on the rotor down to pressures of at least 10^{-6} mm of mercury. As a matter of fact, we have found that the deceleration of a "coasting" rotor can be used as a reliable absolute gauge for measuring gaseous pressures. Incidentally, in such experiments the temperature of the rotor must be maintained at a constant level. Otherwise thermal expansion of the rotor will change the rotor speed because of conservation of angular momentum. For example, a change of 1° C of a small steel rotor spinning at 10^6 rps produces a change in speed of about 20 rps.

In experiments where a constant rotational speed free of "hunting" is required, a low rotor friction is highly important. For example, if the rotor friction is high a large driving torque is required to keep the speed constant. Consequently a variation in speed is produced when at any time the frictional and driving torques are not equal. The larger the torques become the more difficult they are to equalize. Also, in practice it is exceedingly difficult to produce a driving torque which is uniform throughout the entire 360°. As a result, a secondary rotation or oscillation is superposed upon the main rotation. This type of motion is called "hunting" and is present in almost all conventional rotating systems. In rotating-mirror experiments, hunting is a source of considerable error and must be eliminated if precision is required. By means of a magnetic suspension similar to that shown in Fig. 4, and using an alloy steel rotor with six plane polished faces 0.8 cm $\times$ 0.8 cm, speeds of 20 000 rps in a good vacuum have been used with no observable hunting present.[32] The mirror operated as the armature of a synchronous motor and was driven by a piezoelectrically controlled circuit. Because of the low rotor friction the driving power could be "very loosely coupled" to the rotor, which avoided the hunting. As a matter of fact, the rotor speed was more constant than the piezoelectric circuit since the inertia of the rotor smoothed out any short period variations of the piezoelectric crystal drive, which in turn was at least as constant as the received signal in Charlottesville of the National Bureau of Standards broadcast station WWV. In view of these results it is possible that one or more magnetically suspended rotors might be used in connection with piezoelectric clocks to improve the short period constancy of their output signals.

The low friction of the magnetic suspension also has made possible the development of a high-precision equilibrium ultracentrifuge.[33, 34, 35] Svedberg originally pointed out that there were two simple methods of determining the molecular weight of a substance by centrifuging.[5] The first method consists in determining the rate of sedimentation in a high centrifugal field and then using Stokes law for determining the molecular weight. The second or equilibrium method consists in centrifuging a solution of the substance for a sufficiently long time at uniform temperature until the sedimentation is balanced by back diffusion. When this equilibrium condition exists, then, by measuring the density of the substance as a function of the radius of the rotor, the molecular weight of the substance can be determined from theory based upon thermodynamics. Consequently the second or equilibrium method is more reliable since it is based upon equilibrium theory and gives results which essentially are independent of the shape of the molecules. Also, it does not require as large a centrifugal field for a given molecular weight determination as the first method. On the other hand, in the past the first or rate of sedimentation method has been much more widely used because the data can be obtained in a maximum of a few hours. The constancy of temperature and rotor speed (especially hunting) requirements are not so great and are easily satisfied by the vacuum-type centrifuge previously described. The usefulness of the equilibrium method in the past has been severely limited because it is necessary to maintain the centrifuge rotor at a constant or a very slowly decreasing speed and at constant uniform temperature for times from several days to a few weeks.

