Light-Pressure Tube

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A device for demonstrating the pressure of light is here described. With present-day techniques it is not only possible to produce a gas pressure sufficiently low to reduce the radiometer effects to a negligible value compared with the light pressure effect, but it is also possible to maintain such a vacuum in a sealed-off tube for long periods of time.

I. INTRODUCTION

THE pressure of electromagnetic radiation was first calculated by Maxwell[1] who showed that it was numerically equal to the energy in unit volume of the radiation. It was in 1903 that Nichols and Hull[2] were able to show experimentally that light did exert the pressure calculated by Maxwell. Using several schemes, they were able to separate the radiometer effect due to the presence of the gas from the light-pressure effect. They used gas pressures from 0.06 to 96 mm Hg.

By using present-day techniques, it is possible to produce a pressure of the contained gas sufficiently low that radiometer effects may be neglected. This is the approach used by Zacharias when he made the PSSC (Physical Science Study Committee) film on light pressure. The apparatus he used was sealed off but was not baked out. Ion pumping (see below) was employed to change the gas pressure when the tube was used. The tubes to be described herein have been sealed off the pumps for a period of a number of months and show no signs of deterioration.

Consider an electrically conducting vane of area A, assumed 100% reflecting, which is normal to a parallel beam of light. Then, according to Maxwell, the force on the vane is

$$f=2pA=2uA,$$

where u is the energy density of the radiation. The power striking the surface is $P=Acu$, where c is the velocity of light. Hence, the force on the vane will be

$$f=2(P/c).$$

Let us take a vane of width l and length $2l$ with one-half completely nonreflecting and the other half a perfect reflector. (See Fig. 1.) The bright side then will be subjected to twice the force of the black side. Hence, the torque L tending to rotate the vane will be

$$L=Pl/2c. \tag{1}$$

For bright sunlight falling normally on a half-black, half-bright vane whose width is 0.65 cm and length is 1.3 cm, the torque should be approximately 1.0×10^{-5} d cm. (See data at end of article.)

Two recently developed techniques have made possible the fabrication of such tubes in a non-specially equipped laboratory. One of these is the means by which a high vacuum can easily be produced by using ion pumping. The second is the technique of sealing together soft glass parts using solder glass.

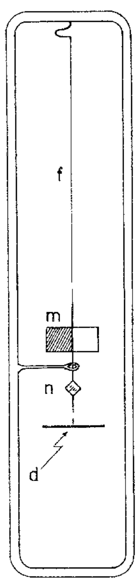

Fig. 1. The entire apparatus, except the aluminum foil vane, is made of fused quartz, fused together. Part *d*, whose moment of inertia is known, is removed after the period for torsional oscillation of the system has been measured. This permits a determination of the torsion constant of the fiber.

[1] J. C. Maxwell *Electricity and Magnetism* (Academic Reprints, Stanford, California, 1953), reproduction of the 3rd ed. of 1891, p. 441.

[2] E. F. Nichols and G. F. Hull, Phys. Rev. **13**, 307 (1901); **17**, 26 (1903).

The author has used the parts supplied by Harries[3] in his "Physikit vacuum tube set No. 100A." The envelope enclosing the light-pressure element consists of an 8-in. length of 1.5-in.-diam glass tube which is sealed at each end with a 1.6-in. diameter, 14 wire, stem. Mounted on the wire leads of the stems are three getters. One of these is barium-aluminum, the other two are titanium. Mounted on one of the stems is a Penning gauge. One of the titanium getters is fired after the BaAl getter has been fired. The other titanium getter is located in such a way that some of the evaporated metal will be deposited on the two plates of the Penning gauge. The final reduction of the gas pressure is accomplished by placing 2500 v dc on the Penning gauge (ring positive with respect to the disks) while it is in an axial magnetic field of 3500 gauss. Repeated evaporation of the titanium and then ion pumping with the gauge will ultimately result in a pressure of between 10^{-7} and 10^{-8} mm of Hg. These techniques are very similar to those described by Harries.[4] The use of soft glass for the envelope not only has the advantage of being easily assembled by the use of solder glass, but soft glass also will not allow helium to diffuse through which would ultimately spoil the vacuum, as would be the case with borosilicate glasses (Pyrex).

II. DESCRIPTION

The moving system inside the glass envelope is suspended by a quartz fiber which in turn is suspended from a quartz frame. This frame is made of 4-mm-diam quartz rod. The quartz ring around the quartz piece joining the vane and the mirror allows the apparatus to be transported without damage to the fiber or moving system. The quartz parts are shown schematically in Fig. 1.

While some general directions for manipulating quartz are given in *Procedures in Experimental Physics*,[5] a few further remarks, particularly applicable to the present apparatus, will be given. The quartz mirror n is $2\times2\times0.17$ mm^3 in dimensions. A small torch allows one to fasten fibers of 40 to 50 μ in diameter to the corners without damaging the optical quality of most of the mirror. Aluminum is evaporated on at this stage. The aluminum vane m is made of foil, 0.5 μ thick, which is commercially available. It is fastened by means of colloidal graphite at its corners to a framework which is slightly smaller than the vane and is made of quartz fibers about 25 μ in diameter. This results in a rigid vane that will not warp on baking. After the vane is mounted on the frame, a black coating is applied to one half. This is done by evaporating aluminum in a residual atmosphere of argon at about 0.1-mm pressure. The aluminum deposits in colloidal form and is therefore black.

