Is Time Dilation ‘Real’ ? Einstein and the Transverse Doppler Effect

Marco Giovanelli

Università di Torino
Department of Philosophy and Educational Sciences
Via S. Ottavio, 20 10124 - Torino, Italy

marco.giovanelli@unito.it

As early as 1907, Einstein realized that the second-order transverse Doppler redshift reported by Stark in the spectral lines of fast-moving ions in canal rays could serve as a direct experimental test of time dilation. He rejected Stark’s *dynamical explanation* of the effect as a real frequency change of the moving ions. Instead, assuming that ions of the same kind emit the same spectral lines when at relative rest, Einstein offered a *kinematical explanation* of the frequency shift as a consequence of time dilation. He labeled the effect *apparent*, since it disappears for the co-moving observer. At the same time, he regarded it as *real*, in the sense that it would not occur if the old kinematics held. From the 1920s onward, Einstein argued that the behavior of atomic clocks calls for a dynamical explanation. The present paper shows, however, that even if an special relativistic explanation of the spectral identity of atoms were available, it would merely reinforce the claim that relativistic time dilation admits a purely kinematical interpretation. It concludes that modern dynamists misread Einstein’s plea for a dynamical account of clock behavior as a demand for *explanation* of the time dilation, whereas it was primarily motivated by the problem of its *confirmation*.

Introduction

Over the last two decades, philosophical discussions of special relativity have repeatedly returned to the question of whether relativistic effects, most notably length contraction and time dilation, ultimately call for a *dynamical* explanation (Brown 2005; Brown and Pooley 2006), a *kinematical* explanation (Norton 2008; Janssen 2009), or whether one should move beyond this binary choice altogether (Acuña 2016). While the debate is primarily theoretical in intent (Read 2020; Acuña and Read 2025), proponents of the dynamical approach have often framed it against a historical background. In particular, it has been argued that, although Einstein initially presented length contraction and time dilation as merely *apparent* coordinate effects, he was ultimately aiming at an account in which these effects reflect *real* physical changes in the equilibrium configurations of moving atomic systems (Brown and Read 2022). Indeed, he later acknowledged that rods and clocks should have been treated as solutions of the underlying dynamical laws (Einstein 1949, 61). It has therefore been suggested that Einstein himself may, at least retrospectively, be seen as gesturing toward a dynamical approach (Brown and Read 2022, 70).

This paper aims to further challenge this historical narrative, in the hope that this result will bear directly on contemporary debates concerning the theoretical role of the dynamical–kinematical distinction. As recent literature has shown (Giovanelli 2023), concerns about the proper use of the categories 'real' and 'apparent,' as well as 'kinematical' and 'dynamical,' had already emerged in the early 1910s. Starting from Max Born's (1909) definition of rigid motion, Paul Ehrenfest (1909) formulated his famous paradox, arguing that a Born rigid disk could not be set into rotation without the emergence of stresses, thereby revealing a contradiction within relativity theory. Some contemporary relativists (Ignatowski 1910; Varićak 1911) challenged Ehrenfest's conclusion. They argued that such stresses would arise only if 'Lorentz contraction' were interpreted as a *real* dynamical effect, produced by molecular forces within the material of the rod. By contrast, 'Einstein contraction' was merely an *apparent* coordinate effect resulting from an arbitrary synchronization of clocks. It could therefore be made to disappear by adopting a different synchronization convention. On this basis, they concluded that no stresses would arise in a rotating rigid disk.

Both Ehrenfest (1910) and Einstein (1911), however, felt the need to take a public stance against this view. Length contraction is indeed *apparent* insofar as it is a coordinate effect that vanishes for a co-moving observer, but it is nevertheless *real*, since it inevitably appears for non-co-moving observers and therefore cannot be eliminated in all frames at once. For this reason, it gives rise to physically meaningful and, in principle, empirically testable consequences: "This is precisely what Ehrenfest made very clear in a very elegant way" (510). As Born (1909) showed, in the case of linear acceleration the proper length of a rod can, in principle, be preserved by appropriately coordinating the accelerations of its different parts. In the case of a rotating disk, by contrast, no global co-moving inertial frame exists, so Lorentz contractions along the rim cannot be eliminated simultaneously. The resulting mismatch between circumference and radius gives rise to internal stresses, illustrating how 'apparent' coordinate effects can have genuinely 'real' physical consequences.[1]

This paper argues that the same dialectic between the *apparent* and the *real* emerges even more clearly in the case of time dilation. Like length contraction, time dilation is 'apparent,' since it is a coordinate effect that vanishes for a suitably chosen co-moving observer; yet it is 'real,' since it cannot be removed for all non-co-moving observers simultaneously, provided that the new kinematics hold.[2] In this case, no comparable philosophical controversy arose, largely because there was no genuine Lorentzian counterpart to time dilation (Rindler 1970). Nevertheless, in contrast to length contraction, the empirical testability of time dilation appeared to be reasonably feasible. As early as 1907, Einstein appealed to Johannes Stark (1906)'s experimental work on fast-moving ions in canal rays, which seemed to suggest the presence of a second-order Doppler effect in the transverse direction of motion, that is, even in the case in which the classical Doppler effect disappears. A concrete possibility for testing relativistic kinematics was thus at hand (Giuliani 2013).

---

[1]Note that this situation is closely analogous to Bell's (1976) rocket thought experiment, which is commonly taken to support a dynamical rather than a purely kinematical reading of relativistic length contraction (Brown and Pooley 2001). The claim is that, if length contraction were a merely innocuous 'coordinate effect,' the emergence of stresses and the possible structural failure of the rope (or of the rotating disk) would be difficult to account for. By contrast, Einstein used the Ehrenfest paradox to show that a 'coordinate-dependent' effect can nevertheless be physically 'real,' as showb by the stresses in Ehrenfest's disk.

[2]In what follows, I use the term 'kinematics' and avoid explicit reference to the 'geometry' of spacetime, since Minkowski's framework was far from being widely adopted in the period discussed in this paper.

As the paper will show, from the outset, Einstein (1907b) rejected Stark's (1906) original explanation, according to which ions in motion were thought to undergo a 'real,' dynamical contraction of their intrinsic frequency. Spectroscopy showed that atoms and ions of the same species always display the same characteristic spectral lines when compared at rest, independently of their prior acceleration history. The principle of relativity implies that atoms of the same kind realize the same intrinsic frequencies in all inertial systems. In the transverse Doppler configuration, there is no relative motion along the line of sight, and hence no classical Doppler contribution. Einstein could then conclude that the reduced frequency must therefore be ascribed to the relativistic relation between time coordinates in different inertial frames, that is, to time dilation itself. Accordingly, Einstein (1908, 422; 1910, 133) initially labeled the change in the observed frequency 'apparent' in order to emphasize that the intrinsic frequency of ions is supposed to be invariant. Nevertheless, the transverse Doppler effect is 'real,' since the frequency shift necessarily appears for non-co-moving observers if the new kinematics hold. The transverse Doppler effect thus offered, at least in principle, a direct test of time dilation, provided that atomic spectral emitters can serve as 'good' clocks.

From the 1920s onward, Einstein explicitly emphasized that the behavior of atomic clocks could not yet be derived from a complete microscopic theory (Einstein 1921, 1923, 1924, 1926, 1949). He conceded that, in a fully developed theory, the existence and behavior of clocks would, in principle, emerge as consequences of the fundamental equations themselves. Any theory capable of supplying oscillatory processes usable as clocks would have to single out solutions characterized by a definite, invariant period, determined by the structural constants of the theory. If the theory were Lorentz invariant, such solutions would recur in all inertial frames in the same way, thereby guaranteeing the identical behavior of clocks when compared at rest. From a modern perspective, an example of such an invariant scale is provided by a mass parameter in relativistic quantum theory, which fixes a characteristic frequency, the Compton frequency $\nu_C = mc^2/h$.

Such a theory would then indeed provide a *dynamical explanation* of why all atomic clocks are *identical* when compared in the same rest frame and therefore emit the same spectral lines. However, this line of reasoning leads to an inevitable conclusion. Given the spectral identity of atoms, and assuming that there is no contribution from motion along the line of sight, the transverse frequency shift must inevitably admit a purely *kinematical explanation*, namely as a consequence of time dilation itself. Somewhat paradoxically, the full realization of the dynamical program shows that time-dilation effects, including the transverse frequency shift, are purely kinematical. In this sense, this paper suggests that the transverse Doppler effect offers a particularly illuminating case for reassessing the long-standing debate between kinematical and dynamical interpretations of special relativity.

In particular, the paper concludes that much of the misunderstanding arises from the fact that Einstein's demand for a dynamical account of rods and clocks has been read as a demand for *explanation* of the new kinematics, whereas it was primarily motivated by the problem of its *confirmation*. Einstein never tired of emphasizing that relativistic kinematics was not merely conventional but, in principle, testable by means of rods and clocks. Yet rods and clocks are complex physical systems governed by dynamical laws that are themselves supposed to conform to relativistic kinematics. From a logical point of view, kinematics and dynamics can receive empirical confirmation only as a whole. Nevertheless, within this whole, dynamical and kinematical explanations remain distinct. The paper argues that the transverse Doppler effect brings this out in especially vivid terms: dynamics explains the sameness of clocks' frequencies when compared at rest, while kinematics alone explains the frequency shift across inertial frames.

1 Time Dilation and the Transverse Doppler Effect in Einstein's 1905 Relativity Paper

Although Einstein's 1905 relativity paper is among the most cited in the history of science, a brief review of its basic structure may nevertheless be useful for locating the respective derivations of time dilation and the transverse Doppler effect. Starting from the two postulates—the relativity principle and the light postulate—the first, kinematical part of the paper aims to develop a new kinematics of "rigid bodies (coordinate systems), clocks, and electromagnetic processes" (892) that resolves their apparent incompatibility. In §1, by introducing the synchronization of clocks using light rays, Einstein shows that there is no *a priori* reason to assume that $t' = t$, that is, that two events which are simultaneous with respect to K' must also be simultaneous with respect to K. In §2 he shows that, as a consequence, there is no *a priori* reason to maintain the classical identification $x' = x$. Since spatial distances depend on the adopted notion of simultaneity, the length of a moving rod as measured in the co-moving system K' is not necessarily equal to the rest length of that rod as measured in the rest frame K.

