The Sign of the Doppler Shift in Ultracentrifuge Experiments

Robert J. Buenker*
Fachbereich C- Mathematik und Naturwissenschaften,
Bergische Universität Wuppertal,
Gaussstrasse 20, 42119 Wuppertal, Germany

Measurements of the transverse Doppler effect have provided important confirmatory evidence for the validity of Einstein's theory of special relativity (SR) as it pertains to time dilation. However, these investigations fall into two distinct categories depending on whether the light source or the detector is accelerated relative to the rest frame of the observer. In their original work employing a moving light source in the laboratory, Ives and Stillwell state explicitly that they observe a wavelength shift to the red, and therefore a slowing down of the initially accelerated clock, in complete agreement with Einstein's predictions. By contrast, although both Hay et al. and Kündig also report complete agreement with SR on the basis of their ultracentrifuge experiments in which *the absorber/detector is under constant high acceleration*, their theoretical discussion actually contradicts this assertion. For example, Kündig states that his work demonstrates "that the clock which experiences acceleration is retarded compared to the clock at rest," thereby giving unequivocal support to the

---

* buenker@uni-wuppertal.de; alternativelorentztransformation.blogspot.com

conclusion that *it is not just a matter of perspective which of two clocks runs slower at any given time*, but rather that the measurement process is perfectly objective. This experience has generally been dismissed by SR proponents, arguing that the latter theory is only to be applied for objects *in uniform motion,* in which case measurement is definitely subjective. It is pointed out that this conclusion overlooks the fact that a version of the Lorentz transformation exists which is consistent with both sets of measurements while still satisfying Einstein's two postulates of SR.

Keywords: transverse Doppler effect, ultracentrifuge experiments, Lorentz transformation (LT), alternative Lorentz transformation (ALT)

I. Introduction

Before the dawn of the twentieth century there was a broad consensus among both philosophers and physicists that that the measurement of physical quantities had an absolute character. Accordingly, there must be perfect agreement as to which of two objects is longer or more massive or which clock is running at a slower rate. On a more quantitative basis, this meant that the *ratio* of the magnitudes of any two such quantities must be the same for all observers, provided of course that any errors in their respective measurement procedures had first been eliminated.

This situation changed dramatically with the introduction of Einstein's special theory of relativity (SR) in 1905 [1]. He concluded on the basis of the Lorentz transformation (LT) that two observers in relative motion could both legitimately find that it was the other's clock that was running slower or the other's measuring rod that was shorter in length. Measurement was now a matter of the perspective of the observer, *subjective* rather than unalterably objective. Einstein concluded that this radical departure from the security of classical physics was unavoidable in order to satisfy his two postulates of SR, the relativity principle and the constancy of the speed of light in free space. However, direct experimental evidence was lacking, at least at first.

The theory itself demanded that space and time be inextricably linked through the LT [1], also in stark contrast to what had previously been taken for granted on the basis of the original Galilean space-time transformation. One of the consequences was the phenomenon of time dilation, which led Einstein to a number of predictions that ultimately were verified experimentally. Ives and Stilwell [2] carried out the first successful empirical investigation of this nature in 1938 on the basis of the transverse Doppler effect. Their results did not provide evidence for the subjectivity principle, however, since it was a "one-way" experiment. The experiment only showed that the frequency of a standard light source decreases when it is accelerated relative to the observer at rest in his laboratory. It remained to be shown that an observer moving with the latter source would register the same *decrease* in frequency for a signal received from the laboratory. The classical (objective) theory predicted that a frequency increase (blue shift) would be registered instead, simply verifying that the frequency of the accelerated source was smaller than that of its stationary counterpart in the laboratory.

Experiments of the required type were then reported in 1960 [3] that had at least the potential of settling this question on a definitive basis. In this case the detector/absorber was mounted on the rim of a rotor (ultracentrifuge) and therefore was moving at a much higher speed relative to the laboratory than the light source located near the axis. The authors (Hay et al. [3]) reported satisfactory agreement with SR with regard to the observed Doppler shift, as did Kündig [4] and Champeney et al. [5] a few years later with a similar experiment. Nonetheless, the discussion of their experimental results contains remarks that stand in direct contradiction to this conclusion, as will be discussed in the following section.

