Understanding the Retardation of the Returned Astronaut's Clock and GPS Clocks Using the Physical Behaviour of Moving Light Clocks

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The prediction of retardation of an astronaut's clock during a round trip, compared to the clock of the stay-at-home, introduced by Einstein in his 1905 paper has been the most contentious issue for relativity. This resulted in a raging controversy in journals in the mid to late 1950s. There was no discussion about the physical nature of clocks. Some current writers still claim that it is necessary to use general relativity. We will show that this is not correct. Special relativity makes correct predictions in accord with experimental data. Here we examine this question using the physical behaviour of moving light clocks and gain insight into the returning astronaut experiment and a deeper understanding of the nature of space and time.

Keywords: Einstein-Lorentz transformation, time-dilation, light clocks, space-travel, biological aging.

I Introduction

We quote from Einstein's original thought experiment that was presented in his 1905 paper.[1]

> *If at points A and B of [the coordinate system] K there are stationary clocks which, viewed in the* stationary *system, are synchronised, and if the clock at A is moved with velocity* V *along the line AB, then on its arrival at B the two clocks will no longer be synchronised, but the clock moved from A to B lags behind the other which has* remained *at B by* $\frac{1}{2}tV^2/c^2$ *(up to magnitudes of fourth and higher order), t being the time occupied in the journey from A to B… It is at once apparent that this result still holds good if the clock moves from A to B in any polygonal line, and also when the points A and B coincide. ...*
>
> *If we assume that the result proved for the polygonal line holds also for a continuously curved line, then we arrive at the following proposition: If there are two synchronised clocks in A, and one of them, (B) is moved along a closed curve with constant velocity (V), until it is* returned *to A which takes t sec, then this clock (B) will lag on its arrival at A by* $\frac{1}{2}tV^2/c^2$ *behind the clock (A) that has not moved.*

An examination of the controversy literature[2,3] reveals that the arguments presented are not easy to understand and many are incomplete. There were at least 250 papers, but the controversy has not yet been fully resolved. Einstein omitted this thought experiment from his simplified book on relativity.[4] The 1950s question was "do clocks lag?" But now we have data verifying Einstein's proposal: cosmic mu-mesons, and those moving in circular paths observed at CERN,[5] decay slower than mu-mesons at rest in the laboratories; GPS clocks have adjustments. Interest in the behaviour of space-travel clocks has increased.

Einstein's proposal was "if one of them is moved until it is returned, then this clock will lag on its arrival". Synchronisation can only be agreed on if the clocks are adjacent, and the tests of Einstein's proposal can only be made on return. In the controversy papers,[3] the analysis is done first from the point of view of the stay-at-home, A. When examined from the frame of the outgoing astronaut B, the stay-at-home clock is predicted to continually retard, but the clocks of A and B are not adjacent. Comparisons cannot be made until return, when information about B's clock is mechanically carried back to A by B. To predict the retardation using the Einstein-Lorentz transformation we need to understand Einstein's original concept; to understand what Einstein meant by "a stationary system" and by "remained"; and to fully understand Einstein's second postulate: that light propagates through empty space with a definite speed c independent of the speed of the source or observer. Textbooks such as Feynman,[6] and French,[7] do not make complete Einstein-Lorentz transformation predictions from the point of view of the outgoing astronaut. To fully understand Einstein's proposal it is essential to do this, and show that the *total* lag of the *returned* astronaut's clock, predicted from the outgoing astronaut's frame using the Einstein-Lorentz transformation is the *same* as that made from the stay-at-home frame. We make the full predictions, and use light clocks to show how the lag on the clock physically occurs. These show that general relativity is not required and will help avoid errors like that made by Koks,[8] and Sartori,[9] whose stay-at-home suddenly "ages" in a physically impossible manner, as the astronaut turns.

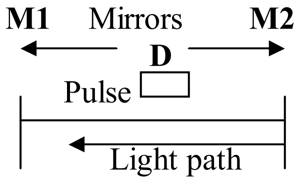
II Light clocks with light transit in vacuum

A pulsed light beam transit clock consists of two flat mirrors mounted facing each other with their planes parallel. A light pulse is emitted from mirror 1 toward mirror 2, where it is reflected back to mirror 1. When it reaches mirror 1 a "tick" is recorded as it reflects again toward mirror 2. It is arranged that the process continues indefinitely. The observer counts the number of ticks recorded between two events that take place adjacent to him. The number is the time interval between events. If the pulsed light beam transit used by the stay-at-home and the astronaut clocks have their mirrors parallel to the relative velocity and to the acceleration, the turn around process will not alter the separation of the mirrors. The speed of light is not affected by the velocity of the clock. The light pulses are not affected by the acceleration and therefore acceleration plays no role in the time dilation of these clocks. Retardation depends *only* on the geometry of the light paths. Light clocks *cannot run fast,* they can only be retarded or dilated.

IIa Light clocks with transit in vacuum perpendicular to the relative motion

We look at pulsed light beam transit clocks mounted at rest in a frame Σ moving with respect to frame Σ' with velocity V as determined in Σ'. We assume that Einstein's 2nd postulate requires that when the observer is at rest in Σ with respect to his light clock, the light path will be *perpendicular* to the mirrors as shown in Fig 1. We will examine this idea later.

Figure 1



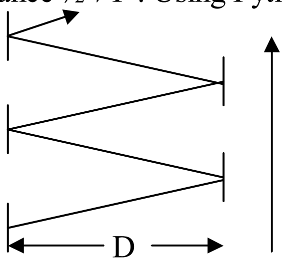
The separation of the mirrors in Σ is D. The period is defined as the round trip transit time of the light pulse. In Σ

$$T = \frac{2D}{c} \tag{1}$$

As seen from Σ, the mirror separation D is perpendicular to V. Length contraction plays no role.

In the Σ′ frame, the prediction for T' is that to maintain continued reflection, on each transit the light beam will travel a distance ½ cT' at velocity c along the hypotenuse of a right angled triangle, while the mirrors move a distance ½ VT'. Using Pythagoras' theorem:

Figure 2



$$\left[\frac{1}{2}cT'\right]^2 = D^2 + \left[\frac{1}{2}VT'\right]^2 \tag{2}$$

$$T' = \left[\frac{2D}{c}\right]\left[1 - \frac{V^2}{c^2}\right]^{-\frac{1}{2}} \tag{3}$$

The factor $\left(1 - V^2/c^2\right)^{-1/2}$ is defined to be γ.

We have used Einstein's second postulate, but not the Einstein-Lorentz transforms. The prediction agrees with special relativity.

III Einstein-Lorentz Transformation Predictions of Clock Counts and Separation Distances Relating to the three Defined Events for the Returning Astronaut Experiment.

