11. Limits of the Theory of Special Relativity

It was already demonstrated at lengths that an impressive number of examples exist, which are conforming to the Theory of Special Relativity. This was shown e.g. for kinematic considerations of moving observers, further it was proved for the processes during clock transport and also for the relations between mass, momentum, force, energy and for elastic or non-elastic collisions of moved bodies and further the relativistic observation of rocket acceleration. It was shown for a large number of configurations that using the Lorentz-Transformation no differences can be found for a system at rest or for moving observers and that no possibility exists to decide inside a system whether it is moving or at rest. This is in accordance with the postulates of the Theory of Special Relativity which stipulates that all observers are considered as equal and so no evidence could be found that the principles of relativity are not valid.

All these examples share the basis that the transport of signals is occurring with the speed of light. However, when superluminal velocities are considered, which were discovered during tunneling processes, it can be shown that – provided that also information are transported with superluminal speed (a concept which is still controversially discussed) – the appearing effects are not in accordance with Special Relativity. This will be reviewed in detail. Finally, the situation concerning synchronization after acceleration will be discussed and it will be shown that in this case conflicts will appear.

11.1 Superluminal effects during tunneling processes and their significance

Optical examinations with prisms were conducted already since a very long time. It is well known that Newton, Huygens, and many other scientists focused their work on the fundamental relations.

With the development of modern research methods, the examination of effects based on quantum mechanics started. Fritz Goos (1883-1968) and Hilda Hänchen (1919-2013) were the first to find that a linear polarized light-wave during the transition from a medium with a higher to a lower optical thickness is not reflected at the boundary layer but at a virtual surface with an orientation parallel to it situated inside the medium with the lower optical thickness. It is not possible to explain this observation with a standard model and quantum mechanics are used instead. The investigations were made during the 2nd world war in Berlin and published partly not before 1947 [60,61].

Further examinations revealed that optical boundaries generate tunneling effects, which are independent of their thicknesses [62]. This led to intensive discussions concerning the appearing of superluminal velocities.

11.1.1 Tunneling effects

Tunneling effects and connected measurements of velocities of electromagnetic waves during passing of an optical boundary were already part of numerous examinations. For a better understanding a comprehensive survey about the investigations using prisms and other optical devices carried out with waves of different frequencies, published by H. G. Winful, is recommended [63].

Out of the multitude of possibilities an example shall be chosen, where double prisms are used for experiments. A typical experimental set-up is presented as shown in Fig. 11.1.

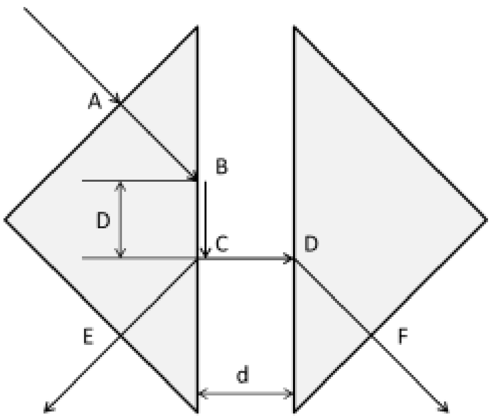

Fig. 11.1: Experimental set-up for measuring of tunneling effects (after [64])

An electromagnetic wave is reaching point A of a prism and is transmitted into the body. If an appropriate angle is taken (see e.g. [64]) the wave will be reflected at point B. When another identical prism is situated opposite to it, a tunneling effect will be observed which can only be explained using quantum mechanics. In this case the paths $\overline{\mathrm{BC}}$ and $\overline{\mathrm{CD}}$ will be passed without delay. The largest part of the wave will reach point E, a much smaller part is detected at F. The exit of both will be exactly at the same time. Experiments of this type allow the use of set-ups with large dimensions, though the intensity of the beam on the way $\overline{\mathrm{DF}}$ is strongly dependent on the distance b of the prisms. Experiments with $d = 280$ mm were already performed and the corresponding effects could be observed. Because of the multitude of possible experiments, it is referred for further details to publications with a general survey [63,64].

At present there is no consensus concerning the interpretation of the observed results at all. Very often the argument is used that superluminal velocities occur, but that it is impossible during these experiments to transport information faster than light. The reason for this is that the results of the measurements are interpreted not as the velocity of a single pulse but as an effect caused by the group velocity of a signal. Complex information (e.g. speech) can only be transported by a wave-packet and the velocity of this is supposed to be the speed of light. Because of the importance of this argument in the following a short introduction concerning this matter shall be presented before a final investigation is made.