The fiber d mounted below the mirror is temporary only and consists of a piece of quartz whose moment of inertia can be computed from its mass[6] and dimensions. The period of torsional oscillations of the system with d attached is measured in a demountable vacuum system, then the period measured again with d removed. From these data the torsion constant of the fiber as well as the moment of inertia of the moving system may be determined.

With the vane, mirror, and cross arm d all fastened together using a small torch, the torsion fiber f is then to be attached. To produce a fiber of 1-μ in diameter or less, the fiber is blown out in an oxygen-hydrogen flame. (See techniques described in reference 5.) A small torch made with a piece of stainless steel tubing with a 0.25-mm hole gives a flame that may be used for fusing such a small fiber onto larger pieces of quartz.

While fusing all quartz parts together is perhaps not the only way these pieces can be fastened together, it does ensure that there will be no difficulty in baking prior to sealing off. A further advantage of fusing the ends of the quartz fiber to the other quartz pieces is that the null position, or zero, remains fixed.

In the original attempts to make these light-pressure devices, it was found that electrostatic charges disturbed the moving system. Not only was there trouble with charges on the quartz inside the envelope, which persisted for days, but

[3] Owen Harries, Consulting Engineers, Warwick, Bermuda.
[4] J. H. Owen Harries, Am. J. Phys. **28**, 698 (1960).
[5] J. Strong, *Procedures in Experimental Physics* (Prentis-Hall, Inc., New York, 1938), pp. 188–217.

[6] See reference 5, p. 215, where a quartz fiber torsion balance is described which is ideal for weighing masses of 10 to 100 μg.

electrostatic fields due to people walking in the same room also disturbed the system. On future models, all quartz parts inside, except the torsion fiber itself, were coated with "Aquadag"[7] to make them conducting. In addition, the glass tube itself was coated inside with a thin layer of tin oxide.[8] Such a coated tube may have a resistance of 10 000 ohms and its transparency will not be seriously affected.

The quartz frame is conveniently held by forming suitable hooks of the nickel wire leads in the upper glass stem. The lower end of the quartz frame may be held by making guides out of the wires in the lower stem. The stems are then sealed on to the tube with the solder glass as described by Harries.[4]

The tubes were baked for 12 hr at 380°C with a gas pressure of 10^{-5} mm of Hg inside. After the baking and the tube had cooled to near room temperature, all getters were heated gradually until some of the metal evaporated. This is particularly important for the BaAl getter since large quantities of gas are given off in this preliminary heating. After the tube is sealed off, the BaAl getter is fired, then the one titanium getter not connected with the Penning gauge is fired. The pressure at this stage will probably be in the range 10^{-5} to 10^{-6} mm of Hg. Next, the Penning gauge is used as an ion pump as described previously and also by Harries.[4] In 12 hr, the pressure will probably be less than 10^{-7} mm of Hg. Evaporation of some titanium on the plates of the Penning gauge and application of potential and magnetic field again will lower the pressure still farther.

A test of whether the gas pressure has been reduced sufficiently far is to observe which way the vane deflects in a broad beam of light when the half-black, half-bright side of the vane is toward the source. If radiometer effects are sufficiently small, approximately twice the deflection should be obtained when the light strikes the bright side only as compared with that obtained when the light strikes the black side only.

The constants of two of the tubes are as follows:

	Tube No. 3	Tube No. 4
Moment of inertia of moving system	0.81×10^{-4}	1.13×10^{-4} g cm^2
Period	127.3	85.5 sec
Thickness of aluminum vane	0.5×10^{-4}	0.5×10^{-4} cm
Area of vane	0.78	0.78 cm^2
Torsion constant of fiber	1.87×10^{-7}	6.2×10^{-7} d cm per rad
Diameter of fiber (calculated)	0.66×10^{-4}	0.90×10^{-4} cm
Approximate radiant power density to produce a steady deflection of 1 rad (calculated)	2.3×10^{-3}	7.7×10^{-3} w cm^{-2}

With the above tubes, the gas pressure inside is sufficiently low if the damping of the vane, as it executes torsional oscillations, is no more than 0.01% per vibration.

It is of interest that all the vanes so far constructed are slightly magnetic. By using a strong bar magnet near the tube, the position of the vane may be controlled.

For a source of light to deflect the vane, sunlight or light from a microscope lamp may be used. In the former case, the radiant power on a bright day is about 0.1 w cm^{-2} so that a large deflection will result if a beam of sunlight is directed on the tube. In the case of the usual microscope lamp, a deflection of one radian is easily achieved.

[7] Made by Atcheson Colloids Company, Port Huron, Michigan.

[8] Robert Gomer, Rev. Sci. Instr. **24**, 993 (1953).