The 1950s question was "do clocks lag?" Now lag is known to be a real physical phenomenon.[3] Our task now is to verify Einstein's predictions and most importantly explain how clock lag happens.

We choose a realisable astronaut velocity V that is much less than c, so $\gamma \sim 1 + V^2/2c^2$. All is in accord with Einstein's original proposal, and is relevant to GPS satellite clock adjustments.

The returning astronaut experiment is set up by the stay-at-home, A with linear paths out and back. To survey the astronaut's turn position A′, at L from A, A counts the ticks on his clock between emitting and receiving a survey light signal reflected by A′. Define the number of ticks to be $2N_{\text{Survey}} = 2N_S$. The light survey signal has travelled the same distance in making the round trip to A′ and back as the light in A's light clock, so $2L = 2N_S.2D$ and $L = 2N_S D$.

The role of the second astronaut C is critical in defining that there are three inertial frames: the frame of A, the stay-at-home; the frame of B, the outgoing astronaut who is travelling at $+V$ relative to A; the returning astronaut B′, travelling in the frame of C having velocity $-V$ relative to A.

A has surveyed A″, the point from which C will depart at a distance $2L$ from A. The remote clocks of A′, A″ and C are synchronised by A who sends a signal out at t_0, instructing A′ and A″

to set their clocks on receiving the signals to $t_0 + L/c$ and $t_0 + 2L/c$ respectively.

To define the velocity V, A sends out a test astronaut at $t = 0$ as recorded on all clocks in his frame. A′ is instructed to record the number of "ticks" on his clock between zero and the test astronaut passing him. We define this recorded number as N. Then $NTV = L$. But $T = 2D/c$ and $L = 2N_S D$. Therefore $V = L/NT = N_S/N$.

There are three defined events: B *departs* from A; B *turns* or C passes B; C *arrives* back at A. At each of these events there are two adjacent observers, each in a different inertial frame.

There are just three measurable time intervals.

Using the 2nd astronaut C, and light clocks the data that can be recorded about these time intervals is:

$N_A = 2N$, counts on A's clock between B departs & C arrives

N_{B1} = counts on B's clock between B departs and C passes

N_{C2} = counts on C's clock between C passing B & C arriving at A.

The Einstein-Lorentz transformation can predict other time "instants" and "intervals" with clocks having:

N_{B2}: the added counts on B's clock between C passes B and C arrives at A

N_{C1}: the counts on C's clock at the time of passing B

N_{A1}: the counts on A's clock at the time C passes B

N_{A2}: the added counts on A's clock between C passing B and C arriving at A

But these "intervals" are symbolic predictions. These are *not* physical entities, that can be measured.

The only data that can be obtained to compare predictions with experiments is $N_A = (N_{A1} + N_{A2})$, N_{B1} and N_{C2}.

Einstein's original proposal was a lag on return:

$$\Delta = N_A - (N_{B1} + N_{C2}) = 2N(V^2/2c^2)$$

IIIa Predictions from the stay-at-home A's frame

For the returning astronaut experiment from the point of view of A, the stay-at-home, his clock will have light paths as shown in Fig 1 and as C passes A.The Einstein-Lorentz transformation predictions for the counts on A's clock are:

$$N_A = N_{A1} + N_{A2} = L/VT + L/VT = N + N = 2N \tag{4}$$

A will predict that the outgoing astronaut B's clock will have light paths as in Fig 2 and be time dilating to read $N_{B1} = N/\gamma$ when C passes B; and C, who sets his clock to zero passing B will record $N_{C2} = N/\gamma$ giving total astronaut counts:

$$N_{B1} + N_{C2} = 2N/\gamma \tag{5}$$

Thus a lag of counts will be observed when the astronaut returns:

$$\Delta = N_A - (N_{B1} + N_{C2}) = 2N - (N/\gamma + N/\gamma) = 2N\,[V^2/2c^2] \tag{6}$$

This is interpreted as a time lag of $\Delta = 2NT\,[V^2/2c^2]$.
The count lag of the astronaut's clock is $\Delta = 2N\,[V^2/2c^2]$.

IIIb Predictions from the outgoing astronaut B's frame

To make the Einstein-Lorentz transformation predictions from B's point of view we must use the fact that the experiment was set up in A's frame. Einstein's 2nd postulate now demands that the light paths in B's clocks are perpendicular to the mirrors, as in Fig 1.

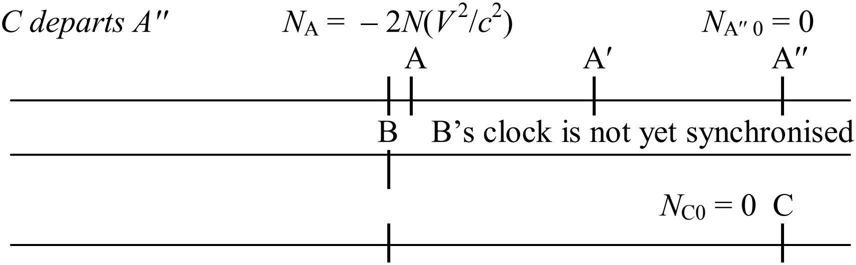
The light signals that A would have sent to set C's clocks was travelling at c toward A″, but from B's point of view, the point A″ from where C was to be launched was moving at V toward B. The synchronisation signals would have arrived early by $2NT(V^2/c^2)$.

Thus the astronaut C would have departed earlier from A″ than A departed from B.

B claims that A has surveyed the location A″ and C to be $2L$ "at rest" in A's frame but as seen by B in B's frame it is length contracted, so A″ and C are separated from A by $2L(1 - V^2/2c^2)$.

Using the Einstein-Lorentz transformations for velocity, B claims C moves at $2V/(1 + V^2/c^2)$ with respect to B. C leaves early and has gone $\sim 2NT\,(V^2/c^2).2V \sim 2L(4V^2/2c^2)$ before A departs from B.

The departure of C from A″, seen from the point of view of B is:

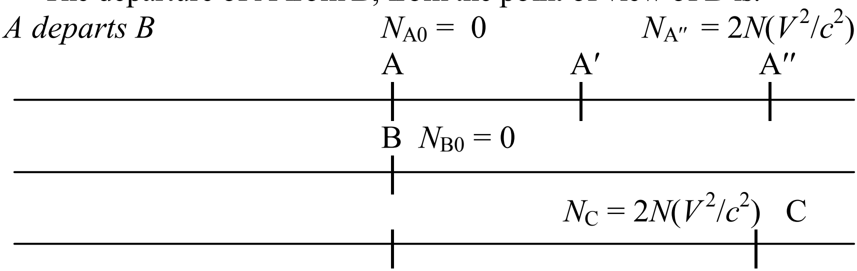


When C departs from A″, A is at $X = 2NT.V(V^2/c^2)$ from B, with A's clock reading $-2N(V^2/c^2)$.