Once these two prejudices are abandoned, it becomes possible to consider linear transformations between coordinate systems in uniform parallel translation that differ from the classical ones, for which $t' = t$ and $x' = x - vt$. In §3 Einstein then seeks a new set of coordinate transformations that leave the velocity of light c invariant. The derivation is somewhat cumbersome (Martinez 2009, 320–354), but Einstein nevertheless arrives at the so-called Lorentz transformations for motion along the common x–x' axis:

$$x' = \gamma(x - vt), \qquad t' = \gamma\left(t - \frac{v}{c^2}x\right), \qquad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}.$$

The transformation appears here for the first time in its modern form, which makes its perfect symmetry in x and t explicit.[3]

Finally, in the concluding sections of the kinematical part, Einstein derives the physical consequences of the Lorentz tranformations. Once coordinates are interpreted as being measured by means of rods and clocks, the theory yields specific predictions about the behavior of such systems that are, in principle, accessible to experiment. In §4 he derives both length contraction and time dilation. In §5 Einstein then derives the relativistic law of velocity addition, which resolves the tension between the principle of relativity and the light postulate. While length contraction had already been discussed in Lorentz's earlier work, time dilation appears here as a genuinely new physical effect. Indeed, notwithstanding the well-known priority disputes surrounding the 'discovery' of the special theory of relativity, there is broad agreement that the introduction of

[3] Although Einstein originally used β to denote the Lorentz factor, in what follows I adopt the modern convention, reserving γ for the Lorentz factor (γ^{-1} for the inverse Lorentz factor) and β for the dimensionless velocity $\beta = v/c$.

time dilation as a physical effect constitutes Einstein's distinctive contribution (Rindler 1970). It would therefore be appropriate—although this is not customary—to speak of 'Einstein dilation' as the natural counterpart to 'Lorentz contraction.'

1.1 Time Dilation and the Relativistic Clock Retardation

As one might expect, the young Einstein's derivation of time dilation relies purely on algebraic manipulation.[4] He considers a clock that is permanently at rest in the moving system K'. This means that its spatial coordinate in K' is constant and, in particular, that $x' = 0$ for all times. The clock, however, moves with respect to K with constant velocity v along the x-axis. Einstein therefore makes implicit use of the Lorentz transformation relating the spatial coordinates of K and K'.

$$x' = \gamma(x - vt),$$

Since $x' = 0$, this condition immediately yields

$$0 = \gamma(x - vt)\,.$$

Formally, a product vanishes if and only if at least one of its factors vanishes. Since $\gamma \neq 0$, it follows that

$$x = vt\,,$$

which is simply the equation of uniform motion with velocity v in the system K: a clock at rest in K' moves uniformly with velocity v in K. The time indicated by this clock is denoted by t', which is related to t by the Lorentz time-transformation equation:

$$t' = \gamma\left(t - \frac{v}{c^2}x\right)\,.$$

Substituting $x = vt$, one obtains

$$\begin{aligned} t' &= \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\left(t - \frac{v^2}{c^2}\,t\right) \\ &= \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\left(1 - \frac{v^2}{c^2}\right)t \\ &= t\sqrt{1-\frac{v^2}{c^2}}. \end{aligned}$$

It follows that the coordinate time interval Δt measured in K between two successive ticks of a clock moving with respect to K is longer by a factor equal to the Lorentz factor γ than the corresponding coordinate time interval $\Delta t'$ measured by the same clock at rest in the co-moving system K'.

Einstein suggests, albeit rather implicitly, that for velocities small compared with c, one may expand the square root in a Taylor series about $v/c = 0$ (i.e., the Maclaurin series in the dimensionless parameter $(v/c)^2$):

$$\sqrt{1-\frac{v^2}{c^2}} = 1 - \frac{1}{2}\frac{v^2}{c^2} - \frac{1}{8}\frac{v^4}{c^4} - \cdots\,.$$

[4] This is one of the reasons I prefer to avoid the adjective 'geometrical' in this context.

Keeping only the leading correction and neglecting terms of fourth and higher order in v/c, one obtains

$$1 - \sqrt{1 - \frac{v^2}{c^2}} \approx \frac{1}{2}\frac{v^2}{c^2}.$$

Hence the retardation per unit time is approximately

$$\frac{\Delta t}{t} \approx \frac{1}{2}\left(\frac{v}{c}\right)^2.$$

The longer the clocks run, the larger the difference between their readings as judged in the frame K. The retardation is second order in v/c. For ordinary velocities ($v \ll c$), the quantity v^2/c^2 is extremely small, so the retardation accumulates only very slowly. However, by expressing the effect *per second*, Einstein emphasizes that the deviation is systematic and cumulative. A precise quantitative prediction, however small, can be tested if either the velocity is sufficiently high, or the observation time is sufficiently long, or both.

1.2 The Longitudinal and Transverse Doppler Effects

After deriving "the required propositions of the kinematics that correspond to our two principles", Einstein proceeds "to show their *application* in electrodynamics" (Einstein 1905b, 907). The sharp separation between the kinematical part of the paper and the subsequent dynamical parts (involving electromagnetism and particle dynamics) is one of the most characteristic features of Einstein's approach to the electrodynamics of moving bodies. The kinematical framework is established independently of dynamics, and in particular independently of Maxwell's equations; only afterward is it brought to bear on dynamical theories. The second part of the paper accordingly 'applies' the new kinematics to well-established dynamical laws in order to test whether they remain unchanged under the Lorentz transformations. The procedure consists in formulating the dynamical equations with reference to the 'moving' system K', performing the Lorentz transformation, and verifying whether the transformed equations retain the same form in the 'rest' system K. If they do not, the equations must be modified, and such modifications may entail empirically testable consequences.

In §6 Einstein shows that Maxwell–Hertz's equations already satisfy this criterion. From his point of view, the fact that no additional terms need to be introduced is a fortunate circumstance, since the Lorentz transformations were not derived from Maxwell's equations themselves. In §7 Einstein applies the same procedure to the description of optical plane waves. The Lorentz invariance of the wave equation entails modified relations between frequency, direction of propagation, and relative motion. This yields a unified derivation of the aberration of light and the relativistic Doppler effect as consequences of the Lorentz transformations. Both aberration and the longitudinal Doppler effect were already known in classical optics; however, Einstein's treatment provides their exact relativistic form, valid to all orders in v/c, without recourse to ether-based dynamical hypotheses. Moreover, Einstein predicts the transverse Doppler effect, a genuinely new phenomenon absent from classical theory, which arises solely from time dilation and has no classical analogue.

Einstein's derivation proceeds as follows (910f.). Consider a moving, non-accelerated system K' in which a very distant light source is at rest. In this system, the emitted radiation can locally be represented as a plane wave, that is, by sinusoidal electric and magnetic field components whose phase

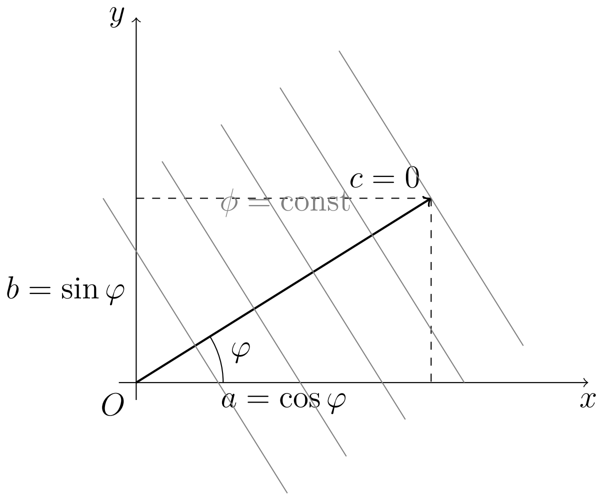

Figure 1: Plane wave propagating in the x–y plane

$$\phi' = \omega'\left[t' - \frac{a'x' + b'y' + c'z'}{c}\right]$$

defines a family of parallel phase planes $\phi' = \text{const}$ propagating rigidly through space. Here $\omega' = 2\pi\nu'$ is the angular frequency in the rest frame of the source, and (a', b', c') are the direction cosines of the wave normal. Without loss of generality, if the wave propagates in the x–y plane, one may set $a' = \cos\varphi$, $b' = \sin\varphi$, and $c' = 0$, where φ is the angle between the direction of propagation and the x-axis.

According to the principle of relativity, the same physical wave must also be describable in the rest system K with respect to which K' moves with uniform velocity. Einstein assumes that the wave preserves its plane-wave character in K, so that it can again be represented by a phase of the same functional form,

$$\phi = \omega\left[t - \frac{ax + by + cz}{c}\right].$$

Since the wavefronts themselves are physical entities, one and the same wavefront must correspond to the same value of the phase in all inertial frames (Einstein 1905b, 911). This requirement is expressed by the condition

$$\phi' = \phi.$$

To implement this condition, the phase ϕ' must be rewritten in terms of the unprimed variables x, y, z, t. That is, the mathematical description of the wave given in K' must be expressed using the coordinates of K. This is achieved by substituting the Lorentz transformations for the time coordinate and for the longitudinal coordinate x, together with $y = y'$ and $z = z'$, into the expression for ϕ'. Upon regrouping terms, the phase again retains the same functional form, but with transformed coefficients:

$$a = \frac{a' + \frac{v}{c}}{1 + \frac{v}{c}a'}, \qquad b = \frac{b'}{\gamma\left(1 + \frac{v}{c}a'\right)}, \qquad c = \frac{c'}{\gamma\left(1 + \frac{v}{c}a'\right)}, \qquad \omega = \gamma\,\omega'\left(1 + \frac{v}{c}a'\right).$$

As mentioned, a, b, c are the direction cosines of the wave normal, that is, the components of the direction of propagation (fig. 1). Their transformation therefore expresses the change in the apparent direction of propagation between K' and K. By definition, the angular frequency ω of a plane wave is given by the coefficient of the time coordinate in the phase when the spatial coordinates are held fixed. Accordingly, the coefficient multiplying t in the transformed phase determines the observed angular frequency ω in the system K. The invariance of the phase thus entails two distinct but closely related effects. The transformation of the temporal coefficient yields a change in frequency, that is, the relativistic Doppler effect, whereas the transformation of the spatial coefficients encodes a change in the apparent direction of propagation of the wave, that is, the aberration of light. The Doppler effect and aberration therefore arise simultaneously from the same Lorentz transformation of the phase, as two aspects of a single kinematical procedure.

We are here interested in the frequency shift (Einstein 1905b, 911). Transforming the phase of the wave from K' to K and passing from angular to ordinary frequency, $\nu = \omega/(2\pi)$, one obtains the relativistic Doppler formula

$$\nu = \nu' \, \frac{1 + \frac{v}{c}\cos\varphi}{\sqrt{1 - \frac{v^2}{c^2}}}.$$

For longitudinal propagation along the x–axis, one has $\varphi = 0$ and hence $\cos\varphi = 1$. The general expression then reduces to the familiar relativistic formula for the longitudinal Doppler effect,

$$\nu = \nu' \, \frac{1 + \frac{v}{c}}{\sqrt{1 - \frac{v^2}{c^2}}} = \nu' \sqrt{\frac{1 + \frac{v}{c}}{1 - \frac{v}{c}}}.$$

As this shows, when one starts from a source at rest in the moving system K' and evaluates the frequency in the system K, the longitudinal Doppler effect combines a classical Doppler factor, $1 + \frac{v}{c}$, associated with relative motion along the line of sight, with an additional relativistic correction $1/\sqrt{1 - \frac{v^2}{c^2}}$. In classical wave theory, if the source is approaching the observer, the wave crests arrive more frequently, and the observed frequency is therefore higher than that of an identical source at rest. Relativity predicts a further frequency shift beyond this classical effect.