II. Measurements of the Transverse Doppler Effect

The first attempts to measure the transverse Doppler effect employed a moving beam of hydrogen atoms whose radiation was observed at small angles in both the incoming and outgoing directions [2, 6-7]. The rationale for this approach was based directly on the SR formula for the relativistic Doppler effect in general. Accordingly, when light of wavelength λ_0 is emitted from a source moving with speed v relative to the laboratory, the observed wavelength λ at an angle Θ relative to the beam direction is given by the formula [7]:

$$\lambda = \lambda_0 \left(1-\beta^2\right)^{-\frac{1}{2}} \left(1-\beta\cos\Theta\right) \approx \lambda_0 \left(1-\beta\cos\Theta+\frac{1}{2}\beta^2\right), \qquad (1)$$

where $\beta = \frac{v}{c}$ and c is the speed of light in free space (2.99792458x10^8 m/s). By measuring λ for light emitted in diametrically opposite directions and averaging the two results, the Θ-dependence can be eliminated and therefore the goal of determining the wavelength λ_Q for transverse radiation $\left(\Theta = \frac{\pi}{2}\right)$ can be achieved to a good degree of approximation, namely as:

$$\lambda_Q = \gamma\lambda_0 \approx \lambda_0 \left(1+\frac{1}{2}\beta^2\right), \qquad (2)$$

with $\gamma = \left(1-\beta^2\right)^{-0.5}$. In the most accurate experiment of this type, Mandelberg and Witten [6] reported a shift to longer wavelength of 0.219 Å for $\lambda_0 = 6562.793$ Å and a relative speed of $\beta = 0.008176$, in excellent agreement in both magnitude and direction with the theoretical result in eq. (2). It was also perfectly consistent with Einstein's prediction of time dilation since it indicated that the period τ of the moving clock/light source also increased by the same factor γ when it was accelerated relative to the laboratory:

$$\tau = \frac{\lambda_Q}{c} = \frac{\gamma\lambda_0}{c} = \gamma\tau_0 . \tag{3}$$

The ultracentrifuge experiments of Hay et al. [3], Kündig [4] and Champeney et al. [5] introduced two new elements into the investigation of the transverse Doppler effect. First, they eliminated the angular dependence in eq. (1) by mounting the light source and absorber on a high-speed rotor so that the relative motion was almost perfectly transverse. However, more importantly in the present context, in each case the light source was located near the rotor's axis whereas the absorber was fastened near its rim. As a result, the "observer" in this version of the transverse Doppler experiment was moving faster in the laboratory than the source.

According to eqs. (1, 2) of SR, the only critical quantity is the relative speed β and thus this distinction between the two types of experiments should be immaterial. Einstein's theory of time dilation and the transverse Doppler effect is *subjective*. Which clock runs slower is purely a matter of the perspective of the observer. A red shift is expected in the ultracentrifuge experiments, just as is found in the Ives-Stillwell experiment [2, 6-7]. If measurement is objective on the other hand, a blue shift must be observed. The contrast could not be clearer.

Angular velocities ω of up to 500 revolutions per second were employed in the study of Hay et al. [3]. Their results for the fractional shift in the light frequency/energy of the photons are found to be in quantitative agreement with the formula: $\left(R_1^2 - R_2^2\right)\frac{\omega^2}{2c^2} = 2.44\text{x}10^{20}\omega^2$. They refer to this as the "expected shift" and claim that it can be derived in either of two ways from theory: a) from Einstein's equivalence principle [8] by treating the acceleration of the rotor as an "effective gravitational field" or b) from the time dilation effect of SR. They do not comment directly as to whether the observed direction of the shift is to higher or lower frequency, but since the proportionality factor in the above equation is positive, a shift to the blue is clearly indicated. As a consequence, this result stands in contradiction to the prediction of SR that the sign of the Doppler shift should be the same as found in the Ives-Stillwell experiment [2, 6-7], namely in the direction of longer wavelengths and lower frequencies.