Both A″ and C have their clocks reading 0, and are separated from B by $[2L(1\text{-}V^2/2c^2)+2NT.V(V^2/c^2)] = 2L(1+V^2/2c^2)$.

At time $2NT(V^2/c^2)$ later, A passes B, and B synchronises his clock to read zero, as on A's clock.

The departure of A from B, from the point of view of B is:



C has travelled at $2V/(1+V^2/c^2)$ a distance ~ $4L(V^2/c^2)$ and so at the departure of A from B, C is separated from B by a distance:

$$2L(1+V^2/2c^2) - 4L(V^2/c^2) = 2L(1 - 3V^2/2c^2)$$

Now calculate the count N_{B1} on B's clock when C passes B.

$$N_{B1} = \frac{2L\left[1-\dfrac{3V^2}{2c^2}\right]\left[1+\dfrac{V^2}{c^2}\right]}{2VT} = N\left[1-\frac{V^2}{2c^2}\right] = \frac{N}{\gamma} \tag{8}$$

B predicts A's clock to count:

$$N_{A1} = N_{B1}/\gamma = N(1 - V^2/c^2) = N/\gamma^2 \tag{9}$$

B predicts C's clock to count:

$$N_{C1} = N_{B1}[1 - 4V^2/2c^2] + 2NV^2/c^2 \tag{10}$$

$$N_{C1} = N/\gamma \tag{11}$$

N_{B1} is one of the *defined* intervals; N_{C1} is not. But note that B's predictions for N_{B1} and N_{C1} are the same as those made by A.

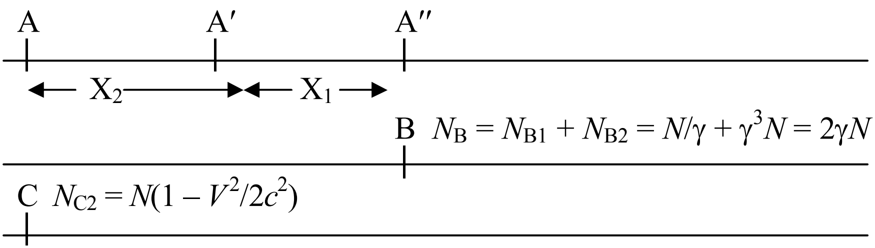
B predicts that A, moving at $-V$ will have travelled a distance X_1 from B where:

$$X_1 = VNT(1 - V^2/2c^2) = L(1 - V^2/2c^2) \tag{12}$$

Therefore B predicts A′ to be opposite him as C passes, in agreement with A.

Where does C pass A ? Let this be at X_2 further from B as shown:

$N_A = 2N$



We calculate X_2 by using the fact that:

$$\frac{X_2}{V} = \frac{\left[X_2 + L\left(1 - V^2/2c^2\right)\right]\left(1 + V^2/c^2\right)}{2V} \tag{13}$$

$$2X_2 = X_2\left[1 + \frac{V^2}{c^2}\right] + L\left[1 - \frac{V^2}{2c^2}\right]\left[1 + \frac{V^2}{c^2}\right] \tag{14}$$

$$X_2\left(1 - V^2/c^2\right) = L\left(1 + V^2/c^2\right) \tag{15}$$

$$X_2 = L(1 + 3V^2/2c^2) \tag{16}$$

B's clock will have added N_{B2} counts such that:

$$N_{B2} = N(1 + 3V^2/2c^2) = \gamma^2 N \tag{17}$$

A's time dilating clock will have increased counts by N_{A2} such that:

$$N_{A2} = N_{B2}/\gamma = N(1 + V^2/c^2) = \gamma^2 N \tag{18}$$

There has not been any sudden change of A's counts (or sudden 'aging') when B was passed by C, as claimed by Koks,[8] and Sartori.[9] A key point of the experiment is to transfer information between frames at adjacent points, avoiding simultaneity problems. C has had no *direct* information about A's clock or age, and must get it from B.

C's extra clock, set to 0 when C passed B will have recorded N_{C2}:

$$N_{C2} = N\left[1 + \frac{3V^2}{2c^2}\right]\left[1 - \frac{4V^2}{2c}\right] = N\left[1 - \frac{V^2}{2c^2}\right] = \frac{N}{\gamma} \tag{19}$$

We now have the prediction of the counts N_{A1}, N_{A2}, N_{B1} and N_{C2} in eqns. 9, 18, 8 and19, to predict the count lag between the clocks:

$$\Delta = (N_{A1} + N_{A2}) - (N_{B1} + N_{C2}) = [N/\gamma^2 + \gamma^2 N] - [N/\gamma + N/\gamma\,] \tag{20}$$

$$\Delta = [N(1-V^2/c^2) + N(1+V^2/c^2)] - [N(1-V^2/2c^2) + N(1-V^2/2c^2)] \tag{21}$$

The lag of the astronaut's clock is:

$$\Delta = 2N - 2N[1 - V^2/2c^2] = 2N[V^2/2c^2] \quad (22)$$

The lag predicted from the astronaut B's frame *is the same* as A's. Now B checks where C passes A. In B's frame this is $X_1 + X_2$ from B.

$$X_1+X_2 = L(1 - V^2/2c^2) + L(1+3V^2/2c^2) = 2L(1+V^2/2c^2) = 2\gamma L \quad (23)$$

This is determined in B's frame; so in A's frame it will be $2L$.

IIIc Comments

The predictions from B's frame are in agreement with those from A's frame for the *total* lag on the clocks when "one of them is moved until it is returned". But B predicts that the rate of A's clock is slower than his at *all times* during the experiment, and that the time lag is recorded *not in B's outgoing frame but by C in the returning astronaut's frame.* Agreement is because C's clock, that B sees travelling at nearly $2V$, is time dilated much more than that of A; and because A is predicted to travel a larger distance $X_2 = L(1 + 3V^2/2c^2)$ between C passing B, and C arrives at A, than $X_1 = L(1 - V^2/2c^2)$ that A travelled between A departed B, and C passed B. In addition, B predicts that N_{B2} is greater than N_{B1}. This allows more "time" for C's clock, running slower during X_2, to "compensate" for B's faster clock during X_1.

