9. New interpretation of experimental results

In the following the most important experiments with impact on Special Relativity will be presented and discussed. In particular concerning the Michelson-Morley- and the Kennedy-Thorndike-Experiments new considerations will be derived when the concept of phase velocity is used. In addition, other fundamental experiments will be described in a short way.

9.1 Michelson-Morley-Experiment

At first the experiment conducted by A. A. Michelson and E. M. Morley will be discussed in detail. Because of the high importance, subsequently a comprehensive literature survey will be presented, and the conclusions derived from this test will be described.

9.1.1 Experimental layout and evaluation

The layout of the experiment presented in Fig. 9.1 is a reproduction out of the original publication in 1887 [7]. In this figure the set-up is shown, where a light beam at mirror a is partly reflected in direction ab and partly transmitted in direction ac, being returned by the mirrors b and c, then reflected resp. transmitted to d and at this point examined with an interferometer. Part 1 of Fig. 9.1 is presenting the position at rest; in part 2 the situation of a moved system (against the supposed ether) is given.

Theoretical basis of the experiment was the assumption, that the speed of light and the speed against the ether at rest could be added and that it would be possible to evaluate the latter by precise measurements. The whole time of going and coming between a and c can be calculated using

$$T_{\parallel} = \frac{D}{c+v} + \frac{D}{c-v} = \frac{2Dc}{c^2 - v^2} \tag{9.01}$$

where D is the distance between a and c. The distance traveled in this time is

$$D_{\parallel} = 2D\,\frac{c^2}{c^2 - v^2} \tag{9.02}$$

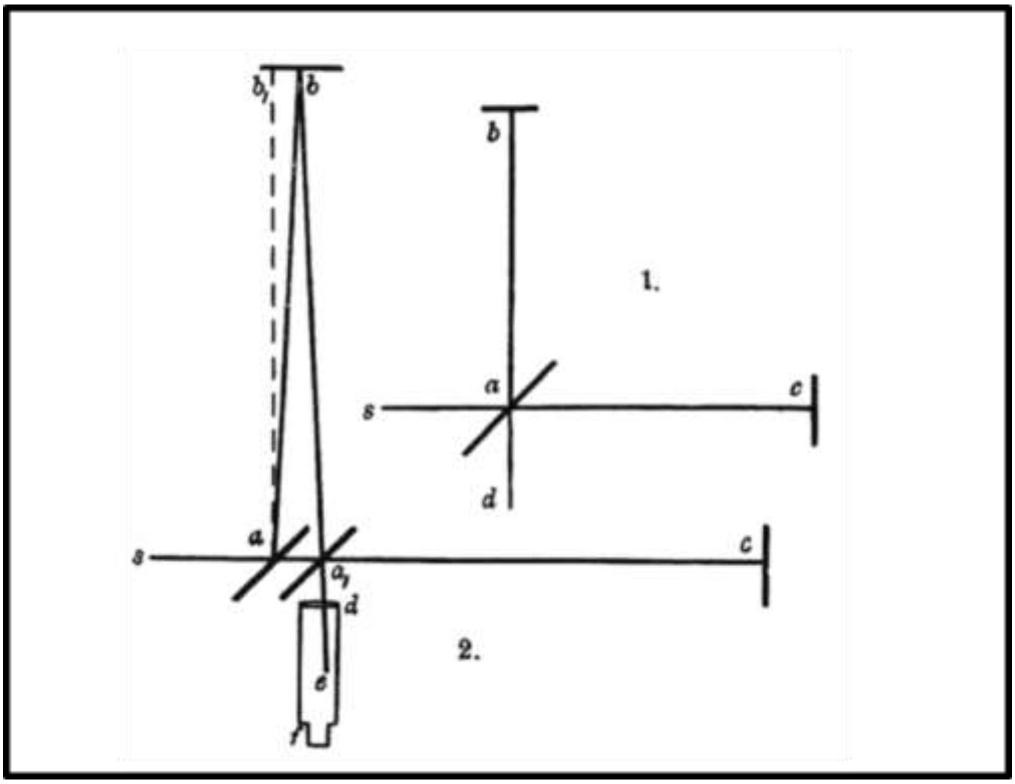

Fig. 9.1: Layout of the Michelson-Morley-Experiment, reproduction from original report [7]