The symmetry characteristics of the above formula are even more telling in this respect. The parameters R_1 and R_2 clearly refer to the distances of the absorber and source from the axis of the rotor, although no explicit designation is given in the text [3]. Since the former distance (R_a) is greater than the latter (R_s), it is clear from the sign on the right-hand side of the formula that $R_1 = R_a$ and $R_2 = R_s$. The dependence of the fractional Doppler shift $\frac{\Delta\nu}{\nu}$ on ω is thus:

$$\frac{\Delta\nu}{\nu} = \left(R_a^2 - R_s^2\right)\frac{\omega^2}{2c^2}. \tag{4}$$

The formula therefore implies that interchanging the positions of the absorber and light source on the rotor's axis causes a reversal in the sign of the Doppler shift.

This is clearly not the result that one expects from SR, since it claims that only the relative speed $\left|\mathrm{R}_\mathrm{a} - \mathrm{R}_\mathrm{s}\right|\omega$ of the source and absorber is material in making this determination. According to the time dilation formula of eq. (3), the empirical results for transverse motion should obey the formula:

$$\frac{\Delta\nu}{\nu} = \gamma^{-1}\left(\left|\mathrm{R}_\mathrm{a} - \mathrm{R}_\mathrm{s}\right|\omega\right) - 1 \approx -\left(\mathrm{R}_\mathrm{a} - \mathrm{R}_\mathrm{s}\right)^2 \frac{\omega^2}{2\mathrm{c}^2}, \tag{5}$$

i.e., predict a red Doppler shift regardless of the relative position of the light source and absorber on the rotor.

Kündig [4] also used the equivalence between acceleration and gravitation [9] to discuss his experimental results and came to the same conclusion as Hay et al. [3] with regard to the potential energy difference Φ between the adsorber and light source mounted on his rotating system (Φ is lower at the adsorber). He went on to argue that *since a clock in the rest frame of the absorber is slowed down* as a result of the acceleration, the frequency (ν_A in his notation) observed with it would be *lower* than that of the signal emitted from the source at a higher gravitational potential [see eq. (3) of Ref. 4]. *However, this conclusion runs contrary to the standard interpretation of the gravitational red shift* [8, 10]. When light falls in a gravitational field, a blue shift is observed because the observer's clock runs slower than that at the location of the light source and thus *more waves per unit time are counted* than would otherwise be the case [10]. The term "gravitational red shift" was coined specifically to describe the case when light *rises* through a gravitational field, as for example when light emitted from a star is observed on earth [8]. Einstein's prediction of a red shift in the latter case is based on the assumption, long since verified experimentally, that terrestrial clocks run faster than those near the sun and therefore must record a lower frequency than is observed for an identical light source when it is located on the earth's surface. In going from his eq. (2) to eq. (3), Kündig [4] assumes that the fractional changes in gravitational potential and observed light frequency are of the same sign, whereas in fact $\frac{\Delta\Phi}{\Phi} = -\frac{\Delta\nu}{\nu}$ is correct [8, 10].

The conclusion from the theoretical analysis of the ultracentrifuge Doppler experiments [3-5] is therefore that an increase in light frequency was observed, that is, a shift in the opposite direction to that found with the Ives-Stilwell approach [2, 6-7]. One can only speculate why this important distinction was not pointed out explicitly by Hay et al. and Kündig in their papers, but the suspicion is that they were dissuaded from doing so by the fact that the SR treatment of the transverse Doppler effect predicts unequivocally that a red shift will be observed in both cases. The very fact that Einstein's equivalence principle [8] was invoked to explain the results of the ultracentrifuge experiments implies that it cannot be simply a matter of perspective whether the absorber clock or that at the location of the light source is running slower.

There is no doubt that the rates of clocks increase when they are raised to a higher gravitational potential. It is not a question of the perspective of the observer. Kündig [4] recognizes this when he states: "We thus see that the transverse Doppler effect and the time dilatation produced by gravitation appears [sic] as two different modes of expressing the same fact, namely that the clock which experiences acceleration is retarded compared to the clock at rest." This is a concise summary of the experimental results that leaves no doubt that the measurement process is perfectly objective.