A has located C at A″ a distance $2L$ from A in A. The Einstein-Lorentz transformation from the point of view of B also predicts A″ to be at distance $2L$ from A in the A frame. B predicts that A″ would have passed him when his clock read $2N/\gamma$ in agreement with A. A predicts that B is *opposite* A″ at the time C and B′ both pass A. But B predicts that at the time C and B′ pass A, A″ has already passed B and is located at $-2L(V^2/c^2)$ from B, and A″ is *not opposite* B. So B disagrees with A about his spatial relationship to A″ but this "event" cannot be measured.

Einstein-Lorentz Transformation Symbolic Predictions of Clock Counts and Separation Distances Relating to all of the Events Defined for the Returning Astronaut Experiment ***as seen from the point of view of A***	**Physical Light Paths in the Clocks to be able to Aquire Data in Accord** ***with A's Predictions***
A sets up the experiment. C is the returning astronaut. ***There are 3 events***	

1. B departs A as C departs A'''

A's frame	*A $N_{A0} = 0$
B's frame	*B $N_{B0} = 0$
C's frame	$N_{C0} = 0$ *C

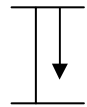
2. C passes B

A's frame	*A $N_{A1} = N$
B's frame	*B $N_{B1} = N/\gamma$
C's frame	*C $N_{C1} = N/\gamma$

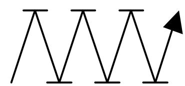
3. C arrives at A

A's frame	*A $N_{A2} = N$, $N_A = 2N$
B's frame	$N_{B2} = N/\gamma$ *B
C's frame	*C $N_{C2} = N/\gamma$, $N_C = N_{B1} + N_{C2} = 2N/\gamma$

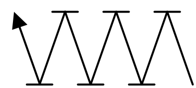
A's Clock



B's Clock



C's Clock



The Lag of the Astronaut's Clock is : $\Delta = N_A - (N_{B1} + N_{C2}) = 2N(V^2/2c^2)$

Comments : When the astronaut returns, and both the stay-at-home and the astronaut compare their clock counts, and have the data demonstrating that the time lag is as predicted, their job is to explain how the apparatus has worked to obtain this data. One posssibility is to claim that not only did A "predict" the light paths to be as in the diagrams above, but the light **actually** travelled on those paths for B and C, and then B and C both carried along their mirrors so that they were in the appropriate location to reflect the light when needed, and cause the "tick".

Figure 3 Spatial relationships and clock counts predicted by A, the stay-at-home.

Einstein-Lorentz Transformation Symbolic Predictions of Clock Counts and Separation Distances Relating to all of the Events Defined for the Returning Astronaut Experiment ***as seen from the point of view of B***	**Physical Light Paths in the Clocks needed to Acquire Data in Accord** ***with B's Predictions***

A sets up the experiment. C is the returning astronaut.

There are agreed 3 events. But B says : A has put A″ at $2L/\gamma$ from A in B, & set C's clock fast by $2N(V^2/c^2)$. A is at $+2L(V^2/c^2)$, & C at $2L(1+V^2/2c^2)$ from B as C leaves early.

0. C departs A‴.

A's frame *A $N_A = -2N(V^2/c^2)$

B's frame *B Not synchronised

C's frame $N_{C0} = 0$ *C

1. A departs B *A $N_{A0} = 0$ **A**'s frame

B's frame *B $N_{B0} = 0$

C's frame. B says C is at $2L(1-3V^2/c^2)$, & $N_C = 2N(V^2/c^2)$ *C

2. C Passes B *A $N_{A1} = N/\gamma^2$ **A**'s frame

B's frame *B $N_{B1} = N/\gamma$

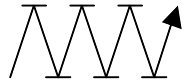
C's frame *C $N_{C1} = N/\gamma$

3. *A **C arrives at A** $N_{A2} = N/\gamma^2$, $N_A = N_{A1} + N_{A2} = 2N$, **A**'s frame

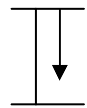
A is $L/\gamma + \gamma^3 L = 2\gamma L$ from B *B $N_{B2} = \gamma^3 N$ **B**'s frame

*C $N_{C2} = N_{B2}/(1+2V^2/c^2) = N/\gamma$, $N_C = N_{B1} + N_{C2} = 2N/\gamma$, **C**'s frame

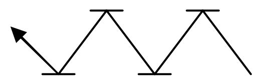
A's Clock



B's Clock



C's Clock



On *return* & observing the data, the astronaut B′ says "My clock did *not* time dilate going out, but on my return trip it *did*. So the light paths must have been as for C (or B′) above, even though I was at rest with respect to it at all times."

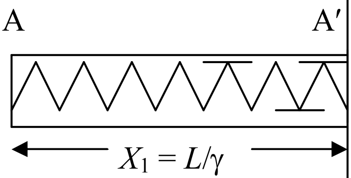
The Lag of the Astronaut's Clock is : $\Delta = N_A - (N_{B1} + N_{C2}) = 2N(V^2/2c^2)$

Comments: The Einstein-Lorentz transformation predictions for the *counts* on the individual clocks that can be *recorded:* $N_A = 2N$; $N_{B1} = N/\gamma$; $N_{C2} = N/\gamma$; $N_{B1} + N_{C2} = 2N/\gamma$ are the *same* from either point of view. But B's predictions require the geometry of the light paths in all the light clocks to be physically different from that predicted by A. However, different physical behaviour *cannot happen during* the *same* experiment.

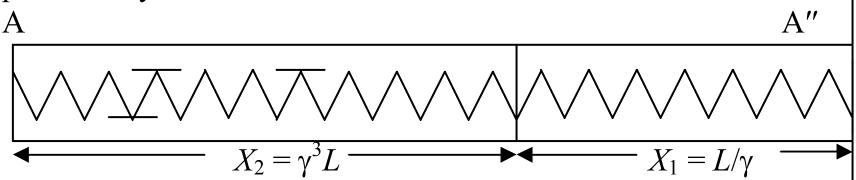
Fig 4 Spatial relationships and clock counts predicted by B, the outgoing astronaut.

IIIc B's record of light paths and space intervals for the light clocks of A and C, that are required to satisfy his predictions

B has predicted that at the time C passes B, his clock will read $N_{B1} = N/\gamma$, and that A will have travelled a distance X_1 from B. B predicts that A's clock will count N/γ^2.



