High Rotational Speeds

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IT is a general historical fact that, following each improvement in experimental technique, rapid progress has been made in the fields of science to which it was applicable. Therefore it may be worth while to review a few of the recent advances made in the production of high rotational speeds because of their possible use in many different types of research. With the exception of Svedberg's, most of the recent successes in the production and use of ultra-high rotational speeds have resulted from the employment of one or a combination of the three following devices: the air or gas bearing, the flexible shaft and the oil or liquid sealed vacuum gland. All of the principles upon which the above are based have been known for a long time but they have been successfully applied to the problem under review only in the last few years.

For many generations of students almost every lecturer in elementary physics has shown his class a ball freely supported upon a jet of air. The ball could be made to remain almost stationary, to move, or to spin, depending upon the wishes of the experimenter. Among other things this demonstration is usually made to illustrate the well-known principle of Bernoulli. However, it was not until 1925 that Henriot and Huguenard,[1] by means of a very ingenious arrangement, successfully utilized the general principles involved in the above experiment to spin small cone shaped rotors to very high speeds in air at atmospheric pressure. Since this original work of Henriot and Huguenard their method has been modified and improved by a number of workers[2–8] until at the present time the rotors are extremely stable. For example, a rotor may be loaded or unloaded while at full speed or made to carry a superstructure which need not be dynamically balanced with extreme care. In this review, space does not permit a full description of the original method of Henriot and Huguenard followed by the modifications which have been introduced in their chronological order. (For this see original references in Bibliography.) Instead, a brief description will be given of a general purpose apparatus that has been found very satisfactory.[7, 8]

Figure 1b is a cross section drawing and Fig. 2 a picture of the apparatus. Compressed air, admitted to the stator cup through flexible tubing, flows through the straight holes or channels LL' (Fig. 1a) and impinges upon the flutings of the rotor. As a result the rotor is both lifted off the stator and given a spin. The Bernoulli forces developed by the motion of the air between the rotor and stator prevent the former from flying out of the latter and, together with the weight of the rotor, balance the forces of the air impinging upon the rotor. This automatic balance takes

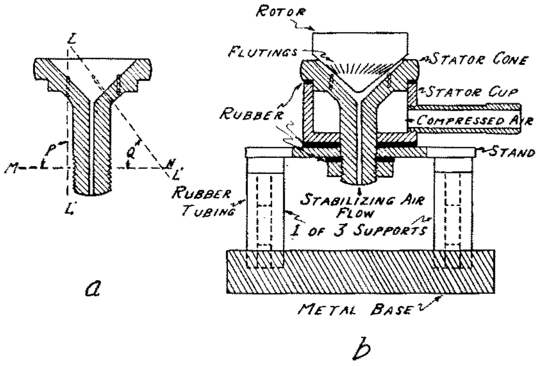

FIG. 1. *a*, Cross-sectional drawing of stator cone; *b*, cross-sectional drawing of stator and support with rotor in place.

place when the rotor is only a fraction of a millimeter above the stator so that the rotor rides upon a very thin cushion of air. In order to increase the stability of this air cushion or "bearing," additional air is allowed to flow from the atmosphere into the vertex of the stator cone (labeled stabilizing air flow, Fig. 1b). In some work[3] this stabilizing air has been forced into the stator under the desired pressure above atmospheric, or a valve[3, 6] has been added to limit the amount of air flow. However, with the dimensions given in Fig. 1b these added complications are unnecessary as the rotor is extremely stable at all usable speeds with the channel simply open to the atmosphere as shown. For example, a rotor can be loaded by suddenly pouring liquid into it while it is spinning, or the driving air pressure can be changed suddenly from 5 to 150 lb./in.^{2} or *vice versa* without disturbing the rotor's stability. In Fig. 1, $P=90°$; $Q=45°$ to $46°$; angle of stator cone $=91°$ to $92°$; angle of rotor cone $=102°$ to $103°$. The upper openings of the 5 to 9 directed channels LL' (bored with no. 65 twist drill in Fig. 2) lie in a circular section of the stator cone approximately midway between vertex and base. The diameter of the base of the stator is $1\frac{1}{8}$ inches. However, the number and size of the channels LL' may be varied over wide ranges. From 3 to 20 channels bored with twist drills of sizes from 45 to 76, depending upon the size of the rotor and stator, have been used successfully. The stator can be built to fit any size of rotor by simply changing all dimensions proportionately. An investigation of the efficiency of different types and directions of channels and rotor flutings has been carried out at the University of Virginia by Garman.[5] The stator should be flexibly mounted because, at certain rotational speeds, the air jets impinging upon the rotor, asymmetries in the rotor, etc., set up resonance vibrations which may be communicated to the stator. Usually the rotor can be accelerated through these resonance frequencies so quickly that they cause no serious trouble, but it is always preferable to keep them damped in the stator mounting, say by rubber or cork. Also it is important to avoid vibrations in the air supply line or stator box caused, for example, by a vibrating valve, constriction in nonflexible tubing, or wrong type of jet opening. A novel way of mounting the stator on flexible metal tubes which take the place of LL' and avoid the stator box has been used by Garman[5] and Girard and Chukri.[6] Fig. 3 shows another satisfactory stator mounting. For the various types of mountings and methods of construction of the various parts of the apparatus reference should be made to the original papers.[1–8] The stators can be made of any easily machinable materials such as steel, brass or Duralumin. However, care must be taken in selecting the rotor material because the bursting strength of the rotor often determines the maximum attainable rotational speed. This subject will be referred to again later in this review. The property of the air bearing of allowing the rotor to seek its own axis of rotation is exceedingly

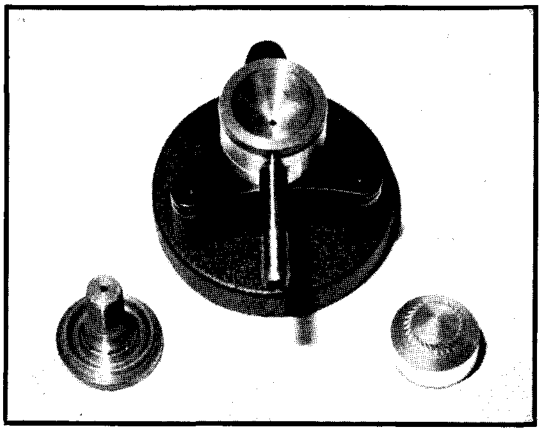

FIG. 2. Photograph of rotor, stator, and stator cone.