To describe the effect of group velocity in a simple way in publications dealing with this matter some analogies are found like the comparison between fly and elephant, the interpretation of a tortoise race or the consideration of the behavior of a very long train [63,65]. Specially the last example is very suitable to understand the circumstances and shall be discussed shortly:

A train needs for the travel between 2 points a defined time span. If this train is considered as extremely long, then a simple definition of departure and arrival time is no longer suitable and differences will occur, whether the locomotive, the middle of the train or the end is observed. If in a second tour a train with the same length travels with the same speed the same distance, and during the trip wagons are uncoupled than the middle and of the train, which is consequently moving forward during the trip, is arriving earlier than in the example discussed before. However, independent of this the locomotives of both trains are reaching the destination at the same time. Following this interpretation, the velocity of the middle of the train (the group velocity) is faster than the speed of the locomotive.

Transferred to the discussed example it is obvious, that during the tunneling of the wave no even damping occurs but that the end of the wave-packet must be perpetually cut off. In this case the group velocity is faster than light although this is not valid for the front and so in this case no violation of the Theory of Relativity would occur.

The authors dealing with superluminal velocities measured at prisms and other optical devices are using quite different interpretations for the results. Beside the argument concerning group velocities described before this covers a total denial of superluminal effects because of complete misinterpretation of the experimental results [63], assumed contamination effects which demands an infinite size of the prisms when a reasonable signal transfer is required [66] or the final discussion is left completely open [67,68]. Some authors still today have the opinion that it is possible during these experiments to transport information with a speed faster than light [65,69]. The main reason for this is the observation, that a tunneled wave after amplification has the same shape compared to a reflected wave and that it shows no cut off like it must be assumed when the above-mentioned example of group velocity would be valid.

However, for clearly documented evidence it is not necessary to transport complex information, but a single pulse would be sufficient (like using the Morse alphabet). Considering this, the thesis that measurements are not possible because of lack of information transport, is assessed as not plausible. If the distinct detection of a transmitted pulse with superluminal velocity would be possible, then this result would cause severe consequences for Special Relativity which will be discussed in the following.

11.1.2 Significance of superluminal velocities for Special Relativity

Whereas all considerations discussed so far have led to the perception that observers during the exchange of signals in a system at rest or when moving will find the same measuring results, this will definitely not be the case when information is transmitted using superluminal velocities. This can be derived easily when the situation presented in Fig. 11.2 is analyzed.