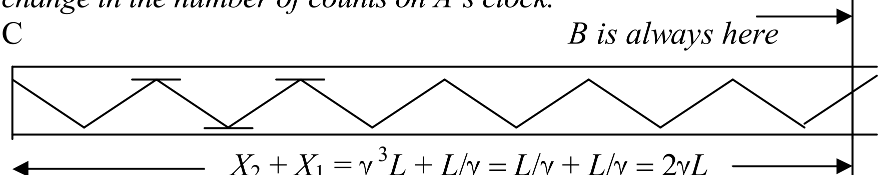
B predicts that when C passes A, A will have travelled a further distance $X_2 = \gamma^3 L$. The records at the time that C passes A will be predicted by B to be as shown:



$$N_{B2} = \gamma^3 N \text{ so } N_B = N_{B1} + N_{B2} = 2\gamma N$$

$$N_A = N_{A1} + N_{A2} = N/\gamma^2 + \gamma^2 N = 2N$$

A's clock has a constant rate of time dilation. There is no sudden *change in the number of counts on A's clock.*



$$N_{C2} = N/\gamma \text{ and } N_{B1} + N_{C2} = \gamma^3 N + N/\gamma = 2\gamma N$$

B predicts that his own clock had total counts $2\gamma N$ at the time C passed A.

B has made the prediction that A was at $-2\gamma L$ from him at the time C passed A. B predicts that A″ will have passed him, and be at $-2L(V^2/c^2)$ as C passed A.

When B′ has turned around and travelled back to A in the same inertial frame as C, both B′ and C will obtain data confirming the lag predicted by B and A.

To explain his predictions, one possibility that must be considered is that the transit time between the mirrors in C's clock is greater than $2D/c$, by a larger amount than in A's clock.

B then requires the light paths in his "space", for the clocks of A and C, to be of the character shown above.

Another possibility is that B and C accept A's prediction, and its associated explanation, that A's clock does not time dilate, but both B's and C's clocks time dilate in a way similar to that in the first sketch above.

One or other interpretation may be right, but not both, because the apparatus cannot behave in two different ways during the same experiment. Both may be wrong; for example the analysis could be made by C claiming his clock never time dilates; or the experiment could be interpreted from an arbitrary inertial frame, and the same time lag predicted.

The Einstein-Lorentz transformation predictions for the *counts* on the individual clocks that can be *recorded* are the *same* from either point of view:

$$N_A = 2N \qquad N_{B1} = N/\gamma \qquad N_{C2} = N/\gamma \qquad N_{B1} + N_{C2} = 2N/\gamma$$

But the predictions require the physical behaviour of the light in the light clocks to be different. Different physical behaviour *cannot happen during* the *same* experiment.

IV On the velocity of light

Which ever interpretation is made, we must now address the questions: "What did Einstein truly mean by his second postulate: that light propagates through empty space with a definite speed c, independent of the speed of the source or the observer." How is the velocity of light measured ? It is crucial to understand that for special relativity the concept of light speed can *only be defined on a round trip path.* This is because in special relativity, *time intervals are defined only between two events that take place at one point.* To measure the light speed the events are emission and reception of a light pulse that is reflected by a distant mirror to the measuring equipment. Thus for special relativity, light velocity is defined as

$$\frac{\text{(Distance Travelled on a Round Trip Path)}}{\text{(Time Taken)}}$$

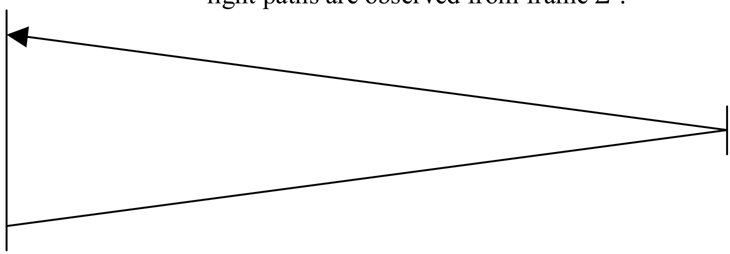
Using these pulsed light beam transit clocks we can now see very clearly by looking at Figure 5, that if the astronaut makes a measure of 'c' using the experimental technique described in the paragraphs immediately above, the light path in the 'c' measuring apparatus *remains parallel to corresponding sections of the light paths in the pulsed light beam transit clocks.*

We set the mirrors in light beam transit clocks at D = 10m. We set up apparatus to measure the speed of light. It is a pulsed emitter and an adjacent receiver, with a reflecting mirror measured by the same rulers to be 1000m away. The mirror is at right angles to the transmitted beam which is set up parallel to the beam in the pulsed light beam transit clocks clock.

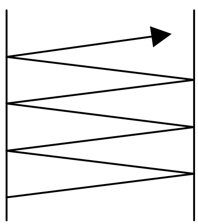
The movement of the spacecraft through space has "slowed down" the transit between mirrors in his pulsed light beam transit clocks *and* in his 'c' measuring apparatus by the same fraction. Therefore the (No. of ticks) for the transit of light across the 2000m remains the same for the astronaut as for the stay-at-home. He will get precisely the same value for ‘c’ in terms of ‘c’ = (2 . 1000m)/ (No. of ticks) as does the stay-at-home, even though on return he finds that his clock has run slow.

Measuring the Speed of Light Using Pulsed Light Beam Transit Clocks

(a) Round trip light paths in light speed measuring apparatus. The apparatus is located in frame Σ. The light paths are observed from frame Σ′.



(b) Light paths in the pulsed light beam transit clock. The clock is located in frame Σ. The light paths are observed from frame Σ′. As perceived from the frame Σ′, the pulsed light beam transit clock will be time dilated because the pulses are being transmitted along the zig-zag lines. But in the light speed measuring apparatus the return light follows diagonal lines parallel to the zig-zag lines.



Comment: In all frames, the measure of the light speed will be the same using this round trip path definition and technique.

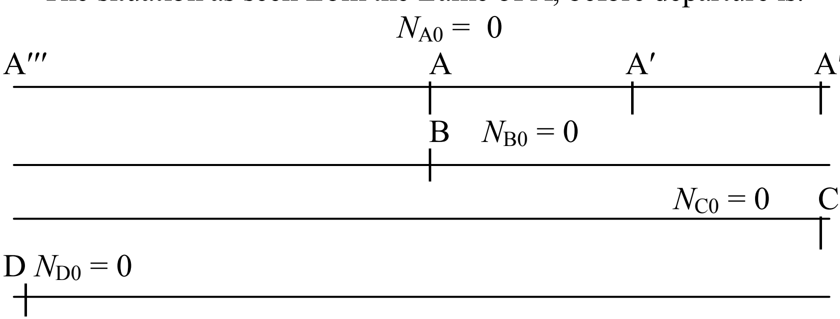
Figure 5. Measuring the speed of light

The measurements of the speed of light can be made using this round trip path technique both on the outward journey, and again on the inward journey, and he will get the same result. Einstein's second postulate: "Light propagates through empty space with a definite speed c, independent of the speed of the source or the observer," *means that the measure of light speed when made on a round trip path will always yield the same value.* In special relativity light speed cannot be agreed on for a one way path. Measures of light velocity have not been made on a one way path. For the international data base of physical constants, the light speed is from data that has been measured on a round trip path.