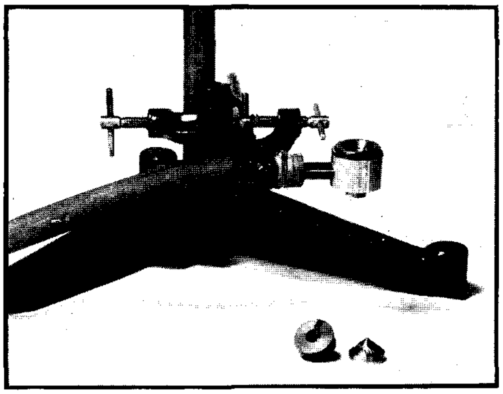

FIG. 3. A simple stator mounting. The stator and rotor (with flutings up) were used to make curve E of Fig. 5.

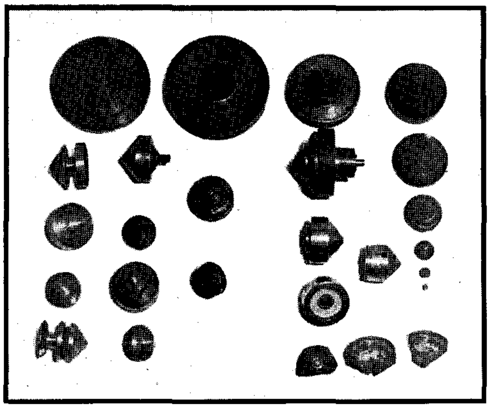

FIG. 4. Miscellaneous collection of rotors. At bottom right are some pieces of exploded rotors.

useful as this not only makes it possible to spin a wide variety of shapes and sizes of rotors (Fig. 4) but also simplifies the mounting of apparatus upon the rotor.

The above method is suitable for spinning almost any size or shape of rotor in air or other gases at about atmospheric pressure. However, as is well known, the air friction on a surface increases very much with its speed so that the power input must be greatly increased with size and speed of rotor. This is well illustrated by the curves of Fig. 5. By using hydrogen instead of air both to drive and surround the rotor the friction is not only reduced but the gas in the jets strikes the rotor with greater speed for a given pressure. For example, with a 9 mm diameter rotor driven and surrounded by hydrogen, we have obtained 21,600 r.p.s. and hence centripetal acceleration in excess of 8 million gravity. With smaller rotor and stator this could probably be much increased.

The above type of apparatus has been used quite successfully for spinning small mirrors to very high speeds.[1, 3, 9–11] Fig. 6 shows a spark photograph taken at Virginia with such a rotating mirror. Two events occurring within a time of the order of 10^{-9} sec. can be resolved. Also the apparatus has been used by H. W. Beams, R. L. King and others [12–16] as a centrifuge in many biological experiments where precise temperature control or thermal equilibrium throughout the centrifuge is not essential. Harvey[16] and Pickels[17] have devised simple optical schemes for viewing biological material with a microscope while it is being centrifuged. Several successful experiments have been carried out on the sedimentation of small particles and molecules from solution.[7, 15, 18, 19] A few successful attempts have been reported where the apparatus has been used for the determination of molecular weights.[15, 18, 19] In these experiments it is necessary to take elaborate precautions to maintain temperature equilibrium throughout the centrifuge "bowl" in order to prevent "remixing" or stirring.[8, 18, 20] Qualitatively it is easy to see that this is essential because the principal factor which produces movements in a liquid is roughly proportional to the "differences in density" multiplied by the centripetal acceleration. Hence stirring may result, even in a pure liquid, if inequalities in density arising from nonuniformity of temperature exist because of the large value of the centripetal acceleration. As a matter of fact this factor is so great that, in an ultracentrifuge, it would be practically impossible to prevent stirring if it were not for a second factor which tends to counterbalance it. This arises from the fact that

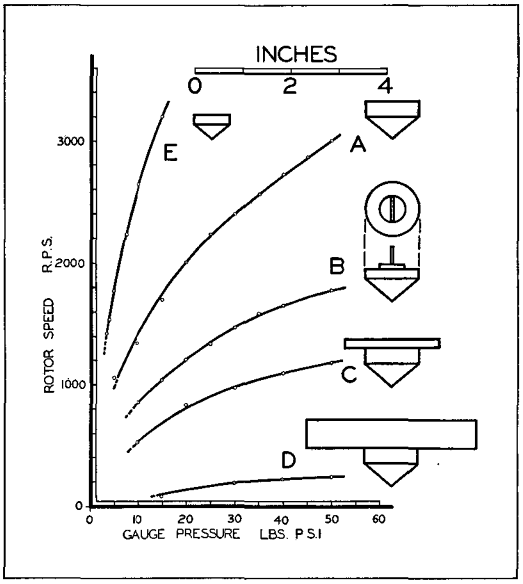

FIG. 5. Curves of the relation of air pressure to rotor speed for the case where the air surrounding the rotor is at atmospheric pressure. Curves *A*, *B*, *C*, and *D* were taken with the same stator (Figs. 1 and 2) and the rotors sketched to scale at right of each curve. Curve *E* was taken with stator shown in Fig. 3. For curves *A*, *B*, *C*, and *D* with driving pressure of 15 lb. per in.², 4.4 cu. ft. of air per minute was required. For curve *C* under same conditions, 5 cu. ft. per min. was required.

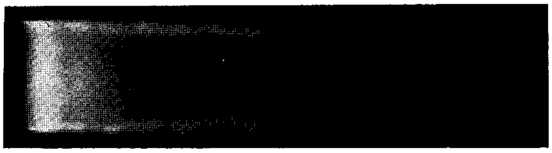

FIG. 6. Image of 8 mm bismuth spark swept from left to right across the photographic plate perpendicular to axis of electrodes by a rotating mirror mounted on an air turbine. Note that the intense luminosity due to air, initially reaching across the gap, soon dies out and that the luminosity from the metal vapor initially starts from each electrode and progresses slowly toward the opposite one. Complete picture shown represents about 4×10^{-6} sec.

the density of a liquid increases with the pressure. Since the density of the liquid increases toward the periphery, due to increased pressure, stirring caused by temperature gradients is counteracted to a certain extent.*

It is especially difficult to maintain temperature equilibrium in the simple air-driven centrifuge which spins in air at atmospheric pressure. First, as can be seen from the curves of Fig. 5, the air friction is so great that the moving surfaces must be considerably heated. This heating is greatest near the periphery and top surface but zero at the center so that the temperature gradients are in the direction to produce stirring in most practical cases. Second, the expanding air jets striking the under side of the rotor may cool it several degrees and hence tend to produce additional temperature gradients from bottom to top of the centrifuge. This difficulty of maintaining temperature equilibrium in the above type of centrifuge, the increased power necessary to drive large rotors in gases at atmospheric pressure and the general desirability of spinning rotors at very high speeds in a vacuum, stimulated us at Virginia to devise the vacuum-type ultracentrifuge.

