Design of experiments for light-speed invariance to moving observers

Qian Chen (✉ georgechen@iefstudy.org)

International Educational Foundation

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International Education Foundation
4667 Highland Ct, Grandville, MI, USA 49418
e-mail: georgechen@iefstudy.org

The principle of the constancy of the velocity of light, which stated that the light velocity is invariant to the motion of the emitter, was well established and directly proven by many experiments. Interestingly, the further assumption that the light velocity is also independent of the motion of the observer was, arguably, never conclusively proven by any experiment for a century. This paper tried to address some perceived technical difficulties in such experiments and proposed two experiments to test this assumption. One is to directly measure the light speed as to moving sensors, with the setup designed in such a way that the concerns of time synchronization and dilation can be avoided. Another experiment is to test the isotropy of the light speed to a high-speed particle by measuring the momentum to acceleration ratio. The experiment results, if positive, will provide direct proof of the assumption. Otherwise, it may imply a need for further investigation. Since the light speed invariance to moving observers is a key assumption of some fundamental physical theory, either way, the experiments will have significant importance.

Keywords: Light speed, Special Relativity, Time dilation, Time synchronization, Sagnac effect, Mass-energy relationship, Particle acceleration, Michelson-Morley experiment, Asymmetry Theory

I.   INTRODUCTION

The second postulate of Special Relativity (Einstein 1905 [1, 2, 3]), "the principle of the constancy of the velocity of light", stated: "in empty space, light is always propagated with a definite velocity V which is independent of the state of motion of the emitting body". This principle was directly validated by many experiments including, the uniformity of the timing signature of the binary x-ray pulsar system Her X1 [8], the measurement of the speed of gamma rays emitted by fast pions [11], and the laboratory experiments with moving optical elements [12]. However, the further implicit inference in Special Relativity that the light velocity is also independent of the motion of the observer, was, arguably, never conclusively proven by any experiment for more than 100 years. For example, all the above-mentioned experiments were done by moving the emitter, while there was never an attempt of moving the detector. There are some experiments claimed to be proof of the assumption, but all are based on inference, not direct proof. Michelson-Morley-experiment [7] was claimed as proof that the light speed is invariant to the directions of moving observers. In fact, the null result of the M-M experiment only proved that the light speed variance, if any, is much smaller than the earth's speed, 30 km/s, which is the theoretic prediction of the ether theory. On the other hand, some experiments questioned the assumption. For example, the Sagnac effect [13, 14] contradicted the assumption of the invariance of light speed to the moving observers in a rotating frame. Special Relativity can not explain the Sagnac effect and the contradiction was attributed to the rotating/accelerating frame and an explanation was provided with General relativity [16]. Besides, the experiments [17, 18] also questioned the assumption of the invariance of light speed to the moving observers.

Because the invariance of light speed is the key assumption for some fundamental physical theory, the search for direct and straightforward experimental proof without relying on inference is of significant importance. Although the reasons why no such a direct experiment was implemented before are not fully clear, the concerns of clock synchronization and time dilation are perceived as part of the reasons.

Two setups are designed to directly test the invariance of light speed as to moving observers. The first is designed to directly measure the travel times of a light beam to two detectors moving at the same constant speed, i.e. no acceleration, in opposite directions. The experiment is also set up so that the concerns of time synchronization and time dilation can be minimized. A high-speed camera can be deployed to capture the exact moments of photon detection by both sensors and determine if there is a sequence of events. Furthermore, a reference setup is leveraged to confirm the time synchronization. The second experiment setup is to simply bring the Sagnac effect experiment into an inertia frame without rotation and acceleration.

Another experiment is to test the isotropy of the light speed as to a high-speed particle in the electromagnetic field. Let's measure the ratio of the momentum to the acceleration of the particle. First, let the particle reach a high speed, say $0.5c$. Then the direction of the electromagnetic field is reversed, i.e. the direction of the

particle's velocity is reversed. If the speed of the electromagnetic wave is isotropic to the moving particle, the momentum to acceleration ratio shouldn't have any immediate impact on the ratio at the moment of direction reversal, just as the relativistic mass formula in Special Relativity predicted. But if the result shows that there is an immediate jump at the moment of direction reversal as predicted in [15], it implied that the electromagnetic wave is not isotropic to the direction of the particle's motion.

II. THEORETIC BACKGROUND

A. The Sagnac Effect

The Sagnac effect [13] shows that two light beams, sent clockwise and counterclockwise around a closed path on a rotating disk, take different time intervals to travel the path. It can be extended to a FOG [14] and the time difference is approximate

$$\Delta t = 2vL / c^2 \qquad (1)$$

where v is the detector's speed, L is the distance. The Sagnac Effect contradicted the assumption that the light velocity is invariant as to the motion of the observer. Special Relativity attributed the contradiction to the rotating/accelerating frame of the Sagnac effect experiment, i.e. outside of the scope of Special Relativity, and an explanation was provided with General Relativity [16].