V A more complete experiment introducing astronaut D to carry A's data back to B.

Again it is A who sets up the whole experiment, but now we add a third astronaut D at $-2L$ from A. Again A surveys the location for A‴ from where D will depart, and synchronises these added clocks of A‴ and D. A sets D up to travel at $+2V$. A provides D with a second clock to synchronise as he passes A and carry that information to B.

The situation as seen from the frame of A, before departure is:



From the point of view of A, B will pass A′ at $+L$ from A when C passes B.

D will have travelled $2L$ from A‴ and be opposite A. The clocks, all originally set to $N = 0$, will read:

$$N_{A1} = N \qquad N_{B1} = N/\gamma \qquad N_{C1} = N/\gamma \qquad N_{D1} = N/\gamma^4$$

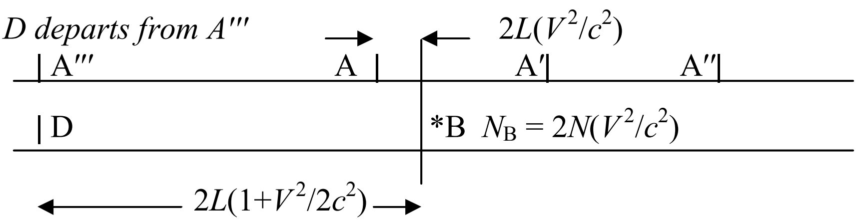
At the time C passes A, D will pass B. The added counts on the clocks will be:

$$N_{A2} = N \qquad N_{B2} = N/\gamma \qquad N_{C2} = N/\gamma \qquad N_{D2} = N/\gamma^4$$

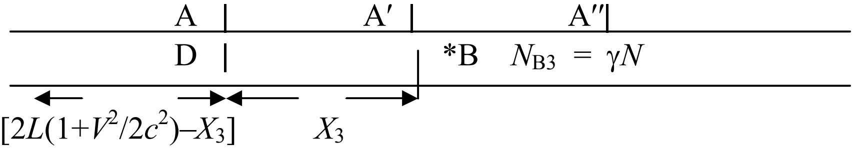
We can then predict from the point of view of A, that A's "returning astronaut" C will carry a total count of $[N_{B1} + N_{C2}] = 2N/\gamma$, and lag A's clock count of $[N_{A1} + N_{A2}] = 2N$, by $2N(V^2/2c^2)$ as we showed above. A will predict that as D passes A, he will record and carry the information N_{A1}, the counts that B will regard as those of his "outgoing astronaut", plus N_{D2} the counts made on the "return trip of B's returning astronaut".

Thus we predict that from the point of view of A, B's "returning astronaut D" will carry a total count of $[N_{A1}+N_{D2}] = [N + N/\gamma^4] = 2N/\gamma^2$. This is a clock reading that lags B's total clock counts $[N_{B1} + N_{B2}] = 2N/\gamma$ again by $(2N/\gamma)(V^2/2c^2)$.

For the prediction from the point of view of B we must take into account that according to B, A has synchronised D's clock to be set slow. Therefore A has already travelled $2L(V^2/c^2)$ from B before D leaves "late" from A‴, and A‴ is then $2L(1 + V^2/2c^2)$ from B. The velocity of D relative to B predicted by the Einstein-Lorentz transformation for velocity is $V/[1 - 2V^2/c^2]$.



We define the separation distance between A and B to be X_3 at the event where *D passes A:*



Thus between D departing A‴ and D passing A, D has travelled a distance $[2L(1+V^2/2c^2) – X_3]$. We can determine X_3 from:

$$\frac{\left[2L(1+V^2/2c^2)-X_3\right]\times\left[1-2V^2/c^2\right]}{V}=\frac{\left[X_3-2L(V^2/c^2)\right]}{V} \qquad (24)$$

$$X_3 = L[1+V^2/2c^2] = \gamma L \qquad (25)$$

The counts on B's clock will be $N_{B3} = \gamma N$.

The counts on A's clock are predicted by B to be $N_A = N$. X_3 is *measured* in B's frame it will be length contracted to L in A.

We now seek the time, N_{B4} it takes for D to reach B.

$$N_{B4}=\frac{L\left[1+V^2/2c^2\right]\times\left[1-2V^2/c^2\right]}{V}=N\left[1-3V^2/2c^2\right]=N/\gamma^3 \qquad (26)$$

B predicts A's clock to have added $N_{A4} = N_{B4}/\gamma$ and D's to added $N_{D2} = N_{B4}/\gamma$.

B predicts the total counts on A's clock to be $N_{A1} + N_{A2} = 2N/\gamma^2$. The total counts on B's clock from A departs B, to D arrives at B, is $N_{B3} + N_{B4}$.

$$N_{B3} + N_{B4} = \gamma N + N/\gamma^3 = 2N/\gamma \qquad (27)$$

D carries information from A, and

$$N_D = N_{A3} + N_{D2} = N + N/\gamma^4 = 2N/\gamma^2 \qquad (28)$$

D, the astronaut "returning" to B has same lag $(2N/\gamma)(V^2/2c^2)$.

Because the value of V can be chosen arbitrarily, we can conclude that *any* "returning" astronaut's clock will be predicted to run slow compared with that of any *"*stationary system*"*, now regarded as the observer who at all times *remains in one single inertial frame.* For GPS clocks, we can think of earth clocks going around the sun as having lag relative to clocks "on the sun", and satellite clocks going around the earth as having lag relative to the earth, caused by relative motion, in the way predicted by Einstein. Satellite and *earth* clocks must have light paths as in Fig. 2. The question arises "Where are the clocks that do not time dilate and have light paths as in Fig.1?" Another paper is in preparation to treat all these matters fully, including the gravitational effects on clocks.

Conclusions

There are concerns with the Einstein-Lorentz transformation predictions when the experiment has been conducted, and physical data acquired using light clocks. We use three astronaut's: B and B′ who are on identical outward voyages, and C who passes B as B′ turns. B′ and C travel back to A in the same inertial frame as C, leaving B in the outgoing frame to pass A″ .

1. The stay-at-home A, *who must remain at all times in the one inertial frame in order to make predictions,* claims that the clocks of the outgoing astronaut B, and the returning astronaut B′ (and C), *are time dilating,* even though *the clocks are at rest* with respect to the frame of reference of those observers.

2. The astronaut B, who must remain at all times in the outgoing inertial frame in order to make predictions, claims that the clocks of the stay-at-home A and returning astronaut B′ (and C), are time dilating, even though the clocks are at rest with respect to the frame of reference of those observers.