Air-Driven Vacuum Type Ultracentrifuge

In the original vacuum type air-driven ultracentrifuge[21, 8] the large rotor or "centrifuge" inside a vacuum chamber was driven and supported by an air turbine such as shown in Figs. 1 and 2 located outside and vertically above the chamber. The turbine and centrifuge were connected by a flexible shaft (steel piano wire) which was coaxial with their axes of rotation and passed through a vacuum tight oil gland or bearing that sealed the vacuum chamber. With this arrangement the centrifuge could seek its own axis of rotation (within limits) and hence was very stable. Also the vacuum attainable depended upon only the vapor pressure of the oil which could be made very small (10^{-6} to 10^{-7} mm for some oils). Furthermore, since the efficiency of the air-driven turbine was not appreciably decreased by the added weight of the centrifuge or by the bearing friction the maximum rotational speed was set only by the mechanical strength of the centrifuge. In the type of air turbine shown in Fig. 1 the turbine is both supported and driven by the same air jets. This naturally gave trouble in bringing the centrifuge to rest because when the

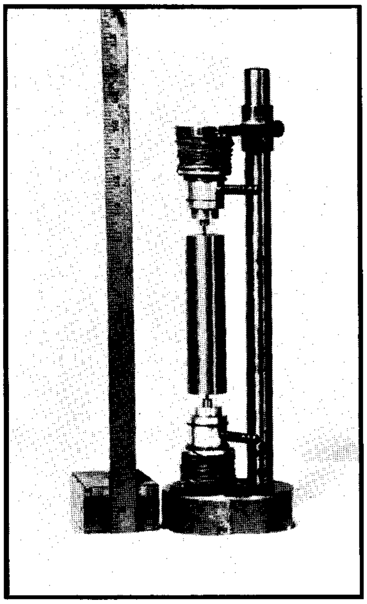

FIG. 7. Method of spinning rods or tubes in air at atmospheric pressure. Stators at top and bottom are flexibly mounted and damped.

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* The maximum stable or adiabatic radial temperature gradient for a substance in a centrifugal field can be calculated from the familiar thermodynamic equations. $dT/dp=(T/c_p)(\partial v/\partial T)_p$ where the symbols have the usual meaning. For air at 20°C treated as an ideal gas we have, approximately $dT_r/dr=(d/dr)(5\times10^{-8})w^2r^2=10^{-7}w^2r$. Where the field is a million times gravity $dT_r/dr=100$ deg./cm app. In the case of water at 20°C $dT/dp=1.8\times10^{-9}$ deg./dyne·cm². Since $dp/dr=w^2r$, $dT_r/dr=1.8\times10^{-9}w^2r$. For a million times gravity $dT_r/dr=1.8$ deg./cm app. The above calculations were taken from Professor L. G. Hoxton's lectures in thermodynamics.

driving air pressure was reduced, unless considerable care was taken, the turbine often "grabbed" and broke the flexible wire. Accordingly a driving turbine was constructed[8] in which the cushion of air that supported it was independent of the air jets that spun it. This made it possible to turn off the driving air and allow the centrifuge to coast smoothly to rest on the air cushion support. Several different workers have adapted and improved the above vacuum-type centrifuge to fit their special problems,[22–32] but unfortunately space does not permit a detailed review of these. Instead a brief description will be given of the essential features and of apparatus which has been used successfully at the University of Virginia for different purposes.

Figures 8 and 9 show a drawing and picture of an apparatus used for the separation of isotopes by evaporative centrifuging,[31, 32] while Figs. 10 and 11 show an arrangement constructed for research in biochemistry. The rotating members consist of the driving turbine, *T*, the flexible shaft, *A*, and the centrifuge or large rotor, *C*. The flexible shaft, *A*, passes through two vacuum tight oil glands (or bearings), G_1 and G_2. G_1 seals the vacuum chamber. G_2 is added so that *C* may be filled with liquid or gas or evacuated while spinning. G_2 also permits the use of the very stable "flat type" of air bearing support. G_1 and G_2 are constructed by machining a brass rod to the shape shown in Figs. 8, 10 and 12, and by boring a hole (usually about $\frac{3}{8}''$ diameter) along its axis. A plug of bearing metal (about $\frac{1}{4}''$ to $\frac{3}{8}''$ long) is then fitted into each end of this hole and another hole bored along the axis of each plug slightly smaller in diameter than the shaft *A*. These holes in the plugs are then reamed to such a size that *A* just slips in without forcing. The kind of bearing metal is determined by the material of *A*. When the latter is steel the former may be brass, bronze, babbitt metal, etc. G_1 and G_2 are mounted, as shown in the figures, in round flexible rings (made of Duprene[33] or other flexible oil-resistant materials). Vacuum pump oil is forced into G_1 and G_2 through the channels shown in Figs. 8

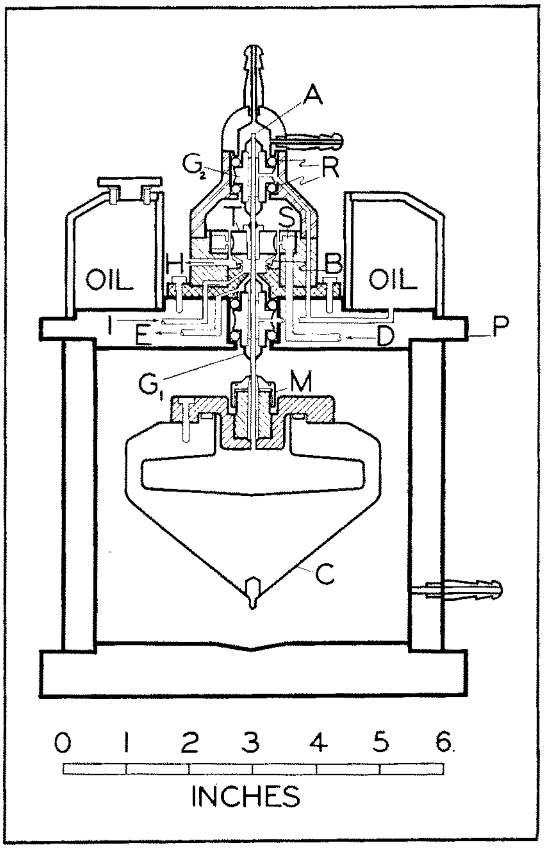

FIG. 8. Drawing approximately to scale of air-driven vacuum type centrifuge employed in the concentration of isotopes.