The idea is to bring the Sagnac effect experiment into the set-up of an inertia framework, i.e. take out the rotation. A transient light beam is sent to two detectors moving at the same constant speed, i.e. no acceleration, in opposite directions. The travel times of the light beam to the detectors are measured. If the travel time difference is 0, the result will directly prove the invariance of light speed as to moving observers. If under this inertia system setup, the measured time difference is still $\Delta t = 2vL / c^2$ as predicted in [15], a further investigation of the assumption may be required.

B. Time synchronization and dilation

The synchronization of Time in [1] stated, "Let a ray of light start at the "A time" t_A from A towards B, let it at the "B time" t_B be reflected at B in the direction of A, and arrive again at A at the "A time" t'_A, the two clocks synchronize if

$$t_B - t_A = t'_A - t_B \qquad (2)$$

For an observer moving with speed v, we must satisfy

$$t_B - t_A = \frac{r_{AB}}{c-v} \ and \ t'_A - t_B = \frac{r_{AB}}{c+v} \qquad (3)$$

The contradiction between these equations is resolved with the "time dilation" in Special Relativity [1]

$$\Delta t' = \Delta t / \sqrt{1 - v^2 / c^2} \qquad (4)$$

Hence, it is important to consider the time dilation and synchronization concerns in the experiment. In the experiment setup, the light source and the detectors are placed in the same initial place. Both detectors are moving at the same speed so that if there is a time dilation effect, it will be the same.

C. The Momentum to Acceleration ratio

It is well known that a particle in the accelerator becomes difficult to accelerate when its speed increases and it is impossible to approach the light speed c. That means that the ratio of the momentum applied by the accelerator to the acceleration of the particle decreases when the speed increases. The explanation of Special Relativity [10] is the relativistic mass increase for a moving particle:

$$m_{rel} = m_0 / \sqrt{1 - v^2 / c^2} \qquad (5)$$

This follows the equation for the ratio of momentum to acceleration:

$$\frac{dP}{P} / \frac{dv_o}{v_o} = 1 / \sqrt{1 - v^2 / c^2} \qquad (6)$$

(5) shows that the ratio is the same for a particle with the same speed in opposite directions as to the magnetic field, i.e. the isotropy of electromagnetic wave to the particle's motion. For example, the ratio is the same for $v = 0.5c$ and $v = -0.5c$. This prediction will be tested in the experiment.

III. EXPERIMENTS DESIGN

Two experiment setups are designed to directly test if the light speed is independent of the motion of observers. Another experiment is designed to test the isotropy of the light speed to a high-speed particle.

A. Light velocity to moving observers

EXPERIMENT SETUP

A transient light source and two moving sensors are in the same initial position and connected to the same precise digital oscilloscope with cables of equal length, see FIG. 1. A high-speed camera is used to capture the exact moments when the photon hits the sensors. This setup is to avoid the time synchronization concern (2). Both sensors are moving at a constant speed v but in opposite directions. Hence if there is a time dilation effect (4), it should be the same for both detectors. The light can be reflected multiple times to increase the path length and improve accuracy.

To further minimize the concern of time/clock synchronization, a reference setup is leveraged to calibrate the time measurement, see FIG. 2. In this reference we use

two light sources moving at the same speed v but in opposite directions. Since the light-speed invariance to the motion of the light source is well-proven, any measured detection time difference can be attributed to the time or clock drift due to the movement at speed v. Hence the results from this reference setup can be used to calibrate any potential time or clock drift in the experiment.

EXPERIMENT STEPS

It is controlled that light is emitted when both sensors coincide in the same initial position. The emitted light will be reflected by a mirror back to the moving sensors. The detection times of both sensors are measured by the digital oscilloscope. Besides, the high-speed camera will capture the exact moments when the photon hits the sensors.

The experiment should always be repeated with the sensors switching directions. For example, the first time is sensor 1 at v and sensor 2 at $-v$, the next time, it is sensor1 at $-v$ and sensor 2 at v. This helps distinguish the time difference due to the clock drift from that due to the motion. The experiment should be repeated many times and with different velocities v. Data analysis, for example, statistics, should be applied to reduce random errors.

RESULT ANALYSIS

If the light speed is independent of the motion of moving observers, both sensors shall detect the light at the same moment. Therefore, if the experiment results show there is no time difference detected, it proves the light-speed invariance to moving observers. However, if a time difference $\Delta t = 2vL / \left(c^2 - v^2 \right)$ is detected, i.e. same as the Sagnac effect as predicted in [15], a further investigation is warranted.
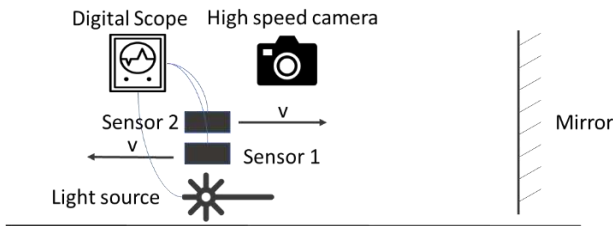

