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Junior Physics Laboratory Experiment #008

# An Optical Measurement of 'c'

**PURPOSE** To measure the speed of light by the rotating mirror method of Foucault.

## 1 PREPARATORY PROBLEMS

1. Derive the speed of electromagnetic waves in vacuum from the Maxwell equations.Derive from first priciples the differential equation for damped, simple, harmonic motion. Derive the solution.

2. Derive the expression for the speed of light in terms of the quantities measured in this experiment.

## 2 INTRODUCTION

Galileo, in his "Dialogues Concerning Two New Sciences" (1638), has Salviati describe an experiment to detect a delay in the transmission of light between two observers separated by a mile or more:

> "Salv: Let each of two persons take a light contained in a lantern, or other receptacle, such that by the interposition of the hand, the one can shut off or admit the light to the vision of the other. Next let them stand opposite each other at a distance of a few cubits and practice until they acquire such skill in uncovering and occulting their lights that the instant one sees the light of his companion he will uncover his own. ....Having acquired skill at this short distance let the two experimenters, equipped as before, take up positions separated by a distance of two or three miles and let them perform the same experiment at night, noting carefully whether the exposure and occultations occur in the same manner as at short distance; if they do, we may safely conclude that the propagation of light is instantaneous; but if time is required at a distance of three miles which, considering the going of one light and the coming of the other, really amounts to six, then the delay ought to be observable.
>
> Sagre: This experiment strikes me as a clever and reliable invention. But tell us what you conclude from the result.

> Salv: In fact I have tried the experiment only at a short distance, less than a mile, from which I have not been able to ascertain with certainty whether the appearance of the opposite light was instantaneous or not; but if not instantaneous, it was extraordinarily rapid - I should call it momentary...."

The present experiment is modeled after the first accurate measurement of the speed of light carried out in 1850 by Foucault. It is, in effect, a version of Galileo's experiment in that it yields a measurement of the delay in transmission of light over a measured distance. Foucault's experiment, done with a rapidly rotating mirror, yielded a value for the speed of light which turned out to be equal, within errors of measurement, to the ratio of the electromagnetic and electrostatic units of charge, $q_{emu}/q_{esu}$. In 1865 James Clerk Maxwell published his theory of the electromagnetic field in which he demonstrated that electromagnetic waves in vacuum also travel with a speed equal to the ratio of the units of charge, one of the facts which he cited as evidence in favor of his electromagnetic theory of light. The Dover republication (1954) of the third edition (1891) of *Maxwell's Treatise on Electricity and Magnetism* contains a complete description of his theory and the relevant measurements.

## 3 THEORY OF THE EXPERIMENT

Figure 1 is a schematic diagram of the experiment. The parallel beam from the laser is brought to a focus at S1 from which it diverges slightly as it travels to the rotating mirror, M1. A portion of the beam is reflected by M1 and, for a small fraction of the rotation period, sweeps across the parabolic mirror M2 whose focal length is $F$. The distances from S1 to M1 and from M1 to M2 should be exactly $F$, and from M2 to M3 exactly 2F. Since M1 is at the focal distance ($\approx$ 80") from M2, the beam reflected from M2 at P is parallel to the beam reflected from P'. Since the optical distances from S1 to M2 and from M2 to M3 are both $2F$, an image of S1 is formed at S2 (S2'). M3 is oriented perpendicular to the incident beams so that the reflected beams coincide with the incident beams on the way back to M2, and on to M1 and M4. Since S1 and S2 (S2') are conjugate foci of M2, the beam returning from M3 and reflected from M2 and M1, is refocused at S1 and, by reflection in M4, at S3, provided M2 is not rotating rapidly. Rotation of M1 during the transit time of the beam from M1 to M3 and back to M1 causes a deflection of S3.

The angle of deflection is $x/L$, where $x$ is the deflection, $L$ is the distance from M1 to the point where the deflection is measured. In principal on should measure $x$ at S3 where the focused image would be a sharp point if all the optical surfaces were perfect. In practice, with the highly collimated laser light, one can more conveniently measure $x$ by marking its positions on a screen at some distance from S3.

## 4 PROCEDURE

The rotating mirror in this experiment is a tiny cube with four mirror faces driven by a turbine in the form of a dentist's "handpiece", a device familiar to people with bad teeth.