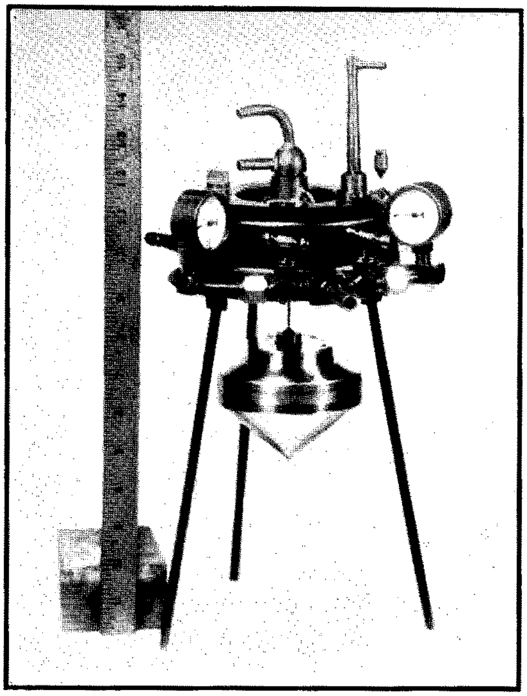

FIG. 9a. Photograph of apparatus of Fig. 8 with vacuum chamber removed. Inch scale on left.

and 10. If properly made, less than one cc of oil will leak into the vacuum chamber per hour through G_1. This type of mounting, besides giving the proper flexibility to G_1, allows any heat generated in the bearing to be carried out by the oil to the plate P. That is, the shaft A is held at approximately the same temperature as the vacuum chamber which, in turn, may be thermostated easily by standard procedure. The flexible shaft A may be either a rod or a tube. A rod is usually preferable when it is not necessary to fill or evacuate C while spinning, although stainless steel hypodermic needle tubing serves almost as well.[34] The diameter of A depends upon the weight and diameter of C. For the $4\frac{1}{4}''$ Duralumin rotor shown in Figs. 8 and 9 hypodermic needle tubing of No. 15 Stubbs gauge is used, while for the rotor, Figs. 10 and 11, the diameter of A was gauge 14. Besides steel and stainless steel, A may be made of any reasonably strong material such as phosphor-bronze, beryllium-copper or German silver. The latter is especially useful when C is spun at low temperatures (dry ice or liquid air) while some of the others are useful in magnetic experiments. The diameter of the "pill box" shaped turbine, T, is also determined by the weight and speed of C. In Figs. 8 and 10 the diameters of T are $\frac{3}{4}''$ and $\frac{7}{8}''$, respectively. The turbine should be made of strong material such as Duralumin, phosphor-bronze or steel. The type of fluting is clear from Figs. 9b and 12. Preferably the under surface of T should be flat when an upper bearing G_2 is used but cone-shaped (apex angle 90° to 92°) when the upper bearing is omitted. The air cushion which supports the turbine is formed between the slightly cone-shaped collar, B, and the under surface of T. B should preferably be made of Bakelite although Duralumin is satisfactory. B rests upon a flexible round or flat ring (Duprene or rubber). The stator, S, is a simple air box with channels bored to direct the driving air jets. The channels have their axes in a horizontal plane and if extended would pass within about $\frac{9}{32}''$ and $\frac{11}{32}''$ of the axis of the turbine in Figs. 10 and 12, respectively. The number and size of the channels depend upon the load and size of T. For Figs. 8 and 10, each has 8 channels bored with a No. 60 twist drill. It should be noted that if the number of flutings on the rotor is odd, the number of channels in the stator should be even and *vice versa*. C is always specially designed for the problem under investigation. A pin or screw clutch, M, fastens A to C in such a way that a lead or soft metal washer between the two makes the connection vacuum tight. A few of the different shapes and sizes are shown in Fig. 13. Special attention should be given to the material and shape of C because its bursting strength is the only factor that limits the rotational speed attainable. Fig. 14 shows a few rotors after they have been exploded by their own centrifugal force as well as some of the vacuum chambers which surrounded them. For solid rotors the bursting speed is set not by the absolute strength of the material but by the absolute strength divided by the density. However, in centrifuge work this is often no longer true and the absolute strength becomes important. At the present time among the lighter alloys Duralumin ST14 (forged) is probably the best general purpose material although in some cases special steels are superior. A large amount of both theoretical and experimental work has been done on the materials and shapes of rotors to give them maximum bursting speed. Nevertheless materials that

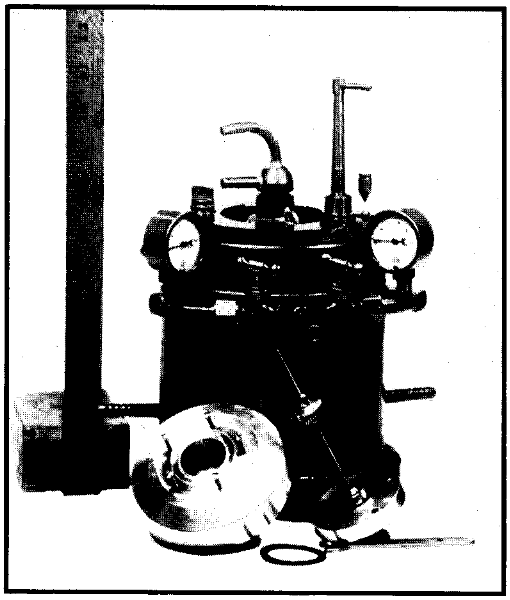

FIG. 9b. The same as 9a with vacuum chamber in place. Rotor parts together with flexible shaft and turbine are in foreground.