In transverse direction the calculation yield

$$T_{\perp} = \frac{D_{\perp}}{v_{\perp}} \tag{9.03}$$

and

$$v_{\perp}^2 = c^2 + v^2 \tag{9.04}$$

$$D_{\perp} = 2D\sqrt{1 + \frac{v^2}{c^2}} \tag{9.05}$$

Neglecting terms of 4th order and higher the equations (9.02) and (9.05) after Taylor expansion develop to

$$D_{\parallel} \approx 2D\left(1 + \frac{v^2}{c^2}\right) \tag{9.06}$$

$$D_{\perp} \approx 2D\left(1 + \frac{v^2}{2c^2}\right) \tag{9.07}$$

Now the difference is

$$\Delta D = D_{\parallel} - D_{\perp} = 2D\left(1 + \frac{v^2}{c^2}\right) - 2D\left(1 + \frac{v^2}{2c^2}\right) = D\frac{v^2}{c^2} \tag{9.08}$$

Looking at the calculation with today's knowledge concerning the speed of light, it contains the obvious problem that the calculations predict velocities $v > c$. In the following it will be shown that this will not be the case when correct calculations are used.

First the value of $T_{\parallel}$ will be considered. For this purpose, the calculations in chapter 2 are used (see Tab. 2.1):

$$T_{\parallel} = \frac{D}{c\left(1-\frac{v}{c}\right)} + \frac{D}{c\left(1+\frac{v}{c}\right)} = \frac{2D}{c}\gamma^2 \tag{9.09}$$

It is clear at first sight that for the consideration according to this approach the time for going and coming is exactly opposite to Michelson's ideas, but that the addition of both reveals the same result.

In transverse direction the calculation is slightly different. For the calculation, the dependencies shown in Fig. 9.2 are used (see also chapters 2.1.2 and 2.2.3).

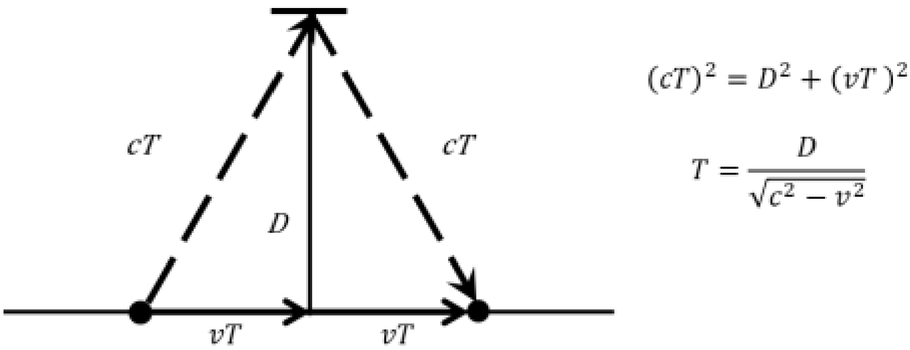

Fig. 9.2: Dependency between distance D to the reflector and velocities v and c.

So, the value for $T_{\perp}$ is

$$T_{\perp} = \frac{2D}{\sqrt{c^2 - v^2}} = \frac{2D}{c}\gamma \tag{9.10}$$

and

$$D_{\perp} = \frac{2D}{\sqrt{1-\frac{v^2}{c^2}}} = 2D\gamma \tag{9.11}$$

This result differs from the conclusion of Michelson according to Eq. (9.05). The difference is appearing with the following term and the connected Taylor expansion

$$\sqrt{1+\frac{v^2}{c^2}} = 1 + \frac{1}{2}\frac{v^2}{c^2} - \frac{1}{8}\frac{v^4}{c^4} + \frac{3}{48}\frac{v^6}{c^6} - \cdots \tag{9.12}$$

in contrast to the correct derivation

$$\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = 1 + \frac{1}{2}\frac{v^2}{c^2} + \frac{3}{8}\frac{v^4}{c^4} + \frac{15}{48}\frac{v^6}{c^6} + \cdots \tag{9.13}$$

If terms of 4th order or higher are neglected the results are the same and both calculations can be used without restrictions.

Now the calculation reveals

$$\Delta D = \frac{T_{\parallel} - T_{\perp}}{c} = 2D(\gamma^2 - \gamma) \tag{9.14}$$

and for $v \ll c$ because of

$$\gamma \approx 1 + \frac{v^2}{2c^2} \tag{9.15}$$

the result is

$$\Delta D \approx 2D\left(\left(1 + \frac{v^2}{2c^2}\right)^2 - \left(1 + \frac{v^2}{2c^2}\right)\right) \approx D\frac{v^2}{c^2} \tag{9.16}$$

A. A. Michelson showed in his calculations, that the experiment was able to detect velocities of about 8km/s but a null result was received instead. The motion of the earth around the sun (without further consideration of the motion of the sun compared to the galaxy) reveals however values of approximately 30km/s.