Shortly after the paper by Hay et al. [3] appeared, Sherwin [9] clarified the interpretation of their experimental results by pointing out explicitly that there was no "ambiguity" as to which clock rate is slower. He went on to make the point that the fact that a blue shift is observed when the absorber is located at the rim of the rotor does not necessarily stand in contradiction to SR. This is because the absorber/detector is subject to high acceleration in the experiment and therefore does not satisfy the conditions for successful application of SR, namely that the "observer" be in uniform motion.

However, this argument was much more plausible to make in 1960 than it was a decade later after the timing results for atomic clocks located on circumnavigating airplanes became available [11]. Despite the fact that these clocks were subject to minimal acceleration for the great majority of the time in flight, it was still found that it was completely unambiguous which of them had been running slower over the duration. This was in fact a very surprising result at the time of the Hafele-Keating experiments, as the authors pointed out at the beginning of the discussion in their work [11].

III. Objectivity and the Lorentz Transformation

The basis for the insistence of physicists on a subjective theory of measurement is the Lorentz transformation (LT) of SR. In the case of time dilation, the key equations are:

$$\mathrm{d}t' = \gamma\left(\mathrm{d}t - \frac{v\mathrm{d}x}{\mathrm{c}^2}\right) \text{ and} \tag{6a}$$

$$\mathrm{d}t = \gamma\left(\mathrm{d}t' + \frac{v\mathrm{d}x'}{\mathrm{c}^2}\right). \tag{6b}$$

These two equations are the inverse of one another. They relate clock readings $\mathrm{d}t$ and $\mathrm{d}t'$ in two different inertial systems (S and S') for the same event. According to these equations, it follows that an observer at rest in S will measure the lifetime $\mathrm{d}t$ of some meta-stable particles at rest in S′ to be larger than does the local observer there ($\mathrm{d}t' = \tau$, the proper lifetime). This follows from eq. (6b) since $\mathrm{d}x' = 0$ in this case and thus $\mathrm{d}t = \gamma \mathrm{d}t' = \gamma\tau$ ($\gamma > 1$). However, if the observer in S′ measures the lifetime of identical particles at rest in S, the opposite ordering is obtained on the basis of eq. (6a) since $\mathrm{d}x = 0$ in this case: $\mathrm{d}t' = \gamma \mathrm{d}t = \gamma\tau$. Goldstein [12] sums up the situation as follows: "But it should be emphasized that observers in the unprimed system examining the rate of a clock fixed in the primed system likewise come to the conclusion that it is running slow compared to theirs." He continues: "Thus no one system is singled out as the stationary one and the other the moving one — the motion is only relative; all (uniformly moving) systems are completely equivalent."

By the above logic, it must be expected that a red shift would occur in both sets of transverse Doppler experiments discussed above, contrary to what was observed. One might argue that the LT is not really applicable in this case because either the light source or the detector/absorber is under acceleration in the experiments, as Sherwin [9] in fact stated. There is another possibility, however. As discussed elsewhere [13-14], the LT is not the only space-time transformation that satisfies both of Einstein's SR postulates. As pointed out by Lorentz [15], there is a degree of freedom in such transformations that is akin to a normalization factor for the resulting space-time vectors [14]. Consequently, it is possible to multiply each of the four LT equations on the right-hand side by the same factor ε [16] without violating Einstein's light speed constancy requirement, in which case eq. (6a) is changed to the more general form:

$$\mathrm{d}t' = \varepsilon\gamma\left(\mathrm{d}t - \frac{v\mathrm{d}x}{\mathrm{c}^2}\right). \tag{7}$$

Einstein was aware of this possibility in his original work [1], but he assumed *without proof* that the factor in question (which he referred to as φ instead of ε; see p. 900 of Ref. 1) was *only a function of the relative velocity* v of the two inertial systems. This assumption was shown from symmetry considerations to lead to the conclusion that the only value possible for ε is unity, thereby producing the LT and its eq. (6a) for $\mathrm{d}t'$.