The rotor of the magnetically suspended equilibrium ultracentrifuge is supported freely inside a brass vacuum chamber in a way similar to the rotor shown in Fig. 4. On the other hand, the rotor is driven by a thin flexible shaft which passes through vacuum tight glands and is spun by a turbine or electrical motor below the vacuum chamber. During an experiment the heavy brass vacuum chamber first is carefully thermostated to the desired temperature and evacuated to a pressure of at least 10^{-5} mm of mercury. The rotor is then spun up to operating speed and the shaft detached in such a way that the chamber is tightly sealed. Consequently the rotor is allowed to "coast" freely during the experiment. The present rotors are made of steel and weigh 14 kg. They are 9.4 cm in diameter and carry a cell which contains the solution of the substance under investigation. The cell is sealed by crystal quartz windows through which the sedimentation is observed. In recent experiments we have used two cells side by side, and sealed by the same windows.[34, 35] One cell contains the solvent and the other the solution. With this arrangement the strains in the windows are compensated and the sedimentation can be measured accurately by an interferometer. It is found that if the pressure surrounding the rotor is less than 10^{-6} mm of mercury the rotor requires more than a day to lose one revolution per second when coasting. Its speed at any time can be measured to less than one part in 10^6 and its temperature to one part in 10^4. The densities of the solution as a function of the radius can be determined to one part in 10^3. These values when substituted into the formula for the molecular weight gives a precision of about three significant figures for the molecular weights, provided the other quantities in the formula (such as the partial specific volume and activity coefficients which are measured outside the centrifuge) are known with this precision. Molecular weights of substances from about 50 to at least 10^8 can be measured by this method with about the same precision. Furthermore, it has been shown theoretically by Archibald[36] that the very slow decrease in speed of the rotor greatly reduces the time required for equilibrium to take place, provided a precision of no greater than one part in 10^3 is required. It is interesting to note that if the substances are pure, it should be possible to determine their molecular weights within one molecular weight unit up to molecular weights of 1000, and to less than, say, one amino acid component up to very large molecular weights.

ANOTHER problem of importance is the production of a beam of particles, atoms, molecules, or neutrons with homogeneous velocities. An obvious method of doing this is shown in Fig. 5. Two rotors, A and B, as nearly identical as possible and spaced

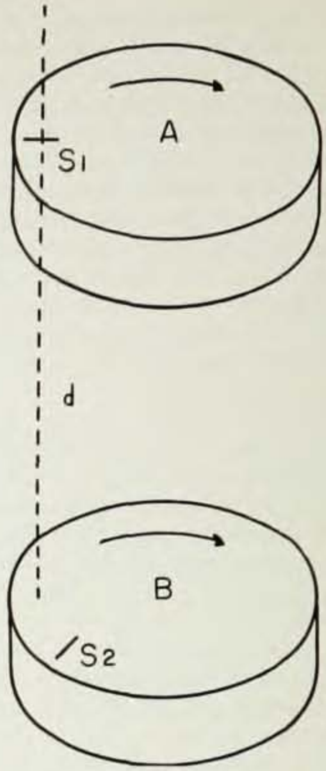

Fig. 5

a distance d apart, spin at the same rotational speed around the same axis. If a nonhomogeneous beam of particles passes through a fine slit S_1 in A, the faster particles will reach the rotor B before the slower ones so that they are spread out into a velocity spectrum around the periphery of B. Consequently, if B contains a fine slit S_2 the particles passing S_2 have only a small spread in velocity determined by the width of S_1, S_2, d and the rotors' speed. However, if the speed of B varies or hunts with respect to A, the beam passing S_2 becomes nonhomogeneous. Therefore, the magnetic suspension is ideal for use in these experiments. In practice, rotor A and rotor B are suspended magnetically in a good vacuum and spun around a common vertical axis up to as high a speed as the strength of the rotors will permit, and then allowed to coast. The speed of one rotor is then decreased with respect to the other by a magnetic field, produced near the periphery of the rotor by a small air-core solenoid, until the rotors have the same speed. The speed of the particles passing S_2 can be found from the phasing of B with respect to A. The phasing can be measured optically with high precision and the distance d in practice is limited only by the beam intensity. Since the rotors are free of hunting and their speeds can be determined to better than one part in 10^6 the velocity homogeneity of the beam is limited in practice by the widths of the slits S_1 and S_2.