The case $\cos\varphi = 0$ corresponds to motion perpendicular to the direction of propagation of the light, that is, to transverse motion (along the y–axis in fig. 1). In this case the formula reduces to

$$\nu = \frac{\nu'}{\sqrt{1 - \frac{v^2}{c^2}}},$$

showing that even when there is no component of the relative motion along the line of sight, the observed frequency nevertheless differs from the emitted one. A frequency shift therefore appears even though there is no classical Doppler effect in the Galilean theory of waves. This purely relativistic transverse Doppler effect has no analogue in pre-relativistic wave theory.

2 Testing the New Kinematics: Stark's Second-Order Doppler Effect

In the 1905 paper, time dilation and the transverse Doppler effect appear, respectively, among the direct and indirect consequences of the Lorentz transformations. Einstein does not explicitly relate the two effects to one another, nor does he discuss the possibility of an empirical test of the transverse Doppler effect. He likely did not think that wave sources were available that could attain velocities large enough for such a small effect to be experimentally accessible. Rather, in §8 of his relativity paper, Einstein derives the transformation law for the frequency of light and argues that the energy of light transforms in the same way as its frequency, i.e. $\frac{E'}{E} = \frac{\nu'}{\nu}$. On this basis, he derives the radiation pressure exerted by light on a perfectly reflecting mirror in uniform motion. This result is subsequently exploited in the September paper on the inertia of energy (Einstein 1905a). In §9 Einstein then turns to the Maxwell equations with sources. The only explicit discussion of the empirical testability of the new theory occurs in §10 of the paper. In this section Einstein derives the equation of motion of the slowly moving 'electron,' an expression that he uses to denote massive charged particles in general. Insofar as electrons (in the sense of elementary particles) function as fast-moving charged test particles, the predicted effects are, in principle, accessible to observation.

Indeed, Einstein's 1905 relativity paper was cited for the first time on November of 1905 by the Göttingen experimentalist Walther Kaufmann (1905, 954), in a short note presented at a plenary session of the Prussian Academy of Sciences. The note reported on Kaufmann's new experiments with Becquerel rays, or β-rays, emitted by radioactive substances. As is well known, Kaufmann's results appeared unfavorable to relativity, a conclusion he articulated more fully in a longer essay published at the beginning of 1906 (Kaufmann 1906). The data aligned more closely with Abraham's theory, according to which the electron was assumed to be non-deformable. The issue thus seemed to be settled against the Lorentz–Einstein electron in favor of Abraham's spherical model. However, in March Planck (1906a) urged caution. The results of Kaufmann's experiments were not sufficiently precise to warrant a definitive refutation.

According to Planck (1906b), relativistic dynamics had the significant advantage of being derived without reliance on any specific model of the electron and was therefore worth exploring. At this juncture, the young Einstein himself clearly regarded experiments on fast-moving electrons as the only means of testing the theory. In August 1906 he submitted a paper (Einstein 1906) proposing a new experimental method to determine the ratio of transverse to longitudinal electron mass at high velocities using electrostatic deflection alone. The paper was published in issue 21 of the *Annalen der Physik*. In the same issue, a contribution by Johannes Stark (1906), submitted in September 1906 , also appeared. It is therefore plausible that Einstein read Stark's paper upon receiving his copy of the *Annalen* issue. He may then have realized that wave sources were indeed available to test the transverse part of the relativistic Doppler effect.

2.1 Stark's Canal–Ray Experiments and Velocity–Dependent Spectral Effects

Stark could rely on decades of spectroscopic work showing that excited gases and vapors do not produce continuous spectra, but rather sharp spectral lines appearing at well-defined positions in a spectrograph (Hentschel 2002). The Zeeman splitting of such lines in a magnetic field was found to be consistent with a charge-to-mass ratio equal to that of the electron, and the sense of the splitting indicated a negative charge. Within the framework of Lorentz's electron theory, it was therefore concluded that the 'centers' (*Zentren*) of emission responsible for line spectra are negatively charged oscillating electrons (Stark 1906, 401). Stark's central aim was to identify the physical systems that serve as the 'carriers' (*Träger*) of different spectra, that is, the material systems bearing the electronic oscillatory processes responsible for line emission (402).

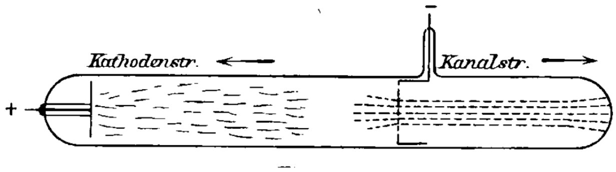

Figure 2: Discharge tube producing cathode rays and canal rays (Stark 1906, 405)

He conceived the carrier as a positive atomic ion containing bound negative electrons executing elastic oscillations about equilibrium positions. Radiation was attributed to these accelerated charges, and spectral lines were identified with their characteristic oscillation frequencies; the sharpness and reproducibility of the lines were taken as empirical evidence for stable intrinsic atomic periodicities. The distinction between 'centers' and 'carriers' is crucial to Stark's theory, since it allows the physical state of the carrier to influence the behavior of the oscillating centers.

Stark's experimental investigations begin with a gas-filled discharge tube, typically containing hydrogen (fig. 2). When an electrical discharge is applied, the discharge current is largely carried by fast negative electrons, which are accelerated by the electric field toward the anode. As these electrons traverse the gas, they undergo collisions with neutral atoms or molecules. In sufficiently energetic collisions, electrons are knocked out of atoms, producing positive ions, that is, "atoms that have lost one or several negative electrons through ionization" (Stark 1906, 402). These ions are accelerated toward the cathode through a potential drop V concentrated in the cathode fall, which sets the velocity scale of the moving ions. If the cathode is perforated, a fraction of the ions passes through the holes and continues beyond the cathode with approximately rectilinear motion, forming a beam propagating away from it. These beams of positive ions are known as canal rays (*Kanalstrahlen*), named after the 'canals' in the cathode through which they pass (403).

When accelerated toward the cathode, the positive ions emit characteristic spectral radiation in all directions as a result of excitation processes in the discharge. Stark analyzed this radiation using a prism spectrograph. The emitted light entered the instrument through a narrow slit, which selected a well-defined direction of propagation (longitudinal or transverse with respect to the ion motion). After the slit, the light is rendered approximately parallel and passed through a glass prism, which separates different wavelengths λ by refraction; the dispersed radiation is finally recorded on a photographic plate. In the case of hydrogen, Stark took the Balmer series as empirically given, that is, as a set of well-defined spectral lines $\mathrm{H}\alpha$, $\mathrm{H}\gamma$, ... (417). Whether the emitting system consisted of neutral hydrogen in a discharge tube or of hydrogen ions in canal rays, the same characteristic lines reappeared. When the emitting ions moved along the line of sight of the spectrograph (toward b or c in fig. 3), Stark observed that the entire pattern of spectral lines was displaced toward longer wavelengths (redshift) for receding motion (toward c), and toward shorter wavelengths (blueshift) for approaching motion (toward b). The magnitude of this Doppler displacement increased with the ratio v/c:

$$\frac{\Delta\lambda}{\lambda} \sim \pm\frac{v}{c}.$$

Stark concluded that sharp line spectra (*Linienspektrum*) are emitted by individual atomic ions in translational motion. By contrast, the *band spectrum* (*Bandenspektrum*)—consisting of groups of closely spaced lines forming characteristic bands—exhibited no

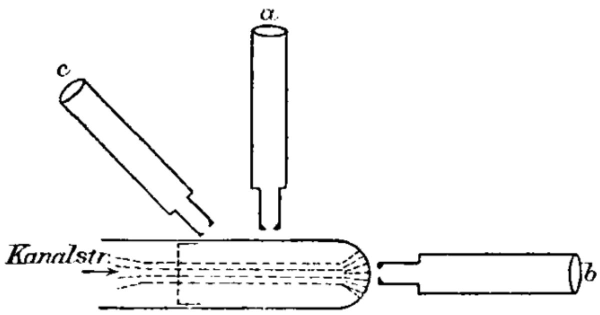

Figure 3: Set up for observing the Doppler shift of canal-ray spectral lines, with spectrographs aligned parallel and perpendicular to the direction of propagation (Stark 1906, 410)

measurable Doppler displacement. Stark therefore attributed band spectra to neutral atoms or molecular aggregates formed in recombination processes, whose translational velocities are much smaller than those of the canal-ray ions (Stark 1906, 426).

In the first two parts of his paper, Stark established the ordinary first-order Doppler effect proportional to v/c and concluded that "[t]he band spectrum and the line spectrum of hydrogen do not have the same carrier" (414). In part III, he raised a further question: whether an additional displacement of spectral lines might exist that depends only on the magnitude of the ion's velocity rather than on its direction. Any such effect would necessarily be proportional to v^2/c^2, since linear terms change sign when the direction of motion is reversed, whereas quadratic terms do not (409f.):

$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{2}\frac{v^2}{c^2}.$$

To test for such a direction-independent effect, Stark arranged observations perpendicular to the direction of ion motion (the spectrograph a in fig. 3). In this transverse configuration, the classical longitudinal Doppler effect vanishes by symmetry, since there is no velocity component along the line of sight.

Stark interpreted any residual shift as potentially dynamical in origin, arising from a velocity-dependent "modification of the electromagnetic forces between the electrons, which is measured by even powers of the ratio v/c" (449). In Stark's model, the ion as a 'carrier' is not a rigid body but a physically deformable system, whose internal state can change with its motion and environment (449). As the translational velocity of the ion increases, the amplitudes of the internal 'centers' of emission (the electrons) were assumed to increase, since the strong electric fields required to accelerate the ions were thought to excite the bound electrons into oscillations of larger amplitude. Moreover, Stark speculated that radiation pressure acting on the oscillating electrons, the finite propagation speed of electromagnetic interactions, or deformation of the oscillatory system at high velocities might contribute to such effects. On this view, the combined action of increased electron amplitudes and radiation pressure could produce a physical deformation of the carrier, which Stark investigated as a possible mechanistic cause of wavelength shifts.