The only reliable way to determine the value of the above factor is by experiment. The transverse Doppler studies discussed above provide the necessary information to accomplish this goal. The key result is that the rates of clocks are slowed when they are accelerated, as Kündig has stated in his summary [4]. Quantitatively, this result can be expressed by the following equation relating the elapsed times $\mathrm{d}t_{\mathrm{a}}$ and $\mathrm{d}t_{\mathrm{s}}$ measured by clocks moving with the absorber/detector and light source, respectively, in the transverse Doppler investigations:

$$\gamma\left(v_{\mathrm{a}}\right)\mathrm{d}t_{\mathrm{a}} = \gamma\left(v_{\mathrm{s}}\right)\mathrm{d}t_{\mathrm{s}}, \tag{8}$$

where v_a and v_s are the speeds of the absorber and source relative to the laboratory from which they were accelerated. This result is consistent with both of the empirically determined relations [3, 7] of eqs. (3-4). It also can be derived in a straightforward manner from SR by assuming that the amount of time dilation for each clock is *proportional* to the $\gamma\left(v\right)$ factor in each case [17-18]. However, this can only be done *by giving up on the concept of a subjective measurement process* and therefore denying one the most basic principles of SR. Instead of eq. (6a) of the LT, we therefore need a simpler relation that expresses the fact that two clocks in uniform motion run at rates that are strictly proportional to one another, hence:

$$\mathrm{d}t' = \frac{\mathrm{d}t}{\mathrm{Q}}, \tag{9}$$

where Q is the proportionality factor as determined by eq. (8) in the transverse Doppler studies. A similar proportionality factor is used to "precorrect" clocks on Global Positioning System (GPS) satellites to ensure that they run at the same rate as identical clocks located on the earth's surface [13]. The latter procedure in turn is based on experience with clocks carried aboard airplanes [11] and rockets [19], so there is ample evidence for the fundamental correctness of this proportionality relation between clock rates.

It is a simple matter to incorporate this clock-rate proportionality into the relativistic space-time transformation. One merely needs to define a value for ε in eq. (7) that leads directly to eq. (9). The required value is:

$$\varepsilon = \left[\gamma \mathrm{Q}\left(1 - \frac{v\mathrm{d}x}{\mathrm{c}^2\mathrm{d}t}\right)\right]^{-1} = \frac{\eta}{\gamma \mathrm{Q}}. \tag{10}$$

Note that the factor η defined in eq. (10) already appears in Einstein's relativistic velocity transformation [1]. More details about the derivation of this alternative Lorentz transformation (ALT) may be found elsewhere [13-14, 20]. In the present context its most important characteristic is that, unlike the LT, it is consistent with the results of both sets of transverse Doppler experiments [2-7] and it restores the principle of the objectivity of measurement to relativity theory. The inverse of eq. (9) is simply

$$\mathrm{d}t = \mathrm{Q}\mathrm{d}t'. \tag{11}$$

There is thus a *hierarchical* relationship between the lifetimes of identical particles located in different rest systems. It is not just a matter of perspective which lifetime or clock period is greater than the other, contrary to what must be concluded on the basis of the original LT [1].

IV. Retrospective: Subjective, Objective or Both?

The main purpose of the various transverse Doppler measurements was to study the time dilation effect predicted on the basis of Einstein's SR [1]. Aside from the basic question of whether the rates of natural clocks are affected by relative motion, there is a much more fundamental issue that was raised in this discussion: is it just a matter of one's perspective which of two moving clocks runs slower than the other, or is this something that everyone can agree on at least in principle? Einstein can be said to have added to the confusion on this point since it is possible to come to either one or both of these conclusions based on his explicit remarks in the paper.

On the one hand, he is quite clear that all inertial systems are equivalent (his first postulate), which leads one to conclude that a moving clock always runs slower relative to an observer's identical stationary clock. This position was seconded by Goldstein [12] in the passage quoted in Sect. III. It also can be inferred from Will's general equation for time dilation [eq. (6.2) of Ref. 21] given below:

$$\frac{\nu_{\mathrm{r}}}{\nu_{\mathrm{e}}} = \left(1 - \mathrm{v}_{\mathrm{e}}^{2}\right)^{0.5} . \tag{12}$$

This relation is fundamentally subjective since it only refers to measurements made from the perspective of the receiver (r) for an emitter (e) in relative motion to it. All that matters is that the emitter is in relative motion to the receiver. The observed frequency ν_{r} must always be smaller than the emitted value ν_{e} measured at the location of the light source.