The stresses in a spinning homogeneous rotor with a simple geometrical shape can be reliably calculated from theory. Consequently, a high-speed rotor may be used effectively for the determination of the mechanical properties of a substance because the uncertainties arising from stress concentrations produced by clamping are absent. Since the maximum stress is near the center for simple spherical and cylindrical rotors, the effect of surface cracks and surface imperfections can be eliminated. For example, the magnetically suspended rotor system has been used to measure the ultimate strength of a number of steel bearing balls made of the same material but of different diameters.[31] It was found that they all exploded at approximately the same peripheral speed (10^5 cm/sec). The tensile strength of thin films of silver electro-deposited on the surface of small cylindrical rotors was found to increase markedly when the thickness became less than the order of 10^{-5} cm.[37] The apparatus was also used for measuring the adhesion of one metal to another.[38] The method is almost unique because it gives precise absolute values of the adhesion.

So far, no mention has been made of the effect of the large gyroscopic forces on a rotor magnetically suspended in a vacuum and coasting freely at a very high speed. It is clear that these forces, unless compensated for, would cause the direction of the spin axis to remain fixed in space. As a result, the spin axis of the rotor soon would cease to coincide with the vertical axis of the diverging magnetic field of the solenoid because of the earth's rotation. However, it can be shown that at least two effects prevent this from occurring. In the first place, if the rotor is electrically conducting and the axis of spin is not coincident with the axis of the magnetic field, induced currents are set up in the rotor. In the second place, any magnetic memory in the material would keep the two axes coincident. These effects produce a finite damping of the rotor speed. However, it can be shown that this damping effect is extremely minute and usually can be neglected. On the other hand, if it were possible to make the rotor out of a ferromagnetic material which is electrically nonconducting and at the same time free of magnetic memory, the rotor would serve as an almost ideal free gyroscope because the "bearing noise" would then be reduced to the Brownian motion of the system, which is much less than can be obtained by other types of bearings. We have carried out some experiments in which a sphere made of fine Permalloy powder dispersed in a nonconducting medium was magnetically suspended and allowed to "coast" while spinning freely in a vacuum. Under these conditions, the axis of spin of the sphere no longer remained coincident with the axis of the magnetic field, and it was possible to observe very roughly the rotation of the earth.

At the present time, a study is being made of the several factors which may cause deceleration of a magnetically suspended rotor "coasting" in an ultrahigh vacuum. If it should turn out that at pressures of the order of 10^{-10} mm of mercury the friction of the magnetic support is still less than the air friction on the rotor, then a number of new and interesting experiments should be possible.