Stark reported tentative empirical indications consistent with this picture, noting a red shift of the midpoints of certain spectral lines with increasing ion velocity—for example, a displacement of about 0.42 Å for the Hγ line at a cathode fall of 7500 Volts (450). He emphasized, however, that while the attainable ion velocities were already sufficient to produce an observable longitudinal Doppler effect, which is first order in

v/c, they were still insufficient, in practice, for the transverse effect proportional to v^2/c^2 to be unambiguously isolated. In addition, he stressed the extreme experimental difficulty of ensuring exact transverseness. The slightest radial component would swamp the transverse effect. In particular, he calculated that a misalignment of only $1°59'$ would suffice to generate a spurious red shift of comparable magnitude through the ordinary longitudinal Doppler effect. For these reasons, Stark explicitly characterized these observations as orienting indications rather than as conclusive experimental confirmation (Stark 1906, 450f.).

2.2 Einstein and Stark's Second–Order Effect as a Test of Time Dilation

At that time, Einstein's new dynamics of free electrons was under attack. The Einstein–Planck approach to electron dynamics was criticized by Ehrenfest (1907): since non-spherical electrons would, in principle, behave differently from spherical ones, the absence of a definite electron model was taken to be a defect rather than a virtue Einstein (1907a), however, was not particularly impressed by this objection. He famously emphasized that relativity was not a complete theory, but merely imposed kinematical constraints on admissible theories. Einstein did not develop a theory of the electron, but modified the equations of motion of a charged particle in general so as to make them Lorentz invariant. After coming across Stark's (1906) paper toward the end of 1906, Einstein may have quickly realized that this work opened the possibility of a more direct test of the new kinematics itself, without recourse to electron dynamics. He addressed this issue in a paper submitted on March of 1907.

Stark's experiments showed that wave sources moving at very high velocities were in fact available: the positive ions forming canal rays emit line spectra that exhibit a longitudinal first–order Doppler effect, that is, an effect proportional to v/c due to their motion. As we have seen, Stark also attempted to detect an additional second–order effect, proportional to v^2/c^2; however, the experimental setup, not specifically designed for this purpose, was insufficient to yield a reliable result. Nevertheless, it was shown that, in principle, it was possible to decide whether the spectral lines of fast–moving ions exhibit a redshift when they are observed spectroscopically at right angles to the direction of motion. Einstein's aim was to show that the principle of relativity, together with the principle of the constancy of the velocity of light, suffices to account for the effect in question (Einstein 1907b, 197). It is worth noting, however, that Einstein did not present Stark's work as a test of the relativistic wave equation as a whole, but rather as a test specifically of time dilation, since in the transverse case the effect depends solely on the time transformation.

Referring to his earlier 1905 paper, Einstein reminds his readers that in relativity theory a uniformly moving clock runs more slowly, when judged from a 'stationary' system, than when judged by an observer co-moving with the clock. Einstein appears implicitly to assume that any periodic system passing through identical phases can be regarded as a clock. If ν_0 denotes the frequency defined as the number of periods N divided by the time interval $\Delta t'$ measured in the co-moving system K', and ν denotes the frequency defined as the same number N divided by the coordinate time interval Δt measured in a system K relative to which the atom is moving, then, since $\Delta t = \gamma\,\Delta t'$, special relativity predicts:

$$\frac{\nu}{\nu_0} = \sqrt{1 - \frac{v^2}{c^2}}, \tag{1}$$

Testing this relation requires clocks that can be accelerated to very high velocities without compromising their accuracy. Direct experimental verification using mechanical clocks is therefore likely to remain unattainable, since the velocities that can be imparted to such devices are negligible in comparison with the speed of light. Nature, however, provides systems that effectively function as clocks and that can be accelerated, by means of an electric field, to extremely high speeds: "The atom ion of the canal rays, which emits and absorbs radiation of definite frequencies, is therefore to be regarded as a rapidly moving clock, and the relation just given is thus applicable to it" (Einstein 1907b, 198).

One might object that the frequency ν_0 of the fast-moving ion cannot be measured by a co-moving spectrograph. However, according to Einstein, there was sufficient evidence to support the claim that, whether the emitting system consisted of neutral hydrogen in a discharge tube or of hydrogen ions produced in canal rays, the same characteristic spectral lines reappeared. This was taken as strong evidence that the Balmer series expresses a stable property of the hydrogen system, rather than something contingent on the manner in which it was produced. Einstein could then point out that the corresponding frequencies are determined solely by the nature of the ion—that is, ions of the same species yield the same frequency ν_0 when measured with a spectrograph at relative rest:

> However, one has to take into consideration that the frequency ν_0 (for the co-moving observer) is unknown, so that the above relation is not accessible to direct experimental verification. But, it may be assumed that ν_0 is also equal to the frequency emitted or absorbed by the same ion while at rest, and this for the following reason. From the fact that one and the same line spectrum is formed under very different conditions, we conclude that the frequency ν_0 does not depend on interactions between moving ions and the stationary gas, but is a characteristic of the ion only; from this one directly concludes with the help of the principle of relativity that ν_0 must equal the frequency of radiation emitted or absorbed by an ion at rest. (198)

Einstein then assumes that ions of a given species can be treated as identical systems: the recurrence of the same sharp spectral lines under widely varying experimental conditions supports the assumption that their characteristic frequencies ν_0 are intrinsic properties of the ions themselves and do not depend on interactions with the surrounding medium. That is, all ions of the same species exhibit the same spectral lines when at relative rest. Since canal-ray ions move at very high velocities, any possible shift ν of the spectral lines with respect to ν_0 would thus become, at least in principle, empirically accessible.

The first–order Doppler effect arises from the relative motion between source and observer and depends linearly on v/c. In classical theory it does not presuppose any particular microphysical account of the emission process, nor does it require modifications of the internal dynamics of the emitter. In Stark's work, however, the second–order Doppler effect—that is, any frequency shift proportional to v^2/c^2 observed in a transverse configuration—could not be explained by simple relative motion along the line of sight. Stark therefore treated the effect as a genuinely dynamical modification of the 'carrier': he assumed that uniform motion produces a real change in the emission process of fast ions—a kind of reduction in the number N of oscillations completed during a *same time* interval (frequency contraction). Einstein explicitly rejected this dynamical explanation. Instead, he invoked the principle of relativity to support the assumption that uniform motion does *not* alter the internal oscillatory processes of the ion; the number N of oscillations associated with a given emission process is the same in all non-accelerated systems, but spread over *different* time intervals time dilation).

This assumption is the key to Einstein's reasoning. The number N of oscillations is fixed, and longitudinal Doppler components are excluded by definition. As a consequence, the remaining transverse Doppler effect, that is, the reduced observed frequency $\nu = N/\Delta t = \nu_0/\gamma$, can *only* be attributed to the transformation properties of the time coordinate between inertial reference systems in uniform relative motion, $\Delta t = \gamma \Delta t'$, as prescribed by Einstein's new kinematics. The transverse Doppler effect thus serves as a test of the time–dilation relation. Expanding eq. (1) in a series, Einstein (1907b, 197) obtains, to second order in v/c,

$$\frac{\nu - \nu'}{\nu'} \approx -\frac{1}{2}\left(\frac{v}{c}\right)^2 , \tag{2}$$

which quantifies this deficit. Equation (2) therefore provides a direct theoretical expression for the sought second–order effect in the radiation emitted by fast canal–ray ions.

Equation (2) can be tested experimentally by means of a spectrograph oriented such that the motion of the emitting ions is perpendicular to the line of sight; in this configuration, all first–order Doppler contributions vanish. A spectrograph registers the wavelength at which a given spectral line appears after dispersion. The observed position of a spectral line therefore determines its wavelength λ, and, via the relation $\lambda = c/\nu$, its frequency ν. By comparing the wavelength λ of the line emitted by the moving ions with the reference wavelength λ_0 measured for ions at rest, the spectrograph allows one to determine the fractional shift $(\lambda - \lambda_0)/\lambda_0$, which is equivalent (up to a change of sign) to $(\nu - \nu_0)/\nu_0$. Comparing the relativistic prediction with Stark's experimental results, Einstein noted that the numerical values reported by Stark exceeded the expected effect by more than an order of magnitude. However, he expressed skepticism regarding the reliability of the existing measurements (198). Nevertheless, in correspondence with Stark in April 1907, Einstein expressed the hope that it might eventually become possible to detect such second–order effects experimentally with greater accuracy (Einstein to Stark, Apr. 13, 1907; CPAE, Vol. 5, Doc. 45).

2.3 The Transverse Doppler Effect in Einstein's 1907/1908 Jahrbuch Paper

Stark was the editor of the *Jahrbuch der Radioaktivität und Elektronik*. In September, he invited Einstein to contribute a comprehensive review article on the theory of relativity, Einstein agreed to "deliver the desired report" (Einstein to Stark, Sep. 25, 1907; Vol. 5, Doc. 58). Stark assisted him by supplying relevant literature that the young Einstein could not easily access (Einstein to Stark, Oct. 7, 1907; Vol. 5, Doc. 61). The paper was ultimately submitted on December 4, 1907 and appeared in the *Jarbuch* at the end of January 22, 1908. Beyond synthesizing his earlier relativity work, the Einstein (1908) incorporated several recent developments, including Laue's (1907) derivation of the drag coefficient, Planck's (1906a) reformulation of relativistic dynamics, and related advances in the treatment of thermodynamics within the relativistic framework (Planck 1907). As expected, Einstein also used the 1908 review to discuss Stark's (1906) observations as a possible means of testing the new kinematics.

A distinctive feature of Einstein's new presentation is that the transverse Doppler effect is no longer treated primarily as a consequence of the Lorentz-invariant wave equation, but is instead relocated within the kinematical framework of the theory.

Stark's work on the second-order transverse Doppler effect is mentioned explicitly in the kinematical part I of Einstein's paper, where time dilation is discussed as one of the consequences of the new kinematics (Einstein 1908, 422). In the electrodynamic part II, by contrast, Einstein derives the Lorentz-invariant wave equation and hence the relativistic Doppler effect without explicitly distinguishing between longitudinal and transverse cases. Although Stark is not mentioned in this context, Einstein does point out that the relativistic Doppler effect can be tested by measuring the frequency shift of light emitted or absorbed by canal rays, which depends both on the velocity of the ions and on the direction in which the radiation is observed (Einstein 1907a, 425). At the time, canal rays were essentially the only laboratory sources capable of reaching velocities sufficiently large for such effects to be spectroscopically accessible.

In this way, the discussion of the transverse Doppler effect is conceptually shifted from the domain of optics and electrodynamics to that of kinematics (Einstein 1908, 421f.). The presentation of the time-dilation effect here differs significantly from that of the 1905 paper: it places far less emphasis on algebraic derivation and is instead oriented toward clarifying the physical interpretation and the prospective experimental testability of the effect. Einstein considers again a clock U' permanently at rest at $x' = 0$, at the origin of the moving system K', which moves uniformly with velocity v relative to K along the x-axis. The clock is modeled as a physical periodic system with an intrinsic rest frequency ν_0. The intrinsic frequency ν_0 characterizes the clock as a physical system and is assumed to be independent of its state of uniform motion. Accordingly, the successive ticks of the clock are invariantly labeled by the integers $n = 1, 2, 3, \ldots$, corresponding to the completion of successive periods of the same physical process. In this sense, the number N of ticks associated with a given physical process used as a clock is assumed from the outset to be invariant.