G. F. FitzGerald proposed already in the year 1889 the idea that the length of material bodies changes, according as there are moving through the ether or across [8]. He expected an amount depending on the square of the ratio of their velocities to that of light. The same issue was also predicted independently by H. A. Lorentz three years later [13]. After the Lorentz equations were fully developed it was shown that contraction of space and dilatation of time is covered by the same parameter and the factor γ was defined (see Eq. 1.03), i.e. [12,13].

The results of the experiment were further leading to the conclusion that the proposed “luminiferous ether" could not exist. This interpretation is correct in so far, if the radiation of light is thought to be connected in a simple way, as e.g. transporting sound through a carrier medium like gas or a liquid. If in a space, however, which is considered as absolutely at rest, time dilatation and spatial contraction in direction of a moved body belong to the characteristics of space, then a simple solution of the problem is also possible. Considering the possible effects of constant phase velocity, then during changes between different inertial systems any discrepancies will disappear.

Summing up the results of the Michelson-Morley-Experiment it can be stated, that in the direction of movement a contraction of space must take place. This contrasted with the assumptions at the end of the 19th century that ether-wind like in a gas would exist. Further interpretations, however, concerning “luminiferous ether” are not possible.

9.1.2 Literature review

The Michelson-Morley-Experiment is discussed in many publications. The “Conference on the Michelson-Morley Experiment” held in Pasadena at the Mount Wilson observatory in 1927 is for sure one of its highlights. Because of the paramount importance of the participating scientists and the detailed discussions laid down in the conference paper published in1928 [49] a very meaningful document of the scientific standard of that time is preserved. The basic understanding has still not changed substantially until today. Because of the particular significance in the following the detailed topics and discussions of the Conference will be presented. Beside the scientific importance there are further interesting historical highlights which will be recognized as well.

First A. A. Michelson presented a report about the historical background [49a]. He told about the first trials at the Helmholtz-Institute in Berlin, which were not successful because of disturbing traffic and were later repeated at the Observatory at Potsdam. The null result that was achieved was questioned by many scientists of that time, because of the short length of the detector arms of the device used. The important improvements realized by E. W. Morley at the University of Cleveland later led to an experiment without doubt.
The theoretical background of the experiment was presented by H. A. Lorentz [49b]. His considerations were far more complex, especially concerning the dependencies of angular measurements which were not covered by A. A. Michelson before (see chapter 7.1.1). Subsequently D. C. Miller [49c] summarized the status of the results of the experiments at that time. He also reported about measurements, which showed positive results concerning the measuring of the ether (Remark: These results could not be repeated in later experiments). R. S. Kennedy then presented information about the special measurement technique of the interferometer [49d].

E. R. Hedrick [49e] and afterwards P. S. Epstein [49f] were covering in their presentations additional theoretical aspects. The focus was directed to the difficulties which occur when a mirror is moved relative to potential ether at rest. A detailed interpretation of the work of A. Righi [50] concerning this subject was presented, although much older publications are existing (e.g. [51,52]). (Remark: Because of the sudden death of the Italian physicist A. Righi only very few and fragmentary records were available. These were summarized and edited by J. Stein S. J. from the observatory of the Vatican [50]). E. R. Hedrick presented a list of 15 publications, which are dealing with theoretical interference-problems concerning the Michelson-Morley-Experiment [49e].

It is noteworthy that some of the results of the cited authors differ significantly. A. Righi expressed the opinion that the Michelson-Morley-Experiment, because of the angular measurement of the mirror through the ether, could not reveal any result; E. R. Hedrick however concluded that these effects exist but could be neglected.

Without further going into detail, it can be stated, that in all cases only the shifting of the mirror in relation to the ether is considered but not the movement of the whole system with the interferometer. H. A. Lorentz made a statement in the discussion, that the presented calculations regarding a moved mirror showed deviations to his results and encouraged an additional survey [49g]. A consideration of phase velocity was not taken into account. H. A. Lorentz died in the year after the conference and no reports exist, whether he ever again dealt with the problem. This is also valid for other authors and no statement of the participants concerning this matter is available.

9.2 Kennedy-Thorndike-Experiment

In this experiment performed by R. J. Kennedy and E. M. Thorndike also, like in the Michelson-Morley experiment, an interferometer as testing equipment was used. The chosen set-up is different from the Michelson-Morley-Experiment mainly using measuring arms with different length in the design of the interferometer. In addition, the very stable construction and the extreme accuracy of the temperature control made it possible to conduct long-term measurements. The measuring device was surrounded by a water system that made it possible to keep the temperature deviations at a level lower than 1/1000 °C. With this equipment experiments were conducted that lasted weeks or even months.