Alternately we consider *just* B, going out; turning; and arriving back at A. When on *arrival* at A, B sees that his light clock has *fewer* counts than A, as he predicted by the Einstein-Lorentz transformations during his outward voyage, B has no alternative but to claim that *his own clock* time dilated on the return voyage even though at all sections of the trip it was at rest with respect to him.

3. It is *not physically possible* for the clocks *to operate in the ways required by A* to satisfy his predictions, and during the same experiment *be operating in the different way required by B* to satisfy his predictions.

The 1950s controversy was presented in terms of symbolism. The physical nature of the retardation in the astronaut's clocks was not discussed. Feynman,[6] in 1965 describes a light transit clock and wrote: "Not only does this particular kind of clock run more slowly ... any other clock operating on any principle whatsoever, would appear to run slower, and in the same proportion – we can say this without further analysis. ….. *We need not know anything about the machinery* of the new clock that might cause the effect – we simply know that whatever the reason, it will appear to run slow, just like the first one." If other clocks are made can "one of these clocks disagree with the other moving clock ? Oh no, if this should happen we could use the mismatch of the clocks to determine the speed of the ship (through space)". Feynman discussed the retardation of the returned astronaut's clock, *but he did not use* the physical behaviour of light transit clocks to explain this thought experiment.

Here we have examined the returned astronaut experiment with light clocks. Predictions are manipulations of symbols, but physical apparatus is unaware of the symbols, and the light in the light clocks *must behave in the same way, independent of who makes the predictions.* Therefore it is a matter of interest that the predicted *rates* of retardation during various sections of the voyage are different when made from different reference frames. This can be explained if there is a preferred inertial frame.[7]

It is possible for the apparatus to physically work in a way satisfying the overall prediction that on return the astronaut's clock will have run slow. The light paths would be as shown below. A is moving at – V_A relative to the preferred frame with clocks dilating proportional to V_A^2. The outgoing clocks moving at V_B relative to A will retard depending on $[V_A - V_B]^2$ and the returning clocks on $[V_A + V_B]^2$. The total retardation will depend on the relative velocity V_B. For a round trip, whose outward path takes time $T[1 - (V_A/c)^2]^{1/2}$ the overall retardation will be: $\Delta \sim T\,[2V_A^2 - \{(V_A - V_B)^2 + (V_A + V_B)^2\}]/2c^2 \sim 2T[V_B^2/2c^2]$.

Light paths in A's clock. Light paths in B's clock. Light paths in C's clock.

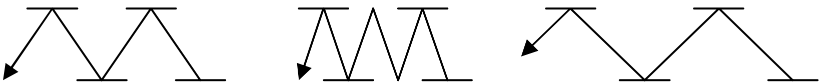


Fig 6. An explanation of how all the light clocks have operated when on return the the returned astronaut's clock is observed to have retarded relative to that of A.

The physical behaviour of moving light clocks provides insight into the returning astronaut experiment and gives a deeper understanding of the nature of space and time.

Acknowledgements

I am deeply indebted to Prof. Reginald T. Cahill for many long and interesting discussions on the physics of time, space and matter.

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Appendix I: The Aging of Biological Systems

Associated with the behaviour of clocks in the returning astronaut thought experiment, is the question of the aging of biological systems, particularly whether the returning astronaut is "younger" on return, than the stay-at-home. This question is sometimes referred to as the *twin paradox,* – a paradox being defined in dictionaries as "a statement seemingly self-contradictory or absurd, though possibly well founded or essentially true"; but it is more correctly the *twin conundrum* – "a riddle that we can now resolve", because we have a deeper understanding of space and time from examining the physical behaviour of moving light clocks.

Readers should be aware that the biological aging was not part of Einstein's original returning astronaut experiment; Einstein's proposal only concerned the idea "this clock will lag". What we have shown in the analysis above, is that the counts on the light clocks, and therefore, according to Feynman, on other types of clocks will lag by exactly the same factor as predicted by Einstein.

Biological systems depend on electromagnetic interactions between molecules. During the voyage of the astronaut, the total number of molecular interactions within the returning astronaut's body will be reduced by the same factor as the number of counts in his light clocks.

The cells in a body are replaced on a continuing basis. There is scientific evidence that in the replacement process errors occur; so the errors increase in a stepwise manner, creating biological damage. The reduction in the number of molecular interactions for the astronaut during the return trip, compared with those for the stay-at-home will reduce the number of cell replacements and reduce the biological damage. The astronaut, having suffered less cell replacement damage will *appear* younger on return. But we must be aware that just as the moving light clock has a longer period, each cell will "live" longer.

This explanation enables us to further increase our understanding of time.

Examine the light paths of the "stationary" and "moving" light clocks. Link together the sections of the paths shown in Fig 1 or in Fig 2, taken by the pulses during the interval between any pair of events. Do this for each of the two observers, one in each of two inertial frames. These linked paths will constitute the paths that could be taken taken by a single pulse.

The outgoing astronaut B, believes his clock is operating as in Fig 1. Between the two events A departs B, and C arrives at A, as examined from the point of view of B he has recorded $2\gamma N$ counts. Therefore the total light path in B's clock has length:

$$[2\gamma N] \,.\, [2D] = 4\gamma ND$$

B has predicted that A's clock has recorded $2N$ pulses, each of which he believes to have taken paths as shown in Fig. 2. The sections have lengths $2\gamma D$. Thus B predicts the total length of the path in A's clock is:

$$[2N] \,.\, [2\gamma D] = 4\gamma ND$$

Further B predicts that the total accumulated path length for the light pulses in the outgoing astronaut B's clock and the returning astronaut C's clock is:

$$N_{B1} \,.\, [2D] + N_{C2} \,.\, [2\gamma^4 D] = [N/\gamma] \,.\, [2D] + [N/\gamma] \,.\, [2\gamma^4 D] = 4\gamma ND$$

Thus the *total light path lengths* are predicted by B to be the same for A, and for the returning astronaut and for himself continually going outward.

Light is travelling at c and thus the total time taken for the light to create the counts is (dist/velocity) and this is therefore the same for A, B and C (or B′). What is referred to as "time" is actually *counts* on the clock, whether it is light clocks, a mechanical pendulum or chronometer or digital watch. What is not generally so carefully taken into account is that not only does the count rate change because of the motion, but the "period" of the device changes as well.

What is referred to as "time lag" is actually "count lag".