Since the clock U' is at rest in K', that is, since $\Delta x' = 0$, its successive ticks occur at equal intervals of the time coordinate t':

$$t'_n = \frac{n}{\nu_0},$$

where the relation between the discrete tick number n and the continuous time coordinate t' is fixed by the convention that assigns the rate ν_0 to the clock. Accordingly,[5] the time instants at which successive periods are completed in the system K' are

$$t'_1 = \frac{1}{\nu_0}, \quad t'_2 = \frac{2}{\nu_0}, \quad t'_3 = \frac{3}{\nu_0}, \quad \cdots \quad t'_n = \frac{n}{\nu_0}.$$

Einstein then asks how fast this same clock runs when viewed from the system K. To answer this question, he determines the coordinate times in K at which the successive periods of the moving clock are completed. These times are obtained by applying the Lorentz transformation to the time coordinate of K':

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

Since the clock U' remains permanently at rest at the origin of K', one always has $x' = 0$. The coordinate time in K corresponding to the completion of the nth period is therefore

$$t_n = \gamma t'_n = \frac{\gamma}{\nu_0} n.$$

[5] In the following I also rely on (Einstein 1910, 131f.) to clarify Einstein's otherwise somewhat elliptical reasoning.

Accordingly, the successive periods of the moving clock U' are completed, in the system K, at the time instants

$$t_1 = \gamma \frac{1}{\nu_0}, \quad t_2 = \gamma \frac{2}{\nu_0}, \quad t_3 = \gamma \frac{3}{\nu_0}, \quad \cdots \quad t_n = \gamma \frac{n}{\nu_0}.$$

Comparing the coordinate-time differences $t_n - t_1$ and $t'_n - t'_1$ assigned to the same 1rs and nth tick of U' in the two systems K and K', one finds that

$$\Delta t = \gamma \, \Delta t'.$$

The frequency of the clock U' at rest in K' is ν_0. When the same clock is described from the system K, the same number N of periods is distributed over a longer elapsed coordinate-time interval $\Delta t = \gamma \, \Delta t'$. From the standpoint of K, U' appears therefore to have reduced frequency ν:

$$\nu = \frac{N}{\Delta t} = \frac{N}{\gamma \, \Delta t'} = \nu_0 \sqrt{1 - \frac{v^2}{c^2}}. \tag{3}$$

In this precise sense, the moving clock runs ‘more slowly’ than an identical clock at rest in K.

This statement, however, must be treated with some caution. As one can see, Einstein’s argument rests on the fundamental assumption that clocks are *physically identical* across non–accelerated reference frames, that is, that they possess the same intrinsic frequency ν_0 independently of their uniform motion. Under this assumption, the number N of periods is taken to be invariant, and time dilation is attributed entirely to the expansion of the elapsed coordinate-time interval Δt. One of the most significant novelties of Einstein’s 1908 paper is that he made this assumption explicit for the first time: “the rate of a clock does not undergo any permanent change if such objects are set in motion and then brought to rest again” (Einstein 1908, 420; fn. 1). If the clock U' were carefully brought to rest and placed next to any of the clocks U at rest in K, the two would run at the same rate ν_0. This requirement may therefore be taken as a criterion for a ‘good’ clock, namely one whose rate is not permanently affected by its past history.

To test the relation eq. (3) empirically, one requires the existence of a physical system that actually behaves in this way, that is, a real clock capable of reproducing the same time units in different non–accelerated reference frames. *If* such a system exists, *then* the consequences of the new kinematics for time become empirically accessible. As we have seen, nature offers objects that possess the character of ideal clocks, namely ions emitting spectral lines:

> The formula $\nu = \nu_0 \sqrt{1 - \frac{v^2}{c^2}}$ admits of a very interesting application. Mr. J. Stark showed in the previous year that the ions forming canal rays emit line spectra, by observing a displacement of spectral lines that is to be interpreted as a Doppler effect. Since the oscillation process that corresponds to a spectral line is to be considered an intra-atomic process *whose frequency is determined by the ion alone*, we may consider such an ion as a clock of a certain frequency ν_0, which can be determined, for example, by investigating the light emitted by *identically constituted* ions which are at rest relative to the observer. The above consideration shows, then, that the effect of motion on the light frequency that is to be ascertained by the observer is not completely given by the [longitudinal] Doppler effect. The motion also reduces the (*apparent*) proper frequency of the emitting ions in accordance with the relation given above. (422; my emphasis)

This passage makes clear that the premise of the argument is that ions of the same species are taken to be physically identical when compared at relative rest; they are all 'identically constituted.' By 1908, spectroscopy had established with great precision that atoms and ions of the same species emit sharp, reproducible spectral lines whose frequencies are invariant across laboratories and experimental conditions, provided the emitters are compared at rest. This empirical stability strongly suggested that atomic emission frequencies ν_0 are intrinsic properties of the emitters, not contingent on macroscopic conditions or preparation histories. Despite the lack of a theoretical explanation, for Einstein this made the atom, the "producer of spectral lines" (Einstein 1908, 459), uniquely well suited to function as a natural clock.

Since ions are assumed to be identical in all frames in uniform relative motion, the frequency shift of fast-moving ions measured by a spectrograph at rest cannot be attributed to a change in the ions themselves. In the longitudinal case, the observed shift may still be explained by motion along the line of sight. By contrast, for a spectrograph oriented perpendicular to the direction of motion, no such explanation is available. In this case, the observed redshift must be understood as a consequence of time dilation alone. For this reason, Einstein described the redshift as *apparent*.[6] The reduction in frequency is frame dependent and disappears entirely for a spectrograph co-moving with the ion. The adjective *apparent* was likely chosen to contrast the relativistic account with Stark's dynamical interpretation.

As we have seen in section 2.1, in Stark's view, the motion of the ion produces a *real* frequency contraction, that is, a modification of the emitting system's intrinsic oscillation frequency ν_0, such that the ion completes a smaller number N of oscillations in the *same* time interval $\Delta t'$ in the moving frame. In Einstein's kinematical interpretation, by contrast, the intrinsic periodic process remains unchanged, since it is fixed by the same physical emission mechanism. The number N of oscillations associated with a given emission process is invariant. The observed redshift is therefore not due to a change in the emitter's frequency ν_0, but to time dilation: relative to a frame K in which the ion is moving the same number of oscillations N is distributed over a *longer* time interval $\Delta t = \gamma \Delta t'$ than in the rest frame K'. The frequency shift is thus explained by the relativistic transformation of the time coordinate, not by a dynamical modification of the source. However, Einstein clearly regarded this 'apparent' effect as an unavoidable consequence of the theory and as one that could, in principle, be empirically detected.

Since the effect is of second order in v/c, it requires clocks moving at sufficiently high velocities, a condition satisfied by ions in canal rays. If two identical spectrographs are at rest with respect to the source but operate for different exposure times, the longer exposure merely collects a larger number N of wave crests: both the elapsed time and the number of accumulated oscillations increase proportionally. As a result, the inferred frequency ν_0 remains unchanged, and the spectral lines appear at the same position; only the intensity varies. In the relativistic case, by contrast, the crucial point is that the same physical emission process is described from two different non-accelerated

[6] If a transversely moving source produces a redshift $\nu = \gamma^{-1}\nu_0$, then a transversely moving spectrograph relative to a source at rest produces the inverse effect, a blueshift $\nu = \gamma\nu_0$. The two situations are completely symmetrical in principle, but only the redshift from a transversely moving source is usually referred to as the transverse Doppler effect. While fast-moving atoms are readily available in canal rays, fast-moving spectrographs are not experimentally feasible. Nevertheless, this symmetry shows that the transverse Doppler effect cannot be attributed to a real, direction-dependent dynamical deformation of the atom.

frames. The same number of oscillations N associated with a given emission process is thus referred to different elapsed times, $\Delta t = \gamma \Delta t'$. The difference in the temporal interval over which the same oscillations N are distributed necessarily entails a change in the observed frequency ν. Through the relation $\lambda = c/\nu$, this difference in temporal rate is translated into a difference in wavelength, which the spectrograph at rest in K registers directly as a redshift of the atom's spectral line.

3 Ritz and the Transverse Doppler Effect as an *Experimentum Crucis*

Replying to a letter from Sommerfeld that is no longer extant, Einstein expresses strong interest in having a canal–ray experiment carried out and welcomes Sommerfeld's willingness to involve Peter Paul Koch (at that time an assistant of Wilhelm Röntgen in Munich) in testing the transverse Doppler effect. Einstein nevertheless betrays some caution as to whether Koch would actually carry out the experiments (Einstein to Sommerfeld, Jan. 14, 1908; CPAE, Vol. 5, Doc. 73). He notes that Stark had already informed him some months earlier of his intention to undertake the same investigation, although Stark had since written to Einstein repeatedly without again mentioning the experiment (Einstein to Sommerfeld, Jan. 14, 1908; Vol. 5, Doc. 73). The letter to Sommerfeld also shows that this was something of a side issue. The main point of debate concerned the empirical test of the variability of the electron mass investigated by Kaufmann. Indeed, Einstein's 1908 paper devotes the entire §10 to a discussion of Kaufmann's experiments and to a comparison between the different predictions of the Abraham electron, the Einstein–Lorentz electron, and the Bucherer electron (Walter 2018).

These electron models were all constructed within a theoretical context shaped by the assumed validity of Maxwellian electrodynamics and by constraints imposed by optical and electrodynamic phenomena, even though they differed markedly in their interpretations of the status and significance of the Lorentz transformations. A more radical challenge to relativistic kinematics was posed by Ritz, who in the winter of 1907–1908 moved from Göttingen to Tübingen, where he worked with the experimentalist Friedrich Paschen. Regarded as a rising star of European physics for his work in spectral theory (Hentschel 2012), Ritz became increasingly skeptical of Lorentz–Maxwell electrodynamics after a stay in Leiden with his close friend Ehrenfest (Martinez 2004). His major polemical paper appeared in the *Annales de chimie et de physique* in February 1908, only a few weeks after the publication of Einstein's 1908 review article. Like Einstein, Ritz (1908a, 147f.) was skeptical of the reliability of Kaufmann's experiments. However, for him, the difficulties involved in constructing a suitable model of the electron and in accounting for the velocity dependence of its mass were not isolated technical problems but rather symptoms of a deeper flaw in Maxwell–Lorentz electrodynamics itself.