In principle the experiment follows the idea, that the measurement device is not moved or tilted but that the deviations in direction to the ether are supposed to be executed by the rotation of the earth and the circulation around the sun, and thus tilting and also accelerations are caused by the movements of the earth [16]. In the literature interpretations exist, where the rotation of the device relates to the Michelson-Morley experiment and only the acceleration is referred to as the original Kennedy-Thorndike experiment [54]. Because of the general situation, that both effects (rotation, acceleration) are always connected to each other, they shall be discussed here together as well.

During this experiment and in following trials with an extraordinary increase of the precision – like for the Michelson-Morley-Experiment – a null-result was achieved.

In the following it shall be demonstrated first that the interpretation by the authors [16] in the year 1932 because of some conceptual shortcomings was not correct. Because of this reason actual considerations follow modified approaches like presented for example by D. Giulini [19]. It shall be demonstrated, however, that these new concepts also contain weak points and that it is possible to overcome this problem by a modified interpretation. This will now be discussed in detail and afterwards a final examination will be presented.

9.2.1 Interpretation according to the original publication

A system S is considered, where a light beam during time dt is traveling the distance ds [16]. Then it applies

$$ds = cdt \tag{9.20}$$

If now a system S′ is introduced which is moving relative to S with a velocity of v then this leads to

$$c^2(dt')^2 = (ds')^2 + v^2(dt')^2 + 2vds'dt'cos\theta' \tag{9.21}$$

where θ' is the angle between the radiation of the light and the moving direction. For $\theta' = 0$ it applies

$$cdt' = ds' + vdt' \tag{9.22}$$

If the results derived by the Michelson-Morley-Experiment are considered, the following relations in longitudinal direction (θ resp. $\theta' = 0°$) and further in transverse direction (θ resp. $\theta' = 90°$) will be found.

	Moved system S'		System at rest S
$\theta' = 0°$	$dt' = \frac{ds'}{c\left(1-\frac{v}{c}\right)}$	$\theta = 0°$	$dt' = \frac{ds}{\gamma c\left(1-\frac{v}{c}\right)}$
$\theta' = 90°$	$dt' = \frac{ds'}{c}\gamma$	$\theta = 90°$	$dt' = \frac{ds}{c}\gamma$

The integration according to [16] show the following result

$$t'_{\parallel} - t'_{\perp} = \frac{s'_{\parallel} - s'_{\perp}}{c}\gamma \tag{9.23}$$

Here conceptual problems become apparent, because only the path in direction to the reflecting mirror is considered, but not the way back. For the distance to the mirror in moving direction and back different values will appear. Further it is assumed, that spatial contraction and time dilatation are exactly the same, what is not possible at this stage of the interpretation without further assumptions. Therefore, the interpretation of the original publication shall be stopped here and thus switched to modern descriptions of the experiment.

9.2.2 Concept according to actual publications

In recent publications (e.g. [19]) the presentation of the experiment is different. It is only possible to derive the equation

$$t'_{\parallel} - t'_{\perp} = B\,\frac{2\left(s'_{\parallel} - s'_{\perp}\right)}{c}\,\gamma \tag{9.24}$$

where the constant B will be measured later, for example by using the Ives-Stilwell-experiment (see chapter 9.3), and then shows a value of $B = 1$.

The real problem concerning the interpretation of the Kennedy-Thorndike-experiment using this concept is the principle of evaluation. Hereby the situation occurs that according to equation

$$\Delta N = f \cdot B\,\frac{2\left(s'_{\parallel} - s'_{\perp}\right)}{c}\,\gamma \tag{9.25}$$

with f as frequency a dependency is established between the number of oscillations of a light beam going and coming the way the from a light source to an interferometer and the connected frequency. If the different length of the measuring arms is taken into account, however, it is clear at first sight that a light beam, which is split and sent out in different directions obviously after reflection does not rejoin at the same place, and that a certain delay will be observed. In the following an alternative interpretation of the experiment will be derived where this condition is respected.

9.2.3 New interpretation of the experiment

As already stated, one of the most important conditions of the experimental set-up is the fact, that measuring arms with different lengths are used. Because of this situation it makes no sense to compare the total amount of oscillations of the light beams between these arms. The concept of constant phase velocity of light discussed in chapter 8 opens a different possibility on the apparent effects of interference. When an interaction between light pulses is observed and a comparison at an interferometer is conducted it becomes clear, that the pulse, which is running the way of going and coming at the shorter measuring arm must be considered as delayed compared to the other one.