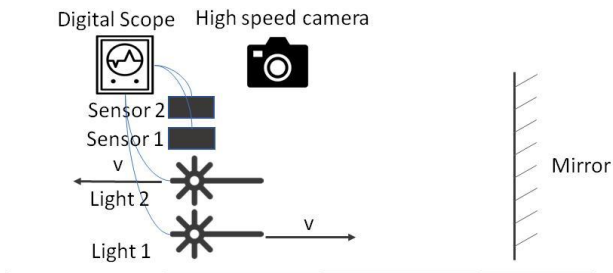FIG. 1. Setup for the light velocity to moving observers

FIG. 2. Reference setup for time calibration

B. Experimental setup using an interferometer

EXPERIMENT SETUP

Similar to experiment A, this experiment is also testing the light speed invariance to moving observer, but using a different setup. A light source and an interferometer are fixed together and move at the speed v, see FIG. 3. The emitted light was split into two light beams travelling in opposite directions by a half-transparent mirror. These two light beams will be reflected by both mirrors in the end and finally reach the interferometer. The travel time difference of the light beams will be measured by the fringe shift in the interferometer.

EXPERIMENT STEPS

The experiment should be repeated by switching the directions of v and changing the value of v and the length of the two ends, so that not only the time difference is measured but also the relationships between the time difference and the value of v and the length of the light path is determined.

RESULT ANALYSIS

If the light speed is independent of the motion of moving observers, there should be no time difference, i.e. no fringe shift. However, if a time difference $\Delta t = 2vL / \left(c^2 - v^2 \right)$ is detected, i.e. same as the Sagnac effect as predicted in [15], a further investigation is warranted.
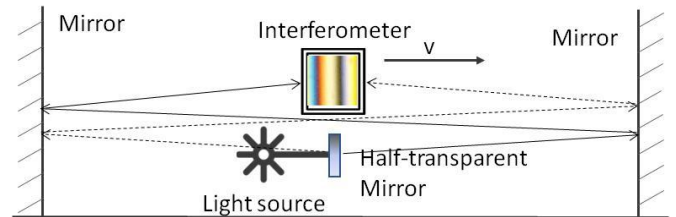

FIG. 3. Experimental setup using an interferometer

C. Momentum to acceleration ratio experiment

EXPERIMENT SETUP

This experiment is to measure the momentum to acceleration ratio of a particle, for example, an electron, in a linear electromagnetic accelerator, see FIG. 4. The linear electromagnetic accelerator could instantly switch the direction of acceleration. The devices are set up so that the momentum applied by the accelerator and the particle's speed can be measured and recorded. The measured data is then used to calculate the momentum to acceleration ratio in a time plot.

EXPERIMENT STEPS

First, the particle is accelerated to a constant speed, say $0.5c$. Then the direction of the accelerator is reversed. The moment applied by the accelerator and the particle's speed is measured continuously during the process. The experiment can be repeated many times and with different types of particles and different particle speeds. Data analysis, for example, statistics, can be applied to reduce random errors. The result is the time plot of the momentum to acceleration ratio.

RESULT ANALYSIS

As predicted by (6) of Special Relativity, the momentum to acceleration ratio should keep constant at the exact moment of the reversal of acceleration direction. If the time plot shows that the momentum to acceleration ratio is continuous at the time of direction reversal, see FIG.5., it proves that the electromagnetic wave is isotropic to the motion of the particle. If the time plot shows there is a significant jump of the ratio at the time of direction reversal as predicted in [15], see FIG.5., a further investigation is warranted.
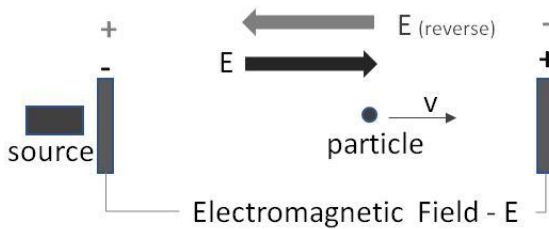

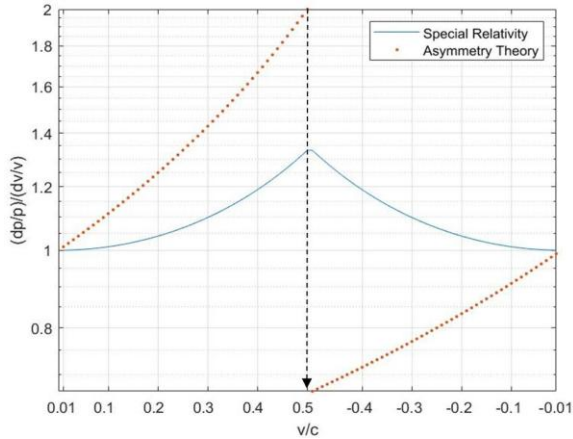FIG. 4. Setup for the particle acceleration/deceleration

FIG. 5. Predictions of momentum to acceleration ratio

IV.   CONCLUSIONS

Two experiments were designed to test the invariance of light speed to moving observers, which is fundamental to some physical theories. The results, if positive, should be able to confirm the assumption, hence closing a loophole for a century. Otherwise, a further investigation is warranted. Either way, these experiments are of significant importance. It is best if these experiments can be carried out by multiple independent groups so that the results are more convincing.

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