Lorentz–Maxwell electrodynamics assumes the existence of an absolute system of ether coordinates, taken to be independent of the motions of matter, with respect to which light moves with velocity c.In order to reconcile this framework with the failure of the Michelson–Morley and other ether-drift experiments, it became necessary to eliminate the absolute system by means of increasingly implausible auxiliary hypotheses (148). As Ritz complained, this strategy, pursued consistently by Lorentz and Einstein, required modifying the principles of kinematics themselves: abandoning absolute time and rigid bodies, and treating the parallelogram rule for the composition of velocities as a mere first approximation, valid only at low speeds. However, "[i]t would be regrettable, for the economy of our thinking, if we were forced to admit such complications" (Ritz 1908a, 148). By abandoning Maxwellian electrodynamics in favor of a description based solely on retarded potentials, Ritz was led naturally to a ballistic theory of light, in which radiation propagates with the velocity of its source, $c \pm v$.

Ritz (1908c, 203) was well aware that the approaches of Lorentz and Einstein were not identical. Lorentz was committed to the reality (*réalité*) of length contraction and time dilation, whereas for Einstein lengths and times only appear (*semblera*) to be contracted and dilated, while true lengths and times remain invariable (203). Nevertheless, this difference appeared to him to be marginal, since both approaches led to the same observable consequences Ritz (1908b, 213). After returning to Göttingen in the spring of 1908, Ritz, in correspondence with Paschen and as a leading expert in spectroscopy, naturally singled out the transverse Doppler effect in canal rays as an experimentally decisive test case capable of discriminating between classical and the new kinematics.

> When I was in Tübingen, you had a hydrogen tube in operation for canal-ray investigations. I would like to present to you a problem which is of the greatest importance for the question of the principle of relativity, and thus for the whole of electrodynamics. According to the Lorentz–Einstein theory of relativity, the wavelength emitted by a moving atom must change not only in the direction of motion in accordance with the Doppler principle; when observed perpendicular to the direction of the velocity, there must also occur a red shift of magnitude $\frac{1}{2}\left(\frac{v}{c}\right)^2\lambda$ (c = speed of light). For H_γ and $v = 1000$ km/sec, this would amount to about 0.02 Å.
> In observations of canal rays, one would therefore observe an apparent shift of the line by less than 0.02 Å, since the stationary and moving intensities could not, of course, be separated. With fine lines, however, and if one had the normal and the shifted spectrum on the same plate, this displacement could be detected even without a large grating. Would it not be possible to arrange matters so that the question of the existence of this effect could be answered with certainty?
> If the effect exists, then it is the end of our universal time, of the parallelogram of velocities, and of the whole of kinematics. I hope the effect does not exist—that would be much nicer. But since this is a genuine *experimentum crucis*, and since you may perhaps, despite the great difficulty, find a way to realize the matter, I wished to communicate it to you. (Ritz to Paschen, Jun. 14, 1908; Ritz 1911, 523f.)

The null result of the Michelson–Morley experiment could be explained equally well by assuming a ballistic character of light emission. The transverse Doppler effect, by contrast, cannot be accommodated within such an emission theory. Thus, Ritz was the first to characterize explicitly the transverse Doppler effect as an *experimentum crucis* for discriminating between his emission theory and Lorentz–Einstein relativistic kinematics itself, independently of more indirect consequences of the latter, such as the velocity dependence of the electron's mass. In all non-relativistic theories, including emission theories, a longitudinal Doppler effect can be accounted for, even though the underlying explanations differ. By contrast, only Lorentz–Einstein relativity predicts a genuinely relativistic Doppler component transverse to the direction of motion.[7]

After the meeting of the German Association of Natural Scientists and Physicians in Cologne in September 1908, many physicists felt compelled to favor relativity, driven both by Minkowski's (1908, 1909) four–dimensional reformulation of the theory and by

[7]Although the transverse Doppler factor can be retroactively read into Lorentz's equations, Lorentz never identified, interpreted, or proposed it as a physical effect. The effect is not mentioned in Lorentz's (1916) 1909 Columbia lectures.

Bucherer's (1908) alleged experimental confirmation of the Lorentz–Einstein electron. However, Ritz's subsequent correspondence with his friend Ehrenfest suggests that he remained unconvinced (Staley 2008, 268–271): "Minkowski forcefully promotes the principle of relativity *à la* Einstein. Hopefully this nonsense will disappear in 10 years. A wholly miserable makeshift [*Auskunfts-mittel*]. One could salvage any theory, no matter how false, in such a way" (Ritz to Ehrenfest, Dec. 17, 1908, cit. in 270f.; translation modified). Rather than tinkering with the classical kinematical framework, Ritz (1908c) believed that many of the difficulties of contemporary physics, including the so-called ultraviolet catastrophe, could be resolved by reconstructing the foundations of electrodynamics through the abandonment of the ether and the exclusive use of retarded potentials.

Einstein (1909b) was the first to offer a systematic reply to this line of criticism, prompting Ritz's (1909b) rejoinder; Ritz and Einstein (1909) ultimately agreed to disagree. Ritz maintained that irreversibility (the exclusion of the advanced potentials) must be imposed at the level of the fundamental electrodynamic laws, whereas Einstein held that it emerges only at the statistical level. In his March 1909 habilitation lecture on the principle of relativity in optics, Ritz (1909a) reiterated the stark dilemma facing physics at that time: (a) to preserve Maxwell electrodynamics and the wave theory of light with a source-independent velocity c at the price of adopting a new kinematics, or (b) to preserve the classical kinematical framework by radically modifying electrodynamics in the direction of an emission theory of light, in which fictitious light corpuscles would travel with velocities $c \pm v$. Two months after Ritz's death, in September 1909, Einstein, in his Salzburg lecture on the constitution of radiation (Einstein 1909a), outlined, without mentioning Ritz, a contrasting program. Whereas Ritz sought to preserve classical kinematics and the continuity of radiation by abandoning the constancy of the speed of light, Einstein instead accepted the granular character of radiation and upheld the universal constancy of the speed of light by introducing a new kinematics.

4 Conclusion

While struggling with the problem of radiation toward the end of 1909, Einstein (1910) wrote a review paper on relativity, published in French in two installments in the *Archives des sciences physiques et naturelles*. By his own admission, the paper contained nothing physically new (Einstein to Laub, Aug. 27, 1910; CPAE, Vol. 5, Doc. 224). Nevertheless, at least one conceptual novelty can be identified. Einstein explicitly addresses the question "What is a clock?" (Einstein 1910, 21). Einstein famously defined a clock as any periodic system completely isolated from external influence that repeatedly passes through identical phases, such that—by the principle of sufficient reason—each period is taken to be identical to any other: "We therefore postulate that two identical phenomena have the same duration. The perfect clock thus defined plays, for the measurement of time, a role analogous to that of the perfect rigid body in the measurement of lengths" (21; fn. 1). After identifying the beginning and the end of a process, one can count the number N of identical cycles that occur. If the clock takes the form of a mechanism equipped with hands, completed cycles can be labeled by the integers $n = 1, 2, 3, \ldots$ via the positions of the hands. Assuming a stable intrinsic frequency of the clock ν_0 as a unit of time, this counting perspective can be translated into a measuring perspective. A clock at rest in a co-moving system directly measures the time coordinate of that system, such that the time coordinate of the nth tick is given by $t_n = n/\nu_0$.

One may then raise the separate question of whether systems exist in nature that realize the ideal of a perfect clock, that is, systems that ensure the physical stability of the frequency and therefore of the time unit. In classical physics, two objects could never be identical in every respect, since a complete physical description would, in principle, require infinitely many parameters, allowing systems to differ in arbitrarily small details. This is precisely why Einstein's appeal to atomic or ionic processes in the section dedicated to time dilation is epistemologically significant (Pierseaux 2003). Spectroscopy provides strong empirical evidence that atoms and ions of the same species exhibit the same characteristic frequencies when compared at rest, regardless of how they were previously accelerated: the number of oscillations N is the same for the identical emission process. Thus, these systems therefore realize, in nature and to a high degree of accuracy, Einstein's definition of perfect clocks: "Since the oscillatory phenomena that give rise to a spectral line must be regarded as intra-atomic phenomena whose frequency [ν_0] is determined solely by the nature of the ions, we may take these ions to serve as clocks" (Einstein 1910, 132f.).

The proper frequency ν_0 of the oscillatory motion of the ions provides a means of measuring time t: "this frequency will be known if one observes the spectrum produced by ions of the same nature, but at rest with respect to the observer" (133). Ions can be accelerated in canal rays by electric fields. Einstein clearly believed that there was sufficient empirical evidence to justify the assumption that acceleration does not permanently affect ions, which were expected to exhibit the same spectral lines when measured by a co-moving spectrograph. If this assumption is granted, the theory predicts that "there is an influence of the motion on the source, which reduces the *apparent* [*apparente*] frequency of the ion" (133; my emphasis), as measured by a spectrograph when the motion of the source is perpendicular to the line of sight.

As suggested above, the use of the term *apparent* is likely intended to avoid confusion with Stark's interpretation of this 'influence' as a *real* dynamical contraction of the atomic frequency ν_0, that is, a reduction in the number of periods completed during the same time interval in the same frame. In Einstein's reading, by contrast, clocks retain the same intrinsic frequency ν_0. Since there is no relative motion along the line of sight, the observed frequency shift $\nu = \gamma^{-1}\nu_0$ can only be due to the fact that the same number N of periods is associated with different time intervals in different inertial frames:

$$\nu = \frac{N}{\Delta t} = \frac{N}{\gamma \Delta t'} = \frac{\nu_0}{\gamma} = \nu_0 \sqrt{1 - \frac{v^2}{c^2}}.$$

The Lorentz factor thus appears not because of a 'real' reduction in the number N of oscillations occurring during the same time interval. On the contrary, the premise of the argument is that N is the same in all inertial frames. The frequency shift $\nu = \gamma^{-1}\nu_0$ arises because, in a non–co–moving frame K, this same N is referred to a longer coordinate time interval, $\Delta t = \gamma \Delta t'$. The oscillations are therefore less densely packed in time in the non–co–moving frame, which manifests itself as a redshift without any change in the intrinsic emission process given by $\nu_0 = N/\Delta t'$. In this sense, the effect is 'apparent,' since it disappears entirely in the co–moving frame K'.

In the ensuing months, following the debate raised by Ehrenfest's paradox, Einstein realized that the terms 'apparent' and 'real' gave rise to misunderstandings (Einstein to Varićak, Feb. 24, 1911; CPAE, Vol. 5[10], Doc. 255a). Some regarded kinematical effects, such as 'time dilation,' as mere coordinate effects and therefore as 'apparent.'