When the lengths of the measuring arms are defined as L_C (long) and L_B (short) then the time for the delay T_0 until the transmitting of a pulse in a system at rest is

$$T_0 = \frac{2L_C}{c} - \frac{2L_B}{c} = \frac{2L_C(1-k_A)}{c} \tag{9.30}$$

with

$$k_A = \frac{L_B}{L_C} \tag{9.31}$$

defined as the constant for the ratio of the arm lengths. The total time for going and coming of a light beam is therefore

$$T_B = \frac{2L_C(1-k_A)}{c} + \frac{2L_C k_A}{c} \tag{9.32}$$

$$T_C = \frac{2L_C}{c} \tag{9.33}$$

where Eq. (9.32) and Eq. (9.33) are obviously equal. If now the experimental set-up is moving with measuring arms longitudinal and transverse to the moving direction, and for the arm in longitudinal direction a spatial reduction of γ derived by the results of the Michelson-Morley experiment is valid, then the following calculations will be derived for the different situations

$$T_{\parallel B} = T_{\perp B} = a\frac{2L_C(1-k_A)}{c} + b\frac{2L_C k_A}{c}\gamma \tag{9.34}$$

$$T_{\parallel C} = T_{\perp C} = b\frac{2L_C}{c}\gamma \tag{9.35}$$

where a is an initially unknown constant for the correction of the starting time of the signal at the shorter arm. The additional constant b is introduced because the result of the Michelson-Morley experiment shows that just the ratio between the contraction in longitudinal and transverse direction can be derived but not the exact dimension.

Now equations Eq. (9.34) and Eq. (9.35) are set equal

$$b\frac{2L_C}{c}\gamma = a\frac{2L_C(1-k_A)}{c} + b\frac{2L_C k_A}{c}\gamma \tag{9.36}$$