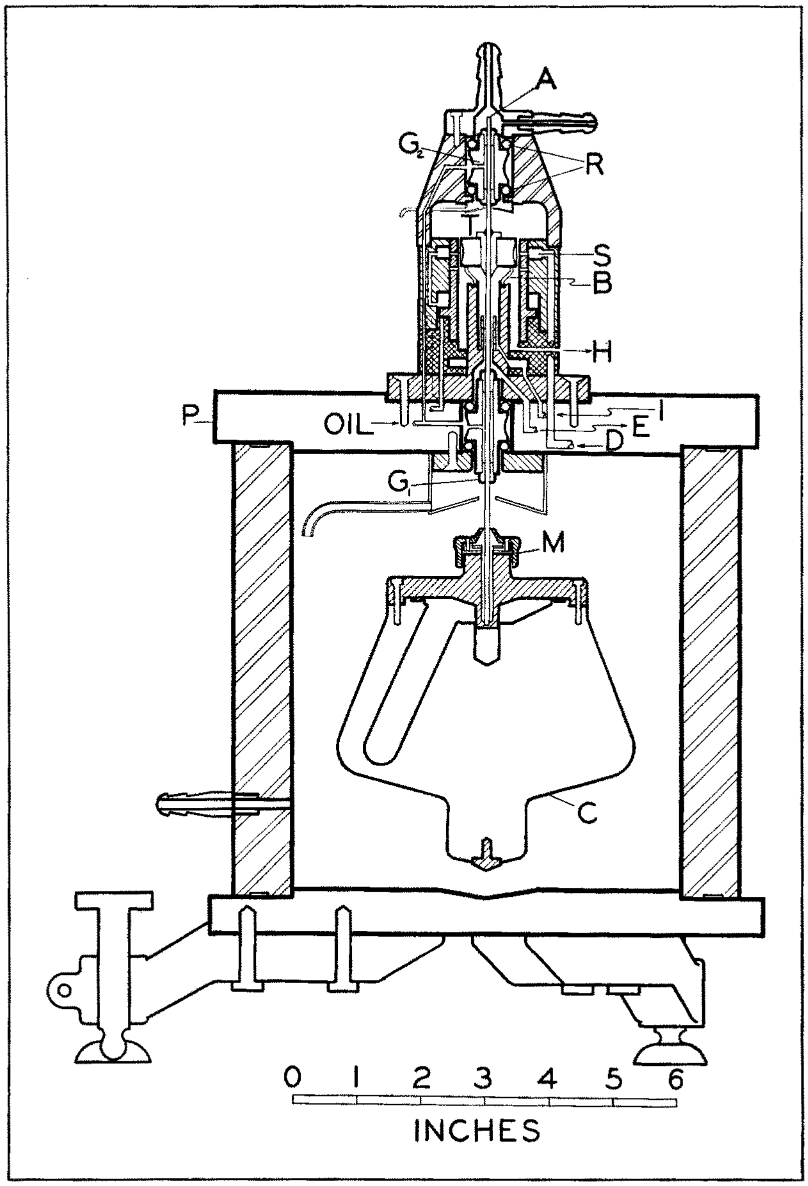

FIG. 10. Drawing approximately to scale of air-driven vacuum type centrifuge made at Virginia for Dr. Alfred Chanutin for research in biochemistry.

will stand higher rotational speeds are at present the greatest need in almost every problem undertaken with the ultracentrifuge. It might also be noted that in a rough way the strength of a homogeneous rotor depends upon the peripheral velocity squared, or w^2r^2, where w = angular velocity and r = radius, while the centripetal acceleration is given by w^2r. Hence when it is desired to obtain large accelerations by the above method small rotors should be employed.

At the time of explosion the peripheral speed of one of the rotors shown in Fig. 14 was 8×10^4 cm/sec. or about 2.6 times the velocity of sound. Hence the vacuum chamber must be either heavily barricaded or made very strong to protect the operator in case of an explosion. The latter procedure is preferable although the former is less expensive. Bauer and Pickels[20, 22] recommend that the vacuum chamber be a heat treated nickel-steel alloy cylinder with wall thickness of at least an inch for the type of Duralumin rotors used in their work, while Pollock and Collie[35] employ a short segment of a discarded cannon barrel for their chamber. In both cases, the tops and bottoms of the chamber should be steel plates at least an inch in thickness. For many purposes the temperature of the chamber must be carefully controlled. This can be done by forcing a liquid at the proper temperature through copper pipes in good thermal contact with both cylinders and end pieces.

To operate the apparatus, *C* is clamped at the desired position on *A*, usually found by trial ($\frac{3}{8}''$ to $\frac{3}{4}''$ from lower bearing is satisfactory in Figs. 8 and 10 although longer distance may be used if specially desired). Air is then admitted through the channel, *I*, and the pressure increased until the rotating parts are freely supported upon the air cushion formed between *B* and *T*. (This pressure was about $6\frac{1}{2}$ lb./in.^{2} and $9\frac{1}{2}$ lb./in.^{2} for the instruments shown in Figs. 8 and 10.) Air pressure equal to or slightly greater than that

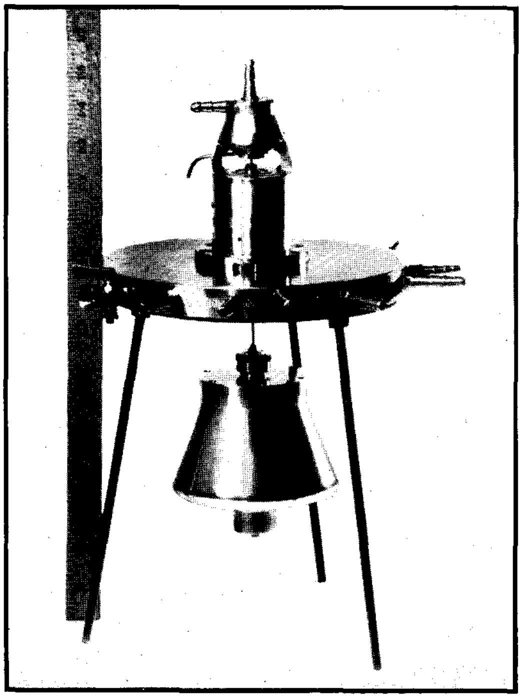

FIG. 11a. Photograph of apparatus of Fig. 10 with vacuum chamber removed.

required to maintain the above air cushion is next applied to the oil tank which forces the vacuum pump oil into the glands G_1 and G_2. The apparatus is then placed in its position upon the vacuum chamber and the vacuum pumps are started. A convenient pumping arrangement consists of an oil diffusion pump backed by, say, a Cenco Hyvac pump. If C must remain at constant temperature the pressure should be below one micron. The driving air is then admitted through the channel, D, to the stator, S. This starts the centrifuge spinning. As the rotors accelerate, they pass through certain speeds at which vibration takes place. Fortunately, these are not violent and consist of rather narrow bands. The first occurs when the rotational frequency approximately equals the frequency with which C will vibrate if, while not spinning, it is given a displacement and allowed to "vibrate as a pendulum." Other critical vibration frequencies due to resonance points in the apparatus, natural vibrations in C itself, standing waves in A, etc., occur at higher rotational speeds. These have harmonics at still higher frequencies, but their amplitudes are very small. It is good practice to carry the centrifuge through the critical speeds as quickly as possible. Also a working speed should be selected which is well removed from a vibration frequency regardless of its amplitude. Sometimes when the apparatus is over-cushioned or over-damped it is difficult to detect these minute vibrations. Hence no more flexibility and damping should be given to the driving parts than necessary. Except at the few critical speeds discussed above, the centrifuge spins extremely steadily and smoothly. Even when examined with a microscope or by reflected light at a distance of a meter the centrifuge shows no observable wobble or vibration. As a matter of fact if properly adjusted the centrifuge accelerates so smoothly that a careful watch must be kept upon its speed to prevent exceeding its "bursting speed." With the apparatus of Figs. 8 and 9 the centrifuge is accelerated with 35 to 40 lb./in.^{2} driving air pressure. It is maintained at working speed (1550 r.p.s.) by 10 lb./in.^{2} driving air pressure. (The volume of air at 10 lb./in.^{2} is 2 ft.^{3}/min. N.T.P.) If the above centrifuge should reach 1650 r.p.s. (found experimentally) it would