The above "symmetry" principle is based on the LT and its eqs.

(6a-b). Yet, in the chapter following this derivation [1], Einstein goes on to consider what has come to be known as the "clock paradox," in which he concludes that when a clock makes a round trip from A to B and back again, it will lose time to an identical clock that has remained stationary there. This conclusion is the exact opposite of what is claimed with the symmetry principle since it clearly states that it is possible to know on an unequivocal basis which clock rate is slower in this case. This is an objective measurement process that can in no way be construed to be subjective. The explanation for this distinction has been given by von Laue [22]: "Inertial systems are observable realities; our thought experiment decides which clock [twin] remained at rest in the same system, which in different ones." Sard [23] elaborates by stating that "it is wrong to confuse the principle of relativity with the belief that the behavior of two clocks depends only on their motion relative to one another, as if there were nothing else in the universe."

The above two views of the measurement process are not necessarily mutually contradictory if each has its own range of applicability. Nor is the subjectivity argument self-contradictory. Sometimes one hears of a supposed logical proof that two clocks cannot both be running slower than one another at the same time, i.e. it is claimed that $A < B$ and $B < A$ are mutually exclusive inequalities. The problem with that argument is that it is based on the premise that only objective relationships are allowed in nature, whereas no *a priori* justification for such a conclusion can definitively be made [9]; observer A's measurement of B's clock is a different event than B's measurement of A's clock.

The only way to settle this issue in a rational manner is through experimental investigation, and that is where the transverse Doppler measurements came into play historically. Unfortunately, the interpretations of the resulting findings have been *wohlwollend* (to borrow a phrase from Einstein's vernacular) in favor of the standard theory of relativity. All three groups of authors [3-5] who carried out Doppler measurements with rotors have claimed, for example, that their findings can be obtained using the time dilation phenomenon of SR as well as by treating acceleration as an "effective gravitational field." This assertion completely ignores the question of whether the results are consistent with the above symmetry principle. For this purpose, placement of the Mössbauer source and the absorber on the axis rotor is critical. Interchanging them should lead to no change in the shift's direction if the latter holds true. The shift should be to lower frequency in each case (red-red), as in Will's eq. (12). If the objective nature of the measurement process should manifest itself, however, the result would be expected to be red-blue, in accordance with eq. (4).

Since the empirical data [3-5] obtained in the rotor experiments agree completely with eq. (4), it is clear that the red-red result expected from the subjective theory embodied in eq. (12) is inoperative. Careful reading of Hay et al.'s conclusion [3] that their results are consistent with the time dilation theory of SR shows that they have assumed that the theory is valid even though the absorber is subject to high acceleration. Subsequent theoretical discussions [17-18] have attempted to justify this conclusion by considering the relative time retardations experienced by the two clocks in the experiment, that of the light source and that of the absorber. This argument leads directly to eq. (4), but it does so by eliminating the basic subjectivity inherent in SR. Once one assumes that two clock rates are strictly proportional, in accord with eq. (8), there is no longer any basis for claiming that the measurement process is subjective.

Does the above argument succeed in proving that SR correctly predicts the results of the rotor experiments? Not unless one agrees that the LT has only limited applicability in the theory. The LT and subjectivity are inseparable. Sherwin [9] recognized this crucial point when he concluded that SR is only applicable for uniform motion. However, there are several points about this assertion that require further consideration. For one thing, *the red-red result expected for uniform motion has never been observed.* The initial experiments of Ives and Stilwell [2] appeared to be consistent with the SR prediction because a red shift was recorded, but proof of the subjectivity proposal can only be achieved with a two-way experiment. It should be noted that Sherwin [9] gives no reference for his claim that "in experiments involving uniform translation … the clock rates (as determined by the prescribed operational procedures) are ambiguous, that is, the observers in each frame measure the *other* clock to be running slow."