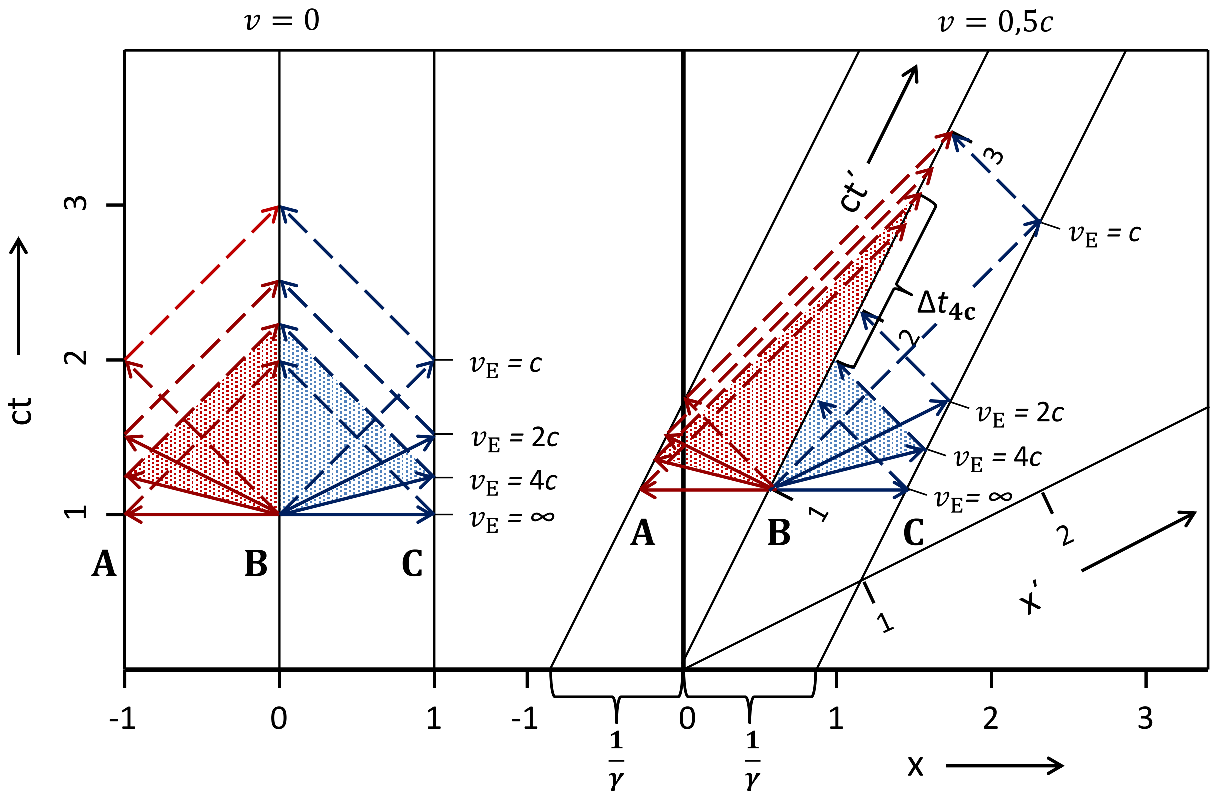

Fig. 11.2: Differences between a system at rest and a moving observer when information is transmitted with superluminal velocity.

On the left-hand side as usual a system at absolute rest is presented. The transmission of signals is carried out with superluminal velocity v_E between observer B to the points A and C. Immediately at arrival a responding light signal ($v = c$) is triggered and sent back to B. Because the experimental set-up is symmetrical the arrival at B will be at the same time.

On the right-hand side the same situation is presented for a moving system. Because observers A and C have different positions, the light signal will arrive at different times at B. The time span is depending on the superluminal velocity (values for $v_E = 2c, 4c$ and ∞ are shown) and also on the speed of the system v_S (in this case values of $v_S = 0$ and $0{,}5c$ were chosen). This diagram also includes the values for the time difference Δt_{4C} that would appear when a superluminal velocity of $v_E = 4c$ would be achieved.

The time span relevant for different superluminal velocities can easily be derived using simple geometric considerations as presented in Fig. 11.3.

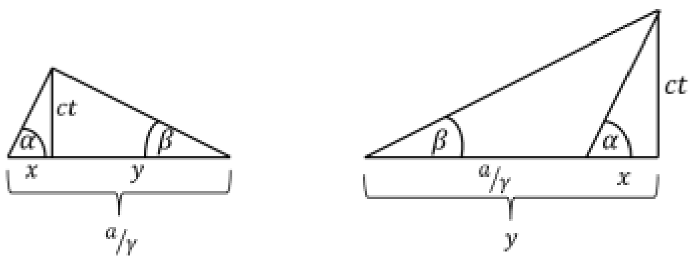

Fig. 11.3: Geometric dependencies of used dimensions for $v_E = 2c$

The following general dependencies apply

$$tan\alpha = \frac{ct}{x} = \frac{c}{v_S} \qquad tan\beta = \frac{ct}{y} = \frac{c}{v_E} \qquad \Rightarrow \qquad xv_E = yv_S \tag{11.01}$$

The cases for the signal transmission in moving direction and opposite to it must be treated separately. It applies

Signal opposite to the moving direction	*Signal in moving direction*	
$\frac{a}{\gamma} = x + y$	$\frac{a}{\gamma} = y - x$	(11.02)
$\Rightarrow \quad xv_E = \frac{a}{\gamma}v_S - xv_S$	$\Rightarrow \quad xv_E = \frac{a}{\gamma}v_S + xv_S$	(11.03)
$t_1 = \frac{a}{\gamma(v_E+v_S)}$	$t_3 = \frac{a}{\gamma(v_E-v_S)}$	(11.04)

To calculate the entire time for the signal exchange the part for the way back must be added. Thus, the total time for the path B→A→B is:

$$t_T(C) = t_1 + t_2 = \frac{a}{\gamma(v_E+v_S)} + \frac{a}{\gamma(c-v_S)} \tag{11.05}$$

The path B→C→B leads to

$$t_T(A) = t_3 + t_4 = \frac{a}{\gamma(v_E-v_S)} + \frac{a}{\gamma(c+v_S)} \tag{11.06}$$

To discuss the influence of the signal velocity on the measuring effect finally the difference must be determined

$$t_T = t_T(C) - t_T(A) = \frac{a}{\gamma(v_E+v_S)} + \frac{a}{\gamma(c-v_S)} - \frac{a}{\gamma(v_E-v_S)} - \frac{a}{\gamma(c+v_S)} \tag{11.07}$$

and be compared with $v_E \to \infty$. Hence

$$t_D = \frac{t_T}{