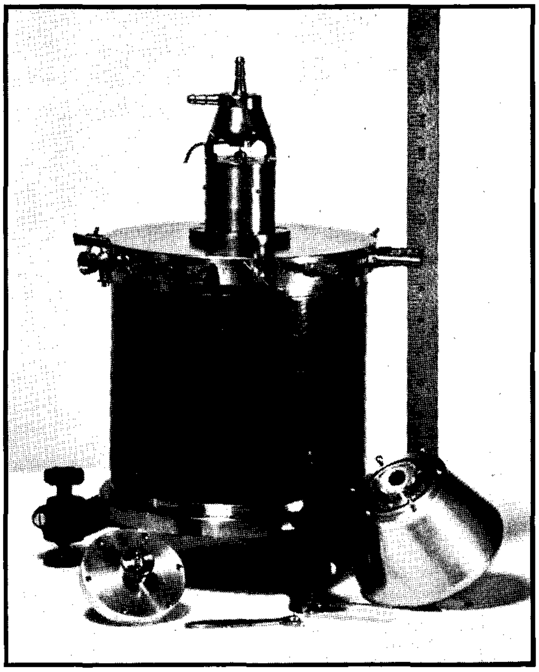

FIG. 11b. Same as 11a with vacuum chamber in place and centrifuge parts in foreground.

start to deform. This emphasizes the fact that it is necessary to maintain not only a constant driving air pressure but an almost continuous check upon the rotational speed. Usually reducing valves and air strainers of various kinds are used to keep the air clean and at constant pressure, while the stroboscopic method is used to measure the speed. Several methods have been described with which it is possible not only to measure the speed but to regulate it as well.[3, 36–38] In the apparatus of Fig. 9, if C is allowed to coast in coming to rest from 1500 r.p.s. it will require more than a day unless air is admitted to the vacuum chamber. For this reason reverse jets are provided in the apparatus of Fig. 10 so that the centrifuge may be stopped smoothly in a few minutes. With an apparatus similar to that shown in Fig. 9 one set of plugs (babbitt bearings) in the glands G_1 and G_2 usually last, if care is taken in starting, until the rotor has made more than 10^9 rev.

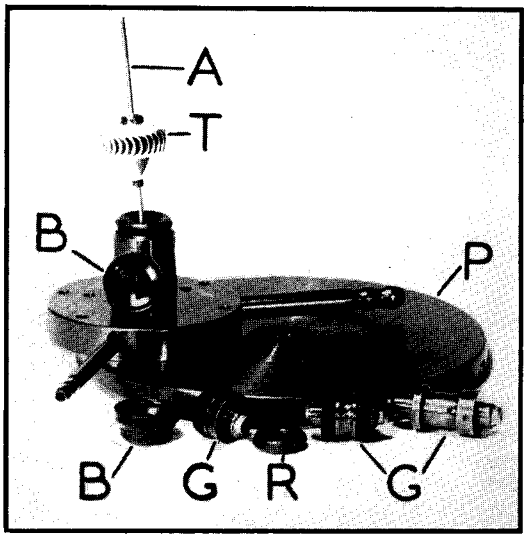

FIG. 12. Photograph of turbine, flexible shaft, Bakelite collar, round Duprene rings, vacuum tight oil glands, and top plate of vacuum chamber. The lettering corresponds to that in Figs. 8 and 10.

Inverted Ultracentrifuges

In many experiments it is necessary to place observing apparatus directly above and on the axis of the centrifuge. Obviously this is impossible with the apparatus described above because of the location of the driving turbine. In order to overcome this difficulty the apparatus shown in Fig. 15 was devised[39] in which the driving turbine, air cushion, supports, etc., are placed below rather than above the vacuum chamber. In this arrangement the centrifuge, instead of hanging on a flexible shaft supported by the turbine above the vacuum chamber, is mounted on a flexible shaft extending upward through a vacuum gland and supported by a turbine below the chamber. The driving and supporting mechanisms are essentially the same as those described above. In practice the stability of this inverted type of centrifuge is as great as if not greater than that of the type (Figs. 8–12) previously described. Like a top spinning on its point any gravitational couple produces a precession which is in the direction of rotation rather than opposed to it as in the original type.

FIG. 13. Photograph of a collection of rotors that have been spun in a vacuum.

Long Rods and Tubes

In the course of some experiments at Virginia we found it necessary to develop the technique of spinning long vertical rods and tubes in a vacuum. They are supported by flexible shafts, one above and one below the rotor. These shafts, which may be either tubes or rods, pass through oil glands similar to those described previously in the top and bottom of the vacuum chamber respectively. The spinning rod or tube is supported and driven by the type of air cushion and turbine already described in connection with Figs. 8–12. This driving mechanism may be either above or

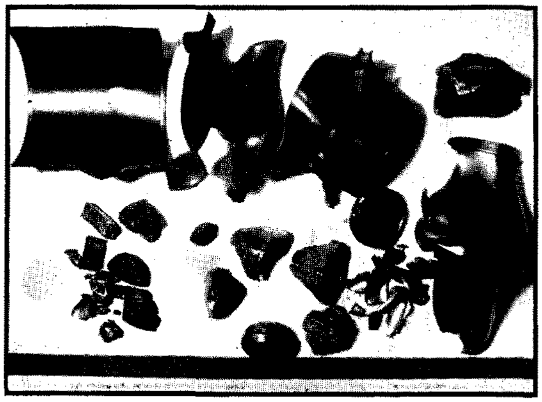

FIG. 14. Photograph of metal rotors and vacuum chambers after explosion. At right are parts of an exploded steel tube.

below the vacuum chamber. It is generally necessary to make the length of shaft between gland and rotor greater than usual. Also, it is desirable to make the mounting of the glands more flexible. However, these adjustments depend upon the length, diameter and weight of the rod or tube. Rods 2.5 feet long and weighing 75 lb. have been spun. Again, the only factor which determines the maximum rotational speed attainable is the bursting strength of the tube or rod. Fig. 14 shows a steel tube 1 foot long and 2.6 inches in diameter exploded by Mr. C. Skarstrom, at Virginia.