Bibliography

1. E. O. Lawrence, J. W. Beams, and W. D. German, Phys. Rev. **31**, 1112 (1928).
2. E. Henriot and E. Huguenard, Comptes Rendus **180**, 1389 (1925).
3. J. W. Beams, Rev. Sci. Instr. **1**, 667 (1930). J. W. Beams and A. J. Weed, Science **74**, 44 (1931).
4. J. W. Beams, Phys. Rev. **35**, 24 (1930); J. Appl. Phys. **8**, 795 (1937).
5. T. Svedberg, *Colloid Chemistry* (Chem. Cat. Co., 1928) second edition; T. Svedberg and K. O. Pederson, *The Ultracentrifuge* (Clarendon Press, Oxford, 1940).
6. H. W. Beams and R. L. King, Anat. Rec. **59**, 363 (1934).
7. E. N. Harvey, J. Appl. Phys. **9**, 68 (1938); Biol. Bull. **66**, 48 (1934).
8. J. W. Beams, E. G. Pickels, and A. J. Weed, J. Chem. Phys. **2**, 143 (1934).
9. J. W. McBain and C. M. O'Sullivan, J. Am. Chem. Soc., **57**, 2631 (1935).
10. E. G. Pickels and J. W. Beams, Science **81**, 342 (1935); J. W. Beams and E. G. Pickels, Rev. Sci. Instr., **6**, 299 (1935).
11. J. W. Beams, J. Appl. Phys. **8**, 795 (1937); Revs. Modern Phys. **10**, 245 (1938); Ann. New York Acad. Sci. **43**, 177 (1942); J. Wash. Acad. Sci. **37**, 221 (1947); Rev. Sci. Instr. **9**, 413 (1938).
12. J. W. Beams and L. B. Snoddy, Science **85**, 185 (1937).
13. C. Skarstrom and J. W. Beams, Rev. Sci. Instr. **11**, 398, (1940).
14. F. A. Lindemann and F. W. Aston, Phil. Mag. [6], **37**, 523 (1919).
15. R. S. Mulliken, J. Am. Chem. Soc. **44**, 1033, 1729 (1922); **45**, 1592 (1923).
16. S. Chapman, Phil. Mag. [6], **38**, 182 (1919); Phil. Trans. **A217**, 115 (1918).
17. W. D. Harkins, J. Frank. Inst. **194**, 783 (1922).
18. J. Joly and J. H. J. Pool, Phil. Mag. [6] **39**, 372 (1920); J. H. J. Pool, Phil. Mag. [6], **41**, 818 (1921).
19. J. W. Beams and F. B. Haynes, Phys. Rev. **50**, 491 (1936).
20. J. W. Beams and A. V. Masket, Phys. Rev. **51**, 384 (1937).
21. J. W. Beams and C. Skarstrom, Phys. Rev. **56**, 266 (1939).
22. R. F. Humphreys, Phys. Rev. **56**, 684 (1939).
23. F. C. Armstead, F. C. Bader, B. C. Belden, H. Carr, A. K. Cocke, C. Hutchison, F. L. Hereford, F. T. Holmes, L. G. Hoxton, M. Irby, W. C. Johnson, A. R. Kuhlthau, A. C. Lapsley, J. H. McQueen, F. W. Linke, A. K. Mann, J. W. Moore, E. P. Ney, M. L. Randolph, C. S. Simons, P. Sommer, and J. L. Young, III. In addition, A. O. Nier of the University of Minnesota, L. J. Briggs of the National Bureau of Standards, a group working at Columbia directed by H. C. Urey, a group at Westinghouse directed by F. C. Rushing, and a group at the Standard Oil Development Co. directed by E. V. Murphree gave us most valuable help.
24. J. W. Beams, L. B. Snoddy, and A. R. Kuhlthau, Second UN Int. Conf. on Peaceful Uses of Atomic Energy, Sept. 1958.
25. K. Cohen, *Theory of Isotope Separation* (McGraw-Hill Book Co., New York, 1951).
26. F. T. Holmes, Rev. Sci. Instr. **8**, 444 (1937).
27. F. T. Holmes and J. W. Beams, Nature **140**, 30 (1937).
28. C. S. Smith, Rev. Sci. Instr. **12**, 15 (1941).
29. L. E. MacHattie, Rev. Sci. Instr. **12**, 429 (1941).
30. J. W. Beams, J. L. Young, III, and J. W. Moore, J. Appl. Phys. **17**, 886 (1946).
31. J. W. Beams, Science **120**, 619 (1954).
32. J. W. Beams, E. C. Smith, and J. M. Watkins, Soc. Mot. Pic. Tel. Engs. **53**, 159 (1952).
33. J. W. Beams, J. D. Ross, and J. F. Dillon, Rev. Sci. Instr. **22**, 77 (1951).
34. J. W. Beams, H. M. Dixon, III, A. Robeson, and N. Snidow, J. Phys. Chem. **59**, 915 (1955).
35. J. W. Beams, Proc. Am. Phil. Soc. **101**, 63 (1957).
36. W. J. Archibald, Private Communication.
37. J. W. Beams, J. B. Breazeale, and W. L. Bart, Phys. Rev. **100**, 1657 (1955).
38. J. W. Beams, 43rd Tech. Proc. Am. Electroplaters Soc. (1956).