By contrast, Stark's 'frequency contraction' was taken to be 'real' in a dynamical effect. To avoid confusion, Einstein suggested disentangling the conceptual pair real/apparent from kinematical/dynamical (Einstein 1911). Relativistic time dilation, although a kinematical effect, is both apparent and real. It is 'apparent,' since it disappears for a suitably chosen co-moving observer; yet it is *real*, since it cannot be eliminated for all non–co–moving observers at once. The 'apparent' change of frequency is 'real' in the sense that it would be absent in a rival theory.[8] As Ehrenfest pointed out, this is precisely the reason why, in his letter to Paschen, his friend Ritz[9] proposed the transverse Doppler effect as an *experimentum crucis* to decide between classical and relativistic kinematics[10]: "Whereas Einstein's theory *unconditionally* demands the existence of this effect [...][,] Ritz's emission theory *unconditionally* demands its nonexistence" (Ehrenfest 1912, 319; my emphasis).

As is well known, Einstein repeatedly insisted that the new kinematics is not a matter of the conventional synchronization of clocks. Once established, the Lorentz transformations are either true or false in the sense that they can be *confirmed* or *disconfirmed* through their empirically accessible consequences, provided that coordinates are interpreted as measurable by means of 'good' rods and clocks. The transverse Doppler effect is indeed one such consequence, and at the time it was the only one feasibly to be detected. Einstein's line of argument, disentangled from the historical details, may be reconstructed as follows:

1. *Empirical premise (spectral identity of atomic clocks at rest).* Atoms (or ions) of the same species, when compared at relative rest, exhibit the same intrinsic frequency ν_0, as evidenced by the reproducibility of their spectral lines.

2. *Physical premise (spectral identity of atomic clocks in uniform motion).* Uniform translational motion does not alter the internal oscillatory process responsible for emission. Hence, the number N of oscillations associated with a given emission process is the same in all non–accelerated inertial frames.[11]

3. *Experimental restriction (transverse configuration).* The observation is arranged so as to eliminate longitudinal Doppler components, that is, any contribution due to motion along the line of sight.

4. *Prediction.* A Doppler shift in the frequency $\nu_0 = N/\Delta t'$ (for an atom at rest in K') persists even in the transverse case, namely

$$\nu = \gamma^{-1}\nu_0.$$

[8]This case is by no means an *unicum* in the history of physics. A useful comparison can be drawn with stellar aberration in classical ether theory, which is likewise both *apparent* and *real*. It is apparent insofar as it disappears for a suitably chosen observer, yet real insofar as it gives rise to systematic, empirically detectable effects that cannot be eliminated for all observers at once. Over the course of the year, astronomers must therefore inevitably reorient their telescopes toward the *apparent* position of the stars, whose annual displacement traces ellipses, although, of course, their *real* positions have remained unchanged. Nevertheless, stellar aberration is undeniably a genuine physical effect that would not be expected in a theory of complete ether drag.

[9]The letter was later published in the 1911 edition of Ritz's collected works.

[10]In the absence of a direct confirmation of the light postulate, which would soon be provided by Sitter (1913).

[11]This premise corresponds to what is often called *boostability* (Brown 2005, 30, 81, 121). As discussed above, Einstein made this assumption explicit as a criterion for 'good' rods and clocks in (Einstein 1908, 420; fn. 1; 126; fn. 2 Einstein 1910).

5. *Explanation.* Since the number N of oscillations associated with a given emission process is invariant, the transverse Doppler effect is entirely a consequence of the relativistic transformation of time, that is, of time dilation:

$$\Delta t = \gamma \, \Delta t'.$$

In this form, the argument amounts at most to a provisional compromise. Whereas premise 3 is a definitional restriction built into the experimental arrangement, Einstein did not yet possess a genuine theoretical account of why atoms or ions behave in accordance with premises 1 and 2. At this stage, he could rely only on the overwhelming empirical evidence provided by spectroscopy.

It is well known that, beginning in the 1920s, Einstein increasingly acknowledged that a dynamical explanation of the periodic processes used as clocks would ultimately be required (Einstein 1921, 1923, 1924, 1926, 1949). From a more fundamental standpoint, clocks may be regarded as particular solutions of the underlying dynamical equations, with their behavior fixed by invariant parameters of the theory. Such parameters determine characteristic frequencies,[12] which in turn set the intrinsic periodicity of the admissible solutions. If the fundamental theory is Lorentz invariant, the same periodic solutions must occur in all co-moving systems, with the *same* proper frequency ν_0, whether atomic or otherwise. In the case of atoms, such a theory would thus provide a dynamical explanation of spectral identity of atoms—the empirical fact that identical atoms, when compared at relative rest, possess the same intrinsic frequency $\nu_0 = N/\Delta t'$ and emit the same spectral lines when measured by a spectrograph co–moving with them in the frame K'.

If such a theory were available, premises 1 and 2 would no longer be merely assumed but would be derived as consequences of the theory itself. Since premise 3 is merely definitional, there would then be no way to avoid conclusion 5, namely that prediction 4, the transverse Doppler effect, is genuinely an *apparent* coordinate effect. Thus, somewhat paradoxically, once a genuine dynamical explanation of the behavior of clocks is in place, one is forced to admit that clock retardation admits only a purely kinematical explanation: the transverse Doppler effect appears because $\Delta t = \gamma \Delta t'$ in the non-co-moving system K. To avoid this conclusion one could deny premises 1 and 2 and search for dynamical explanation of the *real* frequency contraction of the source. Somewhat ironically, this was precisely the strategy defended by Herbert E. Ives (Ives and Stilwell 1938) in connection with the experimental confirmation of the transverse Doppler effect in the late 1930s (Lalli 2013). However, Ives' neo-Lorentzian move does not amount to a dynamical account that would *explain* relativistic kinematics in the sense advocated by modern dynamicists (Brown 2005, vii); rather, it amounts to an ether-based dynamical conspiracy designed to *conceal* an underlying classical kinematics. At this point, however, it becomes unclear what a genuinely dynamical explanation of time dilation would amount to.

In my view, the historically motivated case for the dynamical approach ultimately rests on a misunderstanding. Einstein's plea for a dynamical theory of rods and clocks has often been interpreted as a demand for *explanation* of the new kinematics, whereas it was primarily motivated by the problem of its *confirmation.* The Lorentz transformations define the kinematical structure of special relativity. In order to test them empirically, one must employ rods and clocks as linked to the coordinate system.

[12]For example, a mass parameter fixes the Compton frequency $\nu_C = mc^2/h$.

Yet rods and clocks are themselves physical systems governed by dynamical laws, which are in turn required to invariant with respecto the Lorentz transformations. For this reason, kinematics and dynamics, from a strictly logical point of view, cannot be confronted with experience separately, but only as a whole.[13] From the point of view of explanation, however, the division of labour within this whole remains intact. The paper argues that the case of the transverse Doppler effect illustrates this point particularly clearly. Lorentz invariance of the laws of matter provides a *dynamical* explanation of why all atomic clocks of the same kind emit the same spectral lines at relative rest; once this premise is established, the transverse shift of spectral lines admits only a purely *kinematical* explanation as a time-coordinate effect: the same emission process is described using different time coordinates in different inertial frames. This 'apparent' difference has 'real' testable consequences that would not arise if the old kinematics held.

References

Acuña, Pablo. 2016. "Minkowski Spacetime and Lorentz Invariance: The Cart and the Horse or Two Sides of a Single Coin." *Studies in History and Philosophy of Modern Physics* 55:1–12.

Acuña, Pablo, and James Read. 2025. "Qualification and explanation in the dynamical/geometrical debate." *PhilSci Archive Preprint,* https://philsci-archive.pitt.edu/27604/1/qualification-accepted.pdf.

Bell, John Stewart. 1976. "How to teach special relativity." *Progress in Scientific culture* 1:1–13.

Born, Max. 1909. "Die Theorie des starren Elektrons in der Kinematik des Relativitätsprinzips." *Annalen der Physik,* 4th ser., 29:1–56.

Brown, Harvey R. 2005. *Physical Relativity: Space-time Structure from a Dynamical Perspective.* Oxford: Clarendon.

Brown, Harvey R., and Oliver Pooley. 2001. "The origins of the spacetime metric: Bell's 'Lorentzian pedagogy'and its significance in general relativity." In *Physics meets philosophy at the Planck scale: Contemporary theories in quantum gravity,* edited by Craig Callender and Nick Huggett, 256–272. Cambridge University Press.

———. 2006. "Minkowski Space-Time: A Glorious Non-entity." In *The Ontology of Spacetime,* edited by Dennis Dieks, 1:67–89. Amsterdam: Elsevier.

Brown, Harvey R., and James Read. 2022. "The Dynamical Approach to Spacetime Theories." In *The Routledge Companion to Philosophy of Physics,* edited by Eleanor Knox and Alastair Wilson, 70–85. London, UK: Routledge.

Bucherer, Alfred Heinrich. 1908. "Messungen an Becquerelstrahlen: Die experimentelle Bestätigung der Lorentz-Einsteinschen Theorie." *Physikalische Zeitschrift* 9:755–762.

Ehrenfest, Paul. 1907. "Die Translation deformierbarer Elektronen und der Flächensatz." *Annalen der Physik,* 4th ser., 23:204–205. Repr. in Ehrenfest 1959, Doc. 14.

———. 1909. "Gleichförmige Rotation starrer Körper und Relativitätstheorie." *Physikalische Zeitschrift* 10:918. Repr. in Ehrenfest 1959, Doc. 18.

[13] In this case, relativistic kinematics is not tested independently by observing rods and clocks, but rather indirectly through its role in guiding the construction of empirically adequate dynamical theories, such as relativistic quantum field theory. In the latter, the rest energy mc^2 fixes a fundamental energy scale and is associated, via Planck's relation, with the Compton frequency $\nu_C = mc^2/h$, thereby providing a dynamical basis for the stability of atomic spectral lines that can serve as clocks. The transverse Doppler effect is therefore still expected as a purely coordinate effect, since the invariance of ν_0 is 'secured.' In this sense, it serves primarily as a test of the Lorentz invariance of quantum field theory, rather than of relativistic kinematics in isolation. It may be that what dynamicists have in mind is precisely that the transverse Doppler effect is *explained* by the Lorentz invariance of relativistic quantum field theory. However, the specific details of the theory are largely irrelevant: any Lorentz-invariant theory of matter that secures a frame-independent intrinsic frequency scale would suffice. It is the *requirement* of Lorentz invariance that does the explanatory work (Lange 2016).

Ehrenfest, Paul. 1910. “Zu Herrn v. Ignatowskys Behandlung der Bornschen Starrheitsdefinition.” *Physikalische Zeitschrift* 11:1127–1129.

———. 1912. “Zur Frage nach der Entbehrlichkeit des Lichtäthers.” *Physikalische Zeitschrift* 13:317–319.

———. 1959. *Collected scientific papers.* Edited by Martin J. Klein. Amsterdam/New York: North-Holland / Interscience.

Einstein, Albert. 1905a. “Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?” *Annalen der Physik,* 4th ser., 18:639–641. Repr. in CPAE, Vol. 2, Doc. 24.

———. 1905b. “Zur Elektrodynamik bewegter Körper.” *Annalen der Physik,* 4th ser., 17:891–921. Repr. in CPAE, Vol. 2, Doc. 23.