For the GPS system the "count lag" is adjusted by adjusting the "period". The satellite clock is the one, which in Einstein's original proposal "is moved along a closed curve with constant velocity (V), until it is *returned* ...". For satellite clocks, "returned" can be considered to be having completed one orbit. Further "it will lag on its arrival ...behind the clock that has *not moved*", for satellite clocks, means that during each orbit, the earth essentially remains in a single inertial frame. Thus the Einstein-Lorentz transformation predictions for the clock lag caused by this relative motion on a closed path, of the satellite relative to the earth, account for the appropriate part of the GPS clock adjustments. There are further adjustments required because of gravitational effects on the clocks, and these adjustments are also made. The corrections allow the clocks to have a kind of locally agreed upon time, but even though the clocks have their periods adjusted, the satellite clocks are still "time dilating" as they move in orbit. If light clocks are used, light paths in both satellite and earth clocks would be as in Fig 2. We have not established any clocks that are non time dilating.

Appendix II: Further Important Comments and Conclusions

The understanding of the physical operation of clocks, whose periods are the round trip transit times of light pulses results in the following conclusions when used for the returning astronaut experiment:

1. The Einstein-Lorentz transformation prediction of the *total* numerical value of the time lag of the astronaut's clock on return, from the point of view of the outgoing astronaut agrees with the predictions of the stay-at-home.

2. There exists a "preferred inertial frame" in which the light paths in the clocks are perpendicular to the mirrors. In this frame time dilation does not occur. If this frame is chosen for the stay-at-home the light paths in the stay-at-home clocks will be perpendicular to the mirrors and the time dilation *rate* for the astronaut will be equal on the outward and return journeys. As seen from the sun the light paths in earth clocks are zig zags, *earth based clocks are thus time dilating continually.* The earth is not the preferred frame. There is evidence for other motion with respect to space.[9,10,11,12] We cannot claim that the arbitrarily chosen stay-at-home frame will always be the preferred frame having light paths are perpendicular to the mirrors.

3. Einstein's term "stationary" means *remaining in one inertial frame.* Einstein-Lorentz transformation predictions made by an observer in *any* inertial frame about the numerical value of the *total* lag of the returned astronaut's clock relative to the time interval on the stay-at-home clock give correct values.

4. Einstein's second postulate "that light propagates through empty space with a definite speed c independent of the speed of the source or the observer" involves the definition and measurement of the speed of light on *round trip* paths. The measurement on round trip paths always gives same value.

5. Even though clocks mounted on *earth are time dilated,* the measures of light velocity using the round trip path definition of light velocity and the technique described *give correct value for c.* The measures of c in any frame using this round trip path definition and technique give the same value.

6. Einstein-Lorentz transformations used by the stay-at-home, correctly predict the time *lag* of the returned astronaut's clock relative to the stay-at-home clock *even when the stay-at-home has absolute motion with respect to space and relative motion with respect to the astronaut.*

7. To have a clock that is *not* time dilated, the clock must be *at rest with respect to the locally physically defined space.* This clock can measure local "proper" time intervals. We can then define a local "proper" simultaneity to be agreed upon by observers with relative motion. There may be a universal time but we will have to examine space on a large scale before that can be confirmed.

8. If the Einstein-Lorentz transformations when used by the stay-at-home correctly predicts the *Lorentz contraction* for the astronaut's clocks, the stay-at-home is in the preferred frame and the Einstein-Lorentz transformations *used by that astronaut will not correctly predict* the Lorentz contraction for the stay-at-home. Predicted length contraction of some stay-at-home clocks predicts them to run faster. For a frame at rest with respect to space there is no length contraction. *Lorentz contraction is a physical effect* related to motion through physically defined space, as originally postulated by Lorentz.

9. Even though the Einstein-Lorentz transformation makes correct predictions of relative time dilation for the returning astronaut case when used by the observer who maintains constant velocity with respect to the locally physically defined space, correct predictions by *any* theory for some physical events *does not guarantee correct predictions for all physics.*

10. Conclusion 7 enables us to define and measure the one way speed of light. The definition of light speed then becomes *"c is the one way speed of light with respect to locally physically defined space"*. The one way speed is independent of direction with respect to that space. The one way speed is independent of the motion of the

source. Observers in the locally physically defined space can move independently with respect to that space. If the observer is moving through this space at velocity V in the opposite direction from a light pulse, the distance attained between the observer and the light pulse after a time interval t is not ct but $(c + V)t$ when $V << c$. But nothing moves faster than light with respect to locally physically defined space.

11. It is an *experimentally confirmed fact* that energy is released in nuclear reactions *in accord with the equivalence principle.* The explanation of time dilation from the physical behaviour of light clocks *is not a theory;* it does not enable us *to predict* the equivalence principle**.** *Therefore* it is *essential* for us now to show that the nature of space and time *demanded* by the physical behaviour of light clocks *is in accord with experimental data and in accord with the equivalence principal:* $E = mc^2$.

We define m_0 to be the mass of any object when at rest in physical space and write $E_0 = m_0c^2$.

We can only measure mass in the laboratory. That laboratory is moving at V relative to space. The object and the standard mass will each have [rest mass + kinetic energy $\frac{1}{2}m_0V^2$] and total energy

$$E = E_0 + \tfrac{1}{2}m_0V^2 = m_0c^2(1 + V^2/2c^2)$$

Now define the mass of the object moving relative to space as:

$$m = E/c^2 = m_0(1 + V^2/2c^2)$$

All masses in any one laboratory, including the standard reference mass, change by the same factor. Therefore the measure of the mass is independent of the velocity V of that laboratory through space.

Using the masses of particles for the reaction $H^2 + H^3 = He^3 + n$ +17.6 MeV as measured while *at rest relative to the laboratory* we get [Mass $(H^2+H^3)]c^2$ – Mass$[(He^3 + n)]c^2 = 17.6$ MeV. Motion *relative* to space causes physical Lorentz contraction, changing both internal energy and the mass.

12. The equation $m = m_0\ (1 + V^2/2c^2)$ for a moving mass m, is usually written as the *relativistic mass equation*: $m = m_0\ /(1 - V^2/c^2)^{½}$. The changes of mass have been experimentally verified, especially in particle accelerators like cyclotrons on earth where the accelerator is moving in space with at least $V_{earth} = V_{orbit}$,

$$m_{cyc} \approx m_0 \left[1 + \frac{(V_{earth} \pm V_{cyc})^2}{2c^2} \right]$$

When we average the mass over one complete cycle we get:

$$m_{cyc} \approx m_0 \left[1 + \frac{V_{earth}^2}{2c^2} \right] \left[1 + \frac{V_{cyc}^2}{2c^2} \right] \approx m_{lab} \left[1 + \frac{V_{cyc}^2}{2c^2} \right]$$

So as the particle velocity V_{cyc} increases during the acceleration process, its mass relative to the mass measured in the laboratory increases in accord with experiments. The behaviour is not dependent on the accelerator's velocity through space.

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