$$b\frac{2L_C}{c}(1-k_A)\,\gamma = a\frac{2L_C(1-k_A)}{c} \tag{9.37}$$

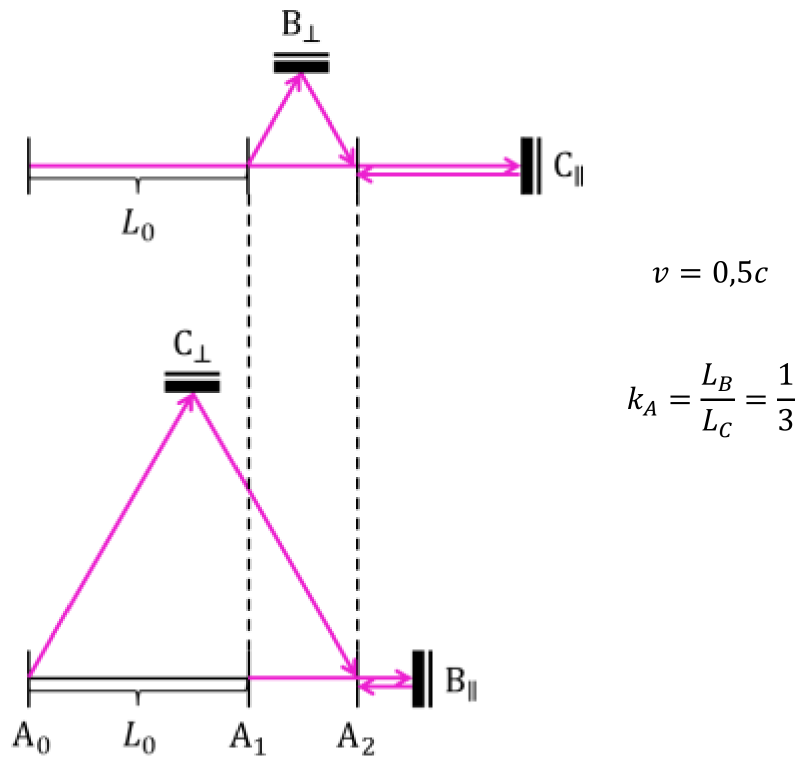

Fig. 9.3: Kennedy-Thorndike experiment: Rotation

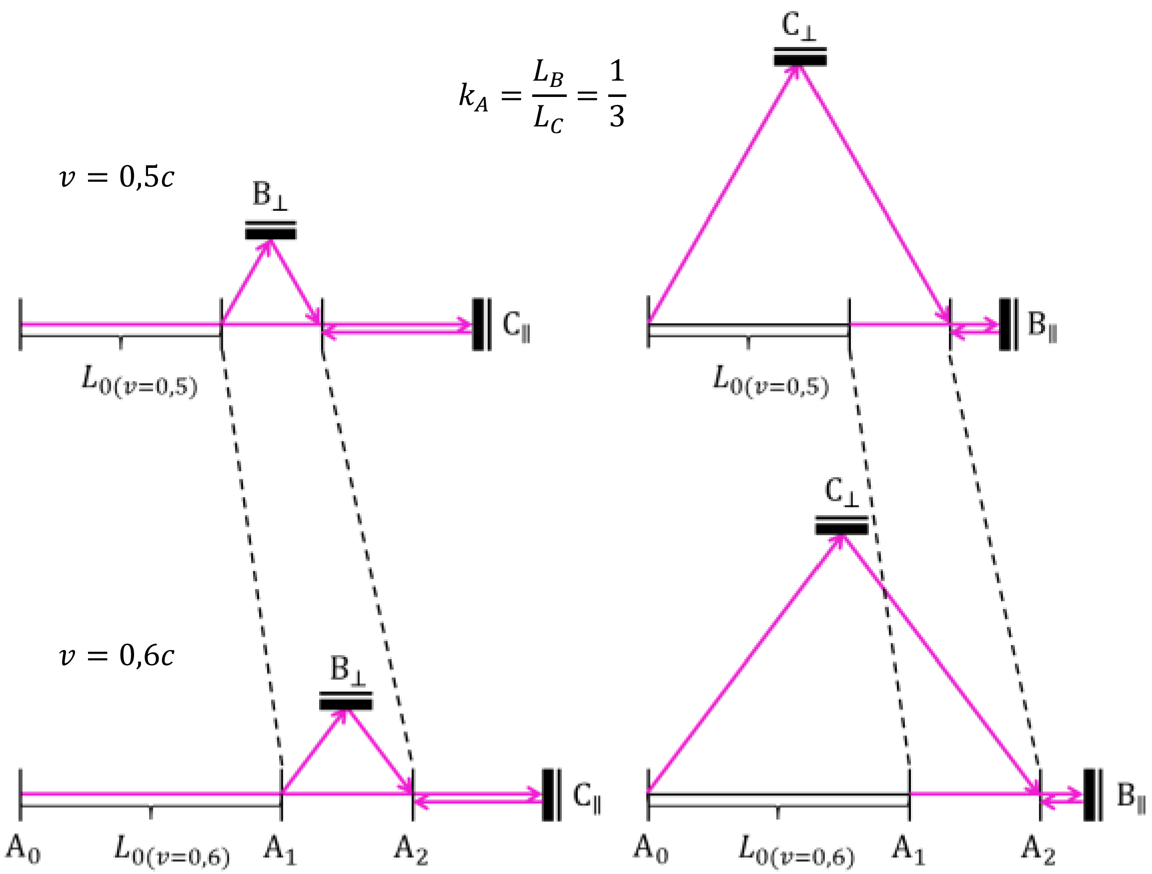

Fig. 9.4: Kennedy-Thorndike experiment: Acceleration

with

$$\frac{a}{b} = \gamma \tag{9.38}$$

The calculation shows that a zero result for the measurements is only possible when the ratio between the constant for the starting time of the shorter measuring arm and the factor for the spatial contraction are exactly equal to the constant γ of the Lorentz Equations. Today we know, derived by additional experiments concerning time dilatation (e.g. by Ives-Stilwell, see chapter 9.3), that $b = 1$. During the time of the first execution of the experiment in the year 1932, however, this was not the case.

It is possible to illustrate the experimental set-up as presented in Fig. 9.3 and Fig. 9.4, were for the relation between the lengths of the measuring arms a ratio of 1/3 was chosen. At first the behavior during a rotation is presented (Fig. 9.3) afterwards the situation for acceleration (Fig. 9.4). In reality, it will be generally the case that both situations cannot be separated and will appear together, so that the effects will superimpose each other. Light pulses are transmitted and reflected at mirrors B and C; the denomination $C_\parallel$, $C_\perp$,$B_\parallel$ and $B_\perp$ shows, whether the reflection will be in longitudinal or in transverse direction relative to the movement of the system.

The coordinates of the relevant points were calculated and are presented in table 9.1. The format x, y, t was chosen; in the direction of z no movement takes place and so those values were not included (this means $z = 0$). For the relation between longitudinal and transverse direction the spatial contraction was considered by the factor of γ according to the results of the Michelson-Morley experiment.