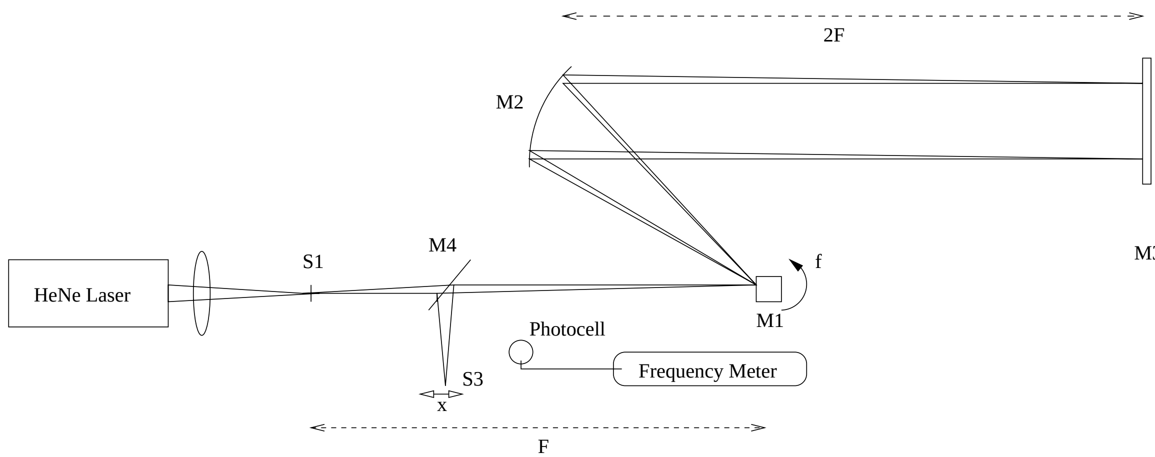


Figure 1: Schematic diagram of the optical arrangement for the optical measurement of the speed of light.

The remarkable feature of a dental handpiece is that its turbine spins at ≈ 300,000 rpm with the application of 20-30 psi of air pressure. That is approximately ten times the speed of the turbine-driven mirrors employed by Foucault and later by Michelson in the classic versions of the experiment, and ten times the speed of the motor employed in the setup marketed by Leybold for education. Because of its high speed, the dental turbine achieves a good deflection with a path length confined to a small room.

M2 is an eight-inch diameter parabolic telescope mirror of focal length F ≈80" purchased from Edmund Scientific Company. M3 is a plane mirror. M4 is a 50% beam-splitter mirror. **Please take care to avoid touching any of the mirror surfaces.**

The cubic mirror is a remarkable object made by David Breslau of the Center for Space Research. It must be treated with great care when spinning to avoid damage to it or your fingers.

The angular velocity of the cubic mirror is determined from a measurement of the frequency of pulses recorded by the frequency meter as the reflected beams from the four sides of the rotating mirror sweep over the photocell.

Adjust the distances from S1 to M1 and from M1 to M2 to be exactly equal to $F$, the focal length of M2, and the distance from M2 to M3 to be $2F$ in order for the optics of the setup to function correctly. Make M3 perpendicular to the incident beam in order that the return beam strikes M1. The position of a return beam that is nearly coincident with an outgoing beam can be traced by judicious use of a white sheet moved in and out of the beams. If the M1-M2 distance is $F$ and M3 is perpendicular, then the return beam will strike M2 at the same spot as the outgoing beam as M1 sweeps the outgoing beam from one side to the other of M2. To achieve this condition the M1-M2 distance must be within ≈0.25" of $F$ . If the return beam moves across M2 a distance less than the outgoing beam, then the M1-M2 distance is too large, and vice versa. **The orientation of M1 can be controlled with the aid of a wooden q-tip stick. Don't touch the cube with your fingers.**

The final test of the optical setup is the verification that the final image S3 (or spot) does not move as M1 is slowly turned so as to sweep the outgoing beam across M2. The laser is bright enough so that S3 can be observed in room light, even when M1 is spinning.

Measure all the relevant distances. Be sure that M1 is free to turn. Check the response of the photocell and frequency meter. Turn on the air pressure and measure the displacement of S3 as a function of the pulse frequency. Repeat the measurements many times. Report the average of the values of the speed of light that you derive from the measurements, and estimate the error from the variance of the values and the estimated errors of the distance measurements.

## SUGGESTED THEORETICAL TOPICS

1. Evidence that light is an electromagnetic wave.
2. Derivation of the relation between the object and image distances of a concave mirror.

## REFERENCES

[1] B. Rossi, 1957, *O*ptics (Addison-Wesley: Reading)

[2] J. C. Maxwell, *A* Treatise on Electricity and Magnetism (Dover, 1954)