Uses of Air-Driven Vacuum Type Ultracentrifuges

Perhaps the most extensive use of the air-driven vacuum type centrifuge has been in the concentration and purification of biological materials. The pioneering work of Bauer and Pickels[20, 22] on the concentration of yellow fever virus, of Wyckoff and his collaborators [23–30] in their investigations of so-called "macromolecular" proteins and the experiments of Severinghaus and Chiles on the concentration of hormones illustrate the possibilities of the ultracentrifuge in biology, medicine, and chemistry. In addition to the above, the air-driven vacuum type centrifuge has been employed in the determination of molecular weights by the classical methods of Svedberg.[20, 22–30] In this work it has been found to yield as accurate results as Svedberg's oil turbine ultracentrifuge.[20, 24] In connection with the above types of work there is need for additional theoretical work on the problems of sedimentation in both liquids and gases (with accompanying tables, etc.). Something similar to the excellent work of Mason and Weaver[40, 41] for settling in liquids in uniform gravitational fields would be exceedingly useful. The vacuum type of ultracentrifuge has also been utilized for the separation of gases and for velocity selection of molecules.[31] As mentioned previously, the apparatus in Figs. 8 and 9 is now being employed in the separation of isotopes.[32] The above apparatus may also be used to study the strength of materials, as an alternator, for mechanically making or breaking electrical circuits, to spin rotors at either high or very low temperature, to spin mirrors at high speeds, to spin rods or other rotors for the study of gyromagnetic phenomena, for moving two surfaces past each other at very high speeds, for rotating drums, and in general in the study of phenomena which occur in intense centrifugal fields.

Electrical, Steam and Oil-Driven Ultracentrifuges

In many laboratories compressed air in sufficient quantities to operate the air-driven ultracentrifuge is not available. Also there is the need for an ultracentrifuge which is comparatively "fool proof" and requires a minimum of attention of the operator, i.e., one which automatically speeds up to the required angular velocity and remains at this value until changed by the operator. Recently an electrically-driven vacuum type ultracentrifuge[42] has been described which has promise of satisfying the above needs. In this apparatus a small electrical motor is used to drive the centrifuge in place of the air turbine while the air cushion support is essentially the same as that previously described (Figs. 8–12). This is a great saving of air because the amount used in the cushion support is small in comparison with that required to drive the turbine. Also it need only be furnished at from 5 to 15 lb./in.^{2} Hence a small, relatively inexpensive air compressor is all that is required. The armature of the electrical motor must be specially designed to stand high centrifugal forces. Both induction and synchronous motors have been used in connection with variable frequency thyratron inverter circuits. Variable frequency oscillator circuits employing high vacuum tubes or other types of alternators[43] also may be used to give the necessary a.c. power. As a matter of fact it is highly probable that a d.c. motor could be made to serve the purpose almost equally well. The electrically driven centrifuge has been used successfully up to 1000 r.p.s. and there seems to be no reason why this method, when fully developed, cannot be made to attain much higher rotational speeds.

The steam-driven vacuum type ultracentrifuge[44] is essentially the same as the air-driven type except that precautions must be taken to insulate thermally the driving turbine from the vacuum chamber. This has been accomplished by mounting the stator upon nonconducting material such as lavite and circulating water in copper coils in thermal contact with all of the upper part of the vacuum chamber. The steam is generated electrically (5 kw water heater unit) and is superheated. The only factor which determines the maximum speed attainable (as in the case of the air-driven centrifuge) is the bursting strength of the centrifuge.

The oil-turbine ultracentrifuge was developed by Professor Svedberg and his students[45–57] and used by them in their epoch-making experiments on the determination of the molecular weights of proteins, etc. The apparatus represents many years of development and is a model of machine design and precise workmanship. The centrifuge is supported in horizontal bearings and is spun by twin oil turbines, on each end of a large rigid shaft. The oil which drives the turbines is supplied by a special compressor and is cooled by a refrigeration plant to a suitable temperature before it enters the turbine chambers. The centrifuge spins in circulating hydrogen at about 25 mm pressure. The rotors are made of chromium-nickel steel. Svedberg was able to obtain his highest centrifugal forces with hard steel but discarded it in favor of softer steels which were found to be more reliable. The centrifuge or large rotor is shaped to give it maximum strength and must be dynamically balanced with extreme care. Reference should be made to the papers of Svedberg[45, 46] for a detailed description.

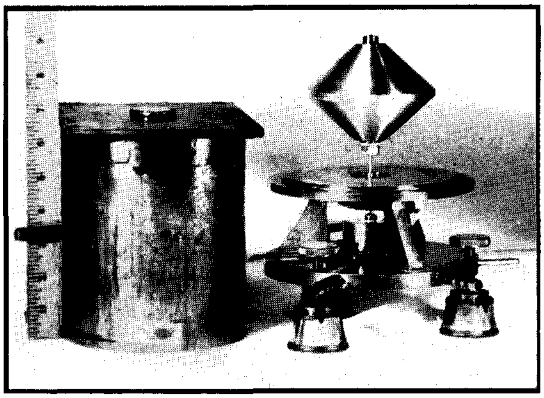

FIG. 15. Photograph of an air-driven inverted vacuum type ultracentrifuge with vacuum chamber removed.

Recently a promising new method of producing high rotational speeds in a vacuum or in gases at various pressures has been made possible by the Holmes magnetic suspension.[58] This consists of a vertical rod of iron suspended in the coaxial field of one or more solenoids. A steady direct current in one solenoid produces a field which almost supports the iron rod to which are attached the other rotating parts. The rotor or vane attached to the rod controls the amount of light incident on a photo-cell. The current from this cell is amplified and fed to the solenoid in such a manner as to automatically maintain the rod at a predetermined height. Such a suspension is macroscopically stable and, in a vacuum, theoretically may have infinitesimal torque against axial rotation. In the preliminary experiments[58, 59] a small rotor (mass and moment of inertia of iron rod and attached Duralumin rotor was 6 g and 0.8 g cm^2, respectively) in a vacuum (10^{-5} mm) was spun to 1200 r.p.s. by the action of the field of a small magnet mounted horizontally on an air-driven turbine spinning below the rotor at 1500 r.p.s. Damping observations were carried out in the neighborhood of 600 r.p.s. with the driving magnet removed. The deceleration observed was 2×10^{-3} rev./sec.^{2} corresponding to a frictional torque of about 10^{-2} dyne cm. This low frictional torque makes possible the production of very constant rotational speeds. For example, if the rotor is driven by the action of a rotating field, the field need not be large and hence can be accurately controlled both in amplitude and frequency (say by a piezoelectric circuit). The large slip resulting from an effectively weak field makes the rotor speed fluctuate much less than that of the rotating field. The experiments indicate that it should be possible to spin rotors of almost any size, which can be surrounded by a vacuum chamber, up to their bursting speeds and that the method should be of considerable use in experiments where extremely high vacuum or constant rotational speeds are required.