Coordinate	x	y	t
$C_\parallel$	$\frac{L_C}{\gamma\left(1-\frac{v}{c}\right)}$	0	$\frac{L_C}{\gamma c\left(1-\frac{v}{c}\right)}$
$C_\perp$	$\frac{\gamma L_C v}{c}$	L_C	$\frac{\gamma L_C}{c}$
A_1	$\frac{2\gamma L_C v}{c}(1-k_A)$	0	$\frac{2\gamma L_C}{c}(1-k_A)$
$B_\parallel$	$\frac{2\gamma L_C v}{c}(1-k_A)+\frac{L_C k_A}{\gamma\left(1-\frac{v}{c}\right)}$	0	$\frac{2\gamma L_C}{c}(1-k_A)+\frac{L_C k_A}{\gamma c\left(1-\frac{v}{c}\right)}$
$B_\perp$	$\frac{2\gamma L_C v}{c}(1-k_A)+\frac{\gamma L_C v}{c}k_A$	$L_C k_A$	$\frac{2\gamma L_C}{c}(1-k_A)+\frac{\gamma L_C}{c}k_A$
A_2	$\frac{2\gamma L_C v}{c}$	0	$\frac{2\gamma L_C}{c}$

Table 9.1: Presentation of coordinates according to Fig. 9.3

The values in Table 9.1 for A_2 can be derived according to the effective length of the beam in 4 different ways which are all leading to the same results. This is presented in Table 9.2. It was presented here, that a rotation of the apparatus and the comparison between a moved system and a system at rest show the same results. The calculation reveals further that correction factors for the starting time and for the spatial contraction are equal and must be exactly γ in both cases. This will be discussed further in more detail in the next chapter.

The presentation for acceleration in Fig. 9.4 shows the same correlations already presented in chapters 4 and 5 and so there is no need for further evaluation. There are in principle no discrepancies when transitions between systems with different velocities are analyzed.

Path over:	x	t
$C_{\parallel}$	$\frac{L_C}{\gamma\left(1-\frac{v}{c}\right)}-\frac{L_C}{\gamma\left(1+\frac{v}{c}\right)}$	$\frac{L_C}{\gamma c\left(1-\frac{v}{c}\right)}+\frac{L_C}{\gamma c\left(1+\frac{v}{c}\right)}$
$C_{\perp}$	$\frac{\gamma L_C v}{c}+\frac{\gamma L_C v}{c}$	$\frac{\gamma L_C}{c}+\frac{\gamma L_C}{c}$
$B_{\parallel}$	$\frac{2\gamma L_C v}{c}(1-k_A)+\frac{L_C k_A}{\gamma\left(1-\frac{v}{c}\right)}-\frac{L_C k_A}{\gamma\left(1+\frac{v}{c}\right)}$	$\frac{2\gamma L_C}{c}(1-k_A)+\frac{L_C k_A}{\gamma c\left(1-\frac{v}{c}\right)}+\frac{L_C k_A}{\gamma c\left(1+\frac{v}{c}\right)}$
$B_{\perp}$	$\frac{2\gamma L_C v}{c}(1-k_A)+\frac{\gamma L_C v}{c}k_A+\frac{\gamma L_C v}{c}k_A$	$\frac{2\gamma L_C}{c}(1-k_A)+\frac{\gamma L_C}{c}k_A+\frac{\gamma L_C}{c}k_A$

Table 9.2: Calculations of value A_2 using paths over the positions $C_{\parallel}$,$C_{\perp}$, $B_{\parallel}$ and $B_{\perp}$. All calculations reveal the same result.

9.2.4 Evaluation of results

When the results of the experiments of Michelson-Morley and Kennedy-Thorndike with the apparent zero results are viewed closely it becomes clear, that a final definition of the constants a and b is not possible without further information and a statement about the validity of the Lorentz equations will remain incomplete. Usually the Ives-Stilwell-experiment will be used for this purpose, which is described shortly in chapter 9.3. It is in addition also possible to use other simple possibilities to validate the results.

If for example the assumption is made that $a = 1$ and thus $b = 1/\gamma$, this would mean that a moving system is not subject to any time dilatation at all, but on the other hand the spatial contraction in moving direction would be of the factor γ^2 and in addition in transverse direction the factor γ must be taken.

Tests concerning effects like these are not complex and could be subject to several different experiments. This would be possible for example for the exchange of signals between moving observers (see chapter 2.1) or for the frequency measurements of moving bodies (chapter 8). Beside the differences in the measurements, furthermore the principle of relativity will be violated, and different results must appear whether a situation is monitored by an observer at absolute rest or from a moving system. The deviations are not only valid for this example but for all other configurations when the constants are not chosen as $a = \gamma$ and $b = 1$.

The title of the publication from Kennedy and Thorndike was "Experimental Establishment of the Relativity of Time". Because of the dependencies between the constants a and b expressed above it is today generally rejected, that the approach expressed in the headline was successful, see e.g. [19]. However, if in the year 1932 the authors would have carried out a correct interpretation by using the principle of constant phase velocity, then already at that time the statement would have been possible. Independent from this, this experiment with all the improvements in accuracy carried out in the meantime, is an important tool for the understanding of the nature of signal exchange between moving observers.