Even if one accepts the possibility that a red-red result would occur if only the relevant experiment could be carried out, there remains a critical question of exactly when the objective provisions of the overall theory take precedence. Consider the case of a rocket traveling with a slightly variable but extremely high rate of speed relative to the observer on earth. Under these conditions, one expects an exchange of signals between the two positions to lead to a red-blue pair of transverse Doppler shifts according to this "dual" theoretical approach. A slight deceleration of the rocket could then bring it into perfectly uniform translation, in which case one of the shifts would have to change from blue to red on an essentially instantaneous basis. The amount of the shift would be expected to be the same in both cases, and it could be extremely large given the rocket's speed relative to the earth. Moreover, the process of deceleration could be quickly reversed, which would then mean a return to the original red-blue result. Whether this argument *ad absurdum* destroys the plausibility of the dual approach might still be a matter of some dispute, but at the very least, it demonstrates that the range of applicability for the subjective portion of the theory is so narrow that it loses any claim to practical significance.

V. Conclusion

The main focus of the present work is to determine whether the frequency shift observed in the ultracentrifuge experiments of Hay et al. [3], Kündig [4] and Champeney et al. [5] is to the blue or to the red. It has been argued that careful examination of the results of both sets of authors leaves no doubt that a blue shift was found in each case. This conclusion is based first and foremost on eq. (4), which is taken directly from the experimental references and was derived from Einstein's equivalence principle between the effects of acceleration and gravitation. It leaves no doubt that the transverse Doppler effect is *anti-symmetric* with respect to the exchange of positions of the light source and absorber on the axis of the rotor employed in the rotor experiments [3-5, 9], in complete analogy to the situation when light signals are exchanged between observers at different gravitational potentials. The original transverse Doppler experiments of Ives and Stilwell [2] and subsequent improvements thereof [6-7] clearly correspond to the case where the absorber/detector is moving at a slower speed relative to the laboratory than is the light source, in which case a red shift is observed. Considering the theoretical significance of the sign of the transverse Doppler shifts, it would be of great interest to carry out new experiments with ultracentrifuges to test the validity of eq. (4) on a quantitative basis, particularly by interchanging the positions of the light source and absorber on the rotor axis.

Why then has there been so much resistance to accepting the fundamentally anti-symmetric character of the transverse Doppler effect? The answer is clearly because it stands in direct contradiction to Einstein's views regarding the nature of time dilation [1, 12, 21], specifically that *it should only be a matter of perspective which of two clocks is running slower than the other*. This position in turn is deduced from the Lorentz transformation (LT) of the special theory of relativity (SR). The latter is thought to be the only space-time transformation that is consistent with his two postulates of relativity, and thus there has been a strong feeling over more than a century that no experimental result exists that can possibly stand in contradiction to the LT.

Nothing could be further from the truth. It is a simple matter to construct an alternative (objective) Lorentz transformation (ALT) that satisfies Einstein's postulates while maintaining consistency with the experimental fact that clocks in relative motion have rates that are strictly proportional to one another at any given time [see eqs. (9,11)]. If this proportionality factor (Q) is known, it is completely predictable on that basis what the *ratio* of elapsed times measured with the two clocks will be in any and all cases. This relationship will last until there is a change in either the state of relative motion of the two clocks or their positions in a gravitational field, but that just means that the value of the proportionality factor changes, not the essential objective character of the measurement process.

The new space-time transformation (ALT) leads to the same velocity transformation as Einstein introduced in his original work but it neither violates the principle of remote simultaneity, contrary to the LT, nor is it consistent with the Lorentz-invariance property of the latter. It is important to recognize that this change does not affect the Lorentz-invariance property of the energy/momentum four-vector or of the equations of motion in the theory of quantum electrodynamics. This is because quantities other than spatial and temporal coordinates are involved in these cases and thus the choice of normalization factor in defining the corresponding transformations is based on different experimental criteria. However, as discussed elsewhere [13], there is no experimental evidence to suggest that the principle of objectivity of measurement does not also hold in these instances. Thus, it should always be possible in principle to say which of two masses or energies is greater and by what factor. Indeed, the same factor applies in these cases as for the rates of clocks in relative motion.

In summary, the sign of the measured transverse Doppler shifts is of critical importance to the development of relativity theory, and it is therefore imperative to clear up any questions that are left open in the theoretical presentations of the original ultracentrifuge determinations of these quantities.

References

[1] A. Einstein, "Zur Elektrodynamik bewegter Körper", *Annalen der Physik* **322(10)** (1905) 891-921.

[2] H.E. Ives and G.R. Stilwell, "An Experimental Study of the Rate of a Moving Atomic Clock", *Journal of the Optical Society of America* **28(7)** (1938) 215-226 (contd. in **31(5)** (1941) 369-374).

[3] H.J. Hay, J.P. Schiffer, T.E. Cranshaw, and P.A. Egelstaff, "Measurement of the Red Shift in an Accelerated System Using the Mössbauer Effect in Fe^{57}" *Physical Review Letters* **4(4)**, (1960) 165-166.

[4] W. Kündig, "Measurement of the Transverse Doppler Effect in an Accelerated System", *Physical Review* **129(6)** (1963) 2371-2375.

[5] D.C. Champeney, G.R. Isaak, A.M. Khan, "Measurement of Relativistic Time Dilatation using the Mössbauer Effect" *Nature* **198** (1963) 1186-1187

[6] G. Otting, "Der quadratische Dopplereffekt", *Physikalische Zeitschrift* **40** (1939) 681-687.

[7] H.I. Mandelberg and L. Witten, "Experimental Verification of the Relativistic Doppler Effect" *Journal of the Optical Society of America* **52(5)** (1962) 529-536.

[8] A. Einstein, "Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen", *Jahrbuch der Radioaktivität und Elektronik* **4** (1907) 411-462.

[9] C.W. Sherwin, "Some Recent Experimental Tests of the 'Clock Paradox'",

Physical Review **120(1)** (1960) 17-21.

[10] R.D. Sard, *Relativistic Mechanics*, W. A. Benjamin (New York, 1970) p. 316.

[11] J.C. Hafele and R.E. Keating, "Around-the-World Atomic Clocks: Predicted Relativistic Time Gains", *Science* **177** (1972) 166-168; 168-170.

[12] H. Goldstein, *Classical Mechanics*, Addison-Wesley Publishing Co. (Reading, Massachusetts, 1950), p. 193.

[13] R.J. Buenker, "The Global Positioning System and the Lorentz Transformation", *Apeiron* **15(3)** (2008) 254-269.

[14] R.J. Buenker, "Simultaneity and the Constancy of the Speed of Light: Normalization of Space-time Vectors in the Lorentz Transformation", *Apeiron* **16(1)** (2009) 96-146.

[15] H.A. Lorentz, "Simplified Theory of Electrical and Optical Phenomena in Moving Systems", *Proceedings of the Royal Netherlands Academy of Arts and Sciences* **1** (1898-1899) 427-442; reprinted in P. Zeeman and A.D. Fokker, eds.,*Collected Papers*, Vol. 5, M. Nijhoff, (The Hague, 1937) p. 139-155.

[16] A. Pais, 'Subtle is the Lord …' The Science and the Life of Albert Einstein, Oxford University Press (1982) p. 125.

[17] W. Rindler, *Essential Relativity*, Springer Verlag (New York, 1977) p. 56.

[18] R.D. Sard, *Relativistic Mechanics*, W. A. Benjamin (New York, 1970) p. 319.

[19] R.F.C. Vessot and M. W. Levine, "A test of the equivalence principle using a space-borne clock", *General Relativity and Gravitation* **10(**3) (1979) 181-204.

[20] R. J. Buenker, "The Clock Riddle: The Failure of Einstein's Lorentz Transformation", *Apeiron* **19(1)** (2012) 84-95.

[21] C.M. Will, "Clock synchronization and isotropy of the one-way speed of light", *Physical Review* D **45** (1992) 403-411.

[22] M. v. Laue, *Die Relativitätstheorie*, Vol. 1, 7th ed., Vieweg (Braunschweig, 1955) p. 36.

[23] R.D. Sard, *Relativistic Mechanics*, W. A. Benjamin (New York, 1970) p. 102.