Bibliography

1. Henriot and Huguenard, Comptes rendus **180**, 1389 (1925); J. de phys. et rad. **8**, 443 (1927).
2. Lawrence, Beams and Garman, Phys. Rev. **31**, A1112 (1928).
3. Beams, Rev. Sci. Inst. **1**, 667 (1930).
4. Beams and Weed, Science **74**, 44 (1931).
5. Garman, Rev. Sci. Inst. **4**, 450 (1933).
6. Girard and Chukri, Comptes rendus **196**, 327 (1933).
7. Beams, Weed and Pickels, Science **78**, 338 (1933).
8. Beams and Pickels, Rev. Sci. Inst. **6**, 299 (1935).
9. Beams, Phys. Rev. **35**, 24 (1930); **36**, 997 (1930); **44**, 803 (1933); J. Opt. Soc. Am. **25**, 48 (1935).
10. Webb, J. Opt. Soc. Am. **26**, 347 (1936).
11. Chiles, Phys. Rev. **49**, 860 (1936).
12. H. W. Beams and R. L. King, Anat. Rec. **59**, 363 (1934); **59**, 395 (1934); J. Comp. Neur. **61**, 175 (1934); Proc. Roy. Soc. Lond. **B118**, 264 (1935); Nature **135**, 232 (1935); **139**, 369 (1937); Science **84**, 138 (1936); Biol. Bull. **71**, 188 (1936); J. Morph. **61**, 27 (1937).
13. H. W. Beams, J. B. Gatenby and J. A. Muliyil, Quart. J. Micr. Sci. **78**, 387 (1936).
14. Guyer and Claus, Proc. Soc. Exp. Biol. and Med. **35**, 146 (1937).
15. McIntosh, J. Path. and Bact. **41**, 215 (1935); McIntosh and Selbie, Brit. J. Exp. Path. **18**, 162 (1937).
16. Harvey, J. Frank. Inst. **214**, 1 (1932); Science **75**, 267 (1932); Biol. Bull. **66**, 48 (1934).
17. Pickels, Science **83**, 471 (1936).
18. Beams, Pickels and Weed, J. Chem. Phys. **2**, 143 (1934).
19. McBain, Nature **135**, 831 (1935); McBain and O'Sullivan, J. Am. Chem. Soc. **57**, 780 (1935); **57**, 2631 (1935); **58**, 2650 (1936); McBain and Alvarez-Tostado, Nature **139**, 1066 (1937).
20. Bauer and Pickels, J. Bact. **31**, 53 (1936); J. Exp. Med. **65**, 565 (1937).
21. Pickels and Beams, Phys. Rev. **47**, 336A (1935); Science **81**, 342 (1935).
22. Bauer and Pickels, J. Exp. Med. **64**, 503 (1936).
23. Biscoe, Pickels and Wyckoff, Rev. Sci. Inst. **7**, 246 (1936); J. Exp. Med. **64**, 39 (1936).
24. Wyckoff, Science **84**, 291 (1936); **85**, 390 (1937); **86**, 92 (1937); Proc. Am. Phil. Soc. **77**, 455 (1937); Naturwiss. **25**, 31 (1937); Proc. Soc. Exp. Biol. and Med. **36**, 771 (1937).
25. Wyckoff and Lagsdin, Rev. Sci. Inst. **8**, 74 (1937).
26. Wyckoff and Corey, Science **84**, 513 (1936); J. Biol. Chem. **116**, 51 (1936).
27. Wyckoff, Biscoe and Stanley, J. Biol. Chem. **117**, 57 (1937).
28. Stanley and Wyckoff, Science **85**, 181 (1937).
29. Biscoe, Herčík and Wyckoff, Science **83**, 602 (1936).
30. Beard and Wyckoff, Science **85**, 201 (1937).
31. Beams and Haynes, Phys. Rev. **49**, 644A (1936); **50**, 491 (1936).
32. Beams and Masket, Phys. Rev. **51**, 384A (1937).
33. Obtained from the Manhattan Rubber Co., Newark, N. J.
34. Obtained from Jensen-Salsbery Laboratory, Inc., Kansas City.
35. Pollock and Collie, Nature **137**, 950 (1936); The Engineer **166**, 102 (1937).
36. Shapiro and Butt, Rev. Sci. Inst. **8**, 35 (1937).
37. Snoddy and Beams, Science **85**, 273 (1937).
38. Davis, Rev. Sci. Inst. **7**, 96 (1936).
39. Beams and Linke, Rev. Sci. Inst. **8**, 160 (1937).
40. Mason and Weaver, Phys. Rev. **23**, 412 (1924).
41. Weaver, Phys. Rev. **27**, 499 (1926).
42. Beams and Snoddy, Science **85**, 185 (1937).
43. Colwell and Hall, J. Frank. Inst. **221**, 797 (1936).
44. Hoxton and Beams, Phys. Rev. **51**, 690A (1937).
45. Svedberg, *Colloid Chemistry* (Chemical Catalog Company, 1928).
46. Svedberg, Zeits. f. physik. Chemie **121**, 65 (1926); Science **79**, 327 (1934); J. de phys. et rad. **7**, 227 (1931); Chem. Rev. **14**, 1 (1934); **20**, 81 (1937); Naturwiss. **22**, 225 (1934); Kolloid Zeits. **67**, 1 (1934); Ber. deutsch Chem. Ges. **67**, 117 (1934); Nature **139**, 1051 (1937).
47. Svedberg and Nichols, J. Am. Chem. Soc. **48**, 3081 (1926); **49**, 2920 (1927).
48. Svedberg and Lamm, Kolloid Zeits. **69**, 44 (1934).
49. Svedberg, Boestad and Eriksson-Quensel, Nature **134**, 98 (1934).
50. Nichols, Physics **1**, 254 (1931).
51. Pedersen, Biol. J. **30**, 948 (1936).
52. Tiselius, Kolloid Zeits. **59**, 306 (1932).
53. Lamm, Zeits. f. physik. Chemie **A138**, 313 (1928); **A143**, 177 (1929); Nova. Acta. Reg. Soc. Scient. Upsaliensis **10**, 1 (1937).
54. McFarlane, Biochem. J. **29**, 407, 660, 1175 (1935).
55. Lundgren, Nature **138**, 122 (1936).
56. Williams and Watson, Nature **139**, 506 (1937).
57. Tiselius, Pedersen and Eriksson-Quensel, Nature **139**, 546 (1937).
58. Holmes, Phys. Rev. **51**, 689 (1937); Rev. Sci. Inst. **8**, 444 (1937).
59. Holmes and Beams, Nature **140**, 30 (1937).