9.3 Further important experiments

There are many further pioneering experiments connected with the nature of light and radiation. Those with high importance concerning the evaluations presented here will be discussed shortly in the following.

a) Rømer-Experiment

This was the first experiment with the attempt to measure the speed of light. Most important was, that it was proved for the first time (in the year 1676!) that the speed of light is limited. The detection was conducted by O. C. Rømer measuring the occultation of the Jupiter moon Io that occurs earlier when the planet is close to earth and later when the distance is larger. With his measurement results C. Huygens in 1678 was able to calculate the speed of light and he found a value of ca. 213.000 km/s which is approximately 71% of the correct result.

b) Aberration of light

This experimental effect was established the first time by J. Bradley in the year 1725. He discovered that the star Gamma Draconis showed a small deviation of its position in the sky during the progress of a year and supposed that this was caused by the finiteness of the speed of light. His measurements already achieved a precision of 2% (for further details see also chapter 1.3).

c) Double star experiment

The examination of double star systems provided evidence for the first time that the speed of light is independent of the speed of the object that is transmitting the signals. These considerations were mainly carried out by W. de Sitter, who was able to verify by spectroscopic examinations that the addition of the speeds of light and the emitting source would lead to a violation of Kepler's laws [55].

d) Ives-Stilwell-Experiment

This experiment is confirming directly that time is running more slowly for a moved observer compared to a reference system [17,18]. To prove this the transversal Doppler Effect of light was investigated using canal rays that were approaching or increasing the distance to the installed measuring equipment. The values found are showing impressively the value of the Lorentz-Factor γ.

e) Trouton-Noble-Experiment

In this case a charged capacitor was taken, which could turn free around an axis. In case of evidence of the ether it would tilt around this axis because of a reaction which would be caused by the rotation of the earth. The basic principle of this experiment is comparable to the Michelson-Morley-Experiment. Although electromagnetic effects are not part of the considerations presented here the mentioning of this important experiment shall not be missed [56].

If additional information is required further experiments can be found in other publications (e.g. [19,21,57,58]).

9.4 Final examination of the experiments

In the year 1949 H. P. Robertson was the first to establish a summarizing classification of the different types of measurements and created a concept that is still in use today [59]. The following measuring methods and the significance connected with these are defined:

1. *Michelson-Morley:*
   The total time required for light to traverse a certain distance and return is independent of its direction.

2. *Kennedy-Thorndike*
   The total time required for light to traverse a closed path is independent of the velocity of the system compared to an arbitrary reference system.

3. *Ives-Stilwell*
   The frequency of a moving atomic source is reduced by the factor γ compared to an arbitrary reference system.

Modern presentations of the experiments are sometimes using slightly different interpretations, but the description shown here is very close to the first classification by Robertson.

When the relations of the invariance of phase velocity presented before are considered, it can be stated that the new improved interpretation of the experiments is leading to a better understanding of the processes, but that the fundamental results of the experiments are still valid. The Michelson-Morley and the Kennedy-Thorndike experiment are not able to describe the situations appearing in moving systems in full detail. It is possible, however, to use other simple experiments to validate the results (see chapter 9.2.4).

The question remains, why the great importance of the phase invariance of light between systems moving relative to each other was not in focus and is not part of the discussion till now. The fundamental principle belongs to the standard knowledge of today's physics, e.g. [46a]. The effect of the movement of an experimental set-up was also discussed quite often (see e.g. [49,50,51,52]). Further comprehensive theoretical examinations concerning the "invariance of phase-velocity" exist [27]. Despite of the great importance of the discussed matter for modern physics up to now no approach was made to combine these findings. It seems to be highly likely, that the results presented here are caused mainly by the consequent approach regarding the observation of a system at rest compared to moving systems and following the resulting relations.

Finally, some examples shall be presented, how the precision of measurements was developing in the last decades.

- In the year 1960 the definition of the length of 1 meter was defined in the following way using the wavelength: "The metre is the length equal to 1650763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p10$ and $5d5$ of the krypton 86 atom" [87].
- This definition was valid for many years and was then replaced by a new regulation with the time as basis. Since 1967 the second has been defined as the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of cesium 133 atoms [88].

Without the principle of invariance of the phase velocity both definitions are not possible, because already smallest movements relative to reference systems containing one of these experiments would have led to discrepancies in observations.

There is a further aspect referring to the invariance of phase velocity. This is the "frequency comb", where pulses of extreme shortness are produced with a femtolaser and then reflected in a mirror-system to interfere. Thus, a standing wave is produced that is also referred to as "comb" (to background and historical development see e.g. [53]). It is interesting that this technique is a "hybrid" type of generation of light; the extreme short pulses can be interpreted in their collectivity as waves. Here a classical interpretation with the comparison of frequencies makes definitely no sense at all.