———. 1906. “Eine Methode zur Bestimmung des Verhältnisses der transversalen und longitudinalen Masse des Elektrons.” *Annalen der Physik,* 4th ser., 21:583–586.

———. 1907a. “Bemerkungen zu der Notiz von Hrn. Paul Ehrenfest: ‘Die Translation deformierbarer Elektronen und der Flächensatz’.” *Annalen der Physik,* 4th ser., 22:206–208. Repr. in CPAE, Vol. 2, Doc. 44.

———. 1907b. “Über die Möglichkeit einer neuen Prüfung des Relativitätsprinzips.” *Annalen der Physik,* 4th ser., 23:197–198. Repr. in CPAE, Vol. 2, Doc. 41.

———. 1908. “Relativitätsprinzip und die aus demselben gezogenen Folgerungen.” *Jahrbuch der Radioaktivität und Elektronik* 4:411–462. Repr. in CPAE, Vol. 2, Doc. 47.

———. 1909a. “Über die Entwicklung unserer Anschauungen über das Wesen und die Konstitution der Strahlung.” Vorgetragen in der Sitzung der physikalischen Abteilung der 81. Versammlung Deutscher Naturforscher und Ärzte zu Salzburg am 21. September 1909. *Verhandlungen der Deutschen Physikalischen Gesellschaft* 7:482–500. Repr. in CPAE, Vol. 2, Doc. 60. Also pub. in: *Physikalische Zeitschrift* 10, 1909, 817–825.

———. 1909b. “Zum gegenwärtigen Stand des Strahlungsproblems” [in German]. *Physikalische Zeitschrift* 10:185–193. Repr. in CPAE, Vol. 2, Doc. 56.

———. 1910. “Le principe de relativité et ses conséquences dans la physique moderne.” Translated by Edouard Guillaume. *Archives des sciences physiques et naturelles* 29:5–28, 125–144. Repr. in CPAE, Vol. 3, Doc. 2.

———. 1911. “Zum Ehrenfestschen Paradoxon: Bemerkung zu V. Varićaks Aufsatz.” *Physikalische Zeitschrift* 12:509–510. Repr. in CPAE, Vol. 3, Doc. 22.

———. “Geometrie und Erfahrung.” Lecture before the Prussian Academy of Sciences, January 27, 1921. *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Halbband 1, 123–130.

———. 1923. “Grundgedanken und Probleme der Relativitätstheorie.” In *Les Prix Nobel en 1921-1922,* edited by Carl Gustaf Santesson, 1–10. Stockholm: Nobel Foundation. Nobel prize lecture, delivered before the Nordische Naturforscherversammlung in Göteborg July 11, 1923.

———. 1924. “Review of Elsbach, *Kant und Einstein* [Elsbach 1924].” *Deutsche Literaturzeitung* 45:1685–1692. Repr. in CPAE, Vol. 14, Doc. 321.

———. 1926. *Space-Time.* In *Encyclopædia Britannica,* 13th ed., edited by James Louis Garvin, 608–609. London/New York: Encyclopædia Britannica, Inc. Repr. in CPAE, Vol. 15, Doc. 148.

———. 1949. “Autobiographical Notes.” In *Albert Einstein, Philosopher-Scientist: Philosopher-Scientist,* edited by Paul Arthur Schilpp, 2–94. Evanston, M.: The Library of Living Philosophers.

Elsbach, Alfred Coppel. 1924. *Kant und Einstein: Untersuchungen über das Verhältnis der modernen Erkenntnistheorie zur Relativitätstheorie.* Berlin: de Gruyter.

Giovanelli, Marco. 2023. “Reality and Appearance: Einstein and the Early Debate on Reality of Length Contraction.” *European Journal for Philosophy of Science* 13.

Giuliani, Giuseppe. 2013. “Experiment and theory: the case of the Doppler effect for photons.” *European Journal of Physics* 34:1035–1047.

Hentschel, Klaus. 2002. *Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching.* Oxford: Oxford University Press.

———. 2012. “Walther Ritz’s theoretical work on spectroscopy, focussing on series formulas.” In *Le Destin Douloureux de Walther Ritz (1878–1909), Physicien Théoricien de Génie,* edited by Jean-Claude Pont, 129–156. Sion, Switzerland: Vallesia, Archives de l’Etat du Valais.

Ignatowski, Vladimir Sergeyevitch. 1910. “Der starre Körper und das Relativitätsprinzip.” *Annalen der Physik,* 4th ser., 34:607–630.

Ives, Herbert E., and G. R. Stilwell. 1938. “An Experimental Study of the Rate of a Moving Atomic Clock.” *Journal of the Optical Society of America* 28:215–226.

Janssen, Michel. 2009. "Drawing the Line between Kinematics and Dynamics in Special Relativity." *Studies in History and Philosophy of Science. Part B: Studies in History and Philosophy of Modern Physics* 40:26–52.

Kaufmann, Walter. "Über die Konstitution des Elektrons." Gesammtsitzung vom 16. November 1905. *Sitzungsberichte der Preußischen Akademie der Wissenschaften,* 949–956.

———. 1906. "Über die Konstitution des Elektrons." *Annalen der Physik,* 4th ser., 18:487–553.

Lalli, Roberto. 2013. "Anti-Relativity in Action: The Scientific Activity of Herbert E. Ives between 1937 and 1953." *Historical Studies in the Natural Sciences* 43:41–104.

Lange, Marc. 2016. *Because without Cause: Non-causal Explanations in Science and Mathematics.* New York: Oxford University Press.

Laue, Max. 1907. "Die Mitführung des Lichtes durch bewegte Körper nach dem Relativitätsprinzip." *Annalen der Physik,* 4th ser., 22:538–547. Repr. in Laue 1961, Vol. 1, Doc. 6.

Laue, Max von. 1961. *Gesammelte Schriften und Vorträge.* 3 vols. Braunschweig: Vieweg.

Lorentz, Hendrik Antoon. 1916. *The Theory of Electrons and its Applications to the Phenomena of Light and Radiant Heat.* A course of lectures delivered at Columbia University, New York, in March and April, 1906. 2nd ed. London: MacMillan.

Martinez, Alberto A. 2004. "Ritz, Einstein, and the Emission Hypothesis." *Physics in Perspective (PIP)* 6:4–28.

———. 2009. *Kinematics: The Lost Origins of Einstein's Relativity.* Baltimore: Johns Hopkins University Press.

Minkowski, Hermann. "Die Grundgleichungen für die elektromagnetischen Vorgänge in bewegten Körpern." *Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen.* Mathematisch-physikalische Klasse, 53–111.

———. 1909. "Raum und Zeit." *Jahresberichte der Deutschen Mathematiker-Vereinigung* 18:75–88. Repr. in Minkowski 1911, Vol. 2, 431–446. Also pub. in: *Physikalische Zeitschrift* 10, 1909, 104–111.

———. 1911. *Gesammelte Abhandlungen.* Edited by David Hilbert et al. Leipzig: Teubner.

Norton, John D. 2008. "Why Constructive Relativity Fails." *The British Journal for the Philosophy of Science* 59:821–834.

Pierseaux, Yves. 2003. "The Principle of Physical Identity of Units of Measure in Einstein's Special Relativity." *Physica Scripta* 68:C59.

Planck, Max. 1906a. "Das Prinzip der Relativität und die Grundgleichungen der Mechanik." *Verhandlungen der Deutschen Physikalischen Gesellschaft* 8:136–141. Repr. in Planck 1958, Vol. 2, Doc. 60.

———. 1906b. "Die Kaufmannschen Messungen der Ablenkbarkeit der β-Strahlen in ihrer Bedeutung für die Dynamik der Elektronen." Vorgetragen in der Sitzung der physikalischen Abteilung der 78. Versammlung Deutscher Naturforscher und Ärzte in Stuttgart am 19. September 1906. *Physikalische Zeitschrift* 7:753–761.

———. "Zur Dynamik bewegter Systeme." Gesammtsitzung von 13. Juni 1907. *Sitzungsberichte der Preußischen Akademie der Wissenschaften,* 542–570. Repr. in Planck 1958, Vol. 2, Doc. 64.

———. 1958. *Physikalische Abhandlungen und Vorträge.* Edited by Verband Deutscher Physikalischer Gesellschaften and Max-Planck-Gesellschaft zur Förderung der Wissenschaften. 3 vols. Braunschweig: Vieweg.

Read, James. 2020. "Explanation, Geometry, and Conspiracy in Relativity Theory." In *Thinking About Space and Time: 100 Years of Applying and Interpreting General Relativity,* edited by Claus Beisbart et al., vol. 15. Basel: Birkhäuser.

Rindler, Wolfgang. 1970. "Einstein's Priority in Recognizing Time Dilation Physically." *American Journal of Physics* 38:1111–1115.

Ritz, Walther. 1908a. "Recherches critiques sur l'Électrodynamique Générale." *Annales de Chimie et de Physique* 13:145–275.

———. 1908b. "Recherches critiques sur les théories électrodynamiques de Cl. Maxwell et de H.-A. Lorentz." *Archives des sciences physiques et naturelles* 26:209–239.

———. 1908c. "Über die Grundlagen der Elektrodynamik und die Theorie der schwarzen Strahlung." *Physikalische Zeitschrift* 9:903–907.

———. 1909a. "Das Prinzip der Relativität in der Optik: Antrittsrede zur Habilitation." In *Gesammelte Werke. Oeuvres,* edited by Pierre Weiss, 509–518. Paris: Gauthier-Villars.

———. 1909b. "Zum gegenwärtigen Stand des Strahlungsproblems: Erwiderung auf den Aufsatz des Herrn A. Einstein." *Physikalische Zeitschrift* 10:224–225.

Ritz, Walther. 1911. *Gesammelte Werke: Oeuvres.* Edited by Pierre Weiss. Paris: Gauthier-Villars.

Ritz, Walther, and Albert Einstein. 1909. "Zum gegenwärtigen Stand des Strahlungsproblems." *Physikalische Zeitschrift* 10:323–324.

Sitter, Willem de. 1913. "Ein astronomischer Beweis für die Konstanz der Lichtgeschwindigkeit." *Physikalische Zeitschrift* (Leipzig) 14:429.

Staley, Richard. 2008. *Einstein's Generation: The Origins of the Relativity Revolution.* Chicago: University of Chicago Press.

Stark, Johannes. 1906. "Über die Lichtemission der Kanalstrahlen in Wasserstoff." *Annalen der Physik* 326:401–456.

Varićak, Vladimir. 1911. "Zum Ehrenfestschen Paradoxon." *Physikalische Zeitschrift* 12:169–170.

Walter, Scott A. 2018. "Ether and Electrons in Relativity Theory." In *Ether and Modernity,* 67–87. Oxford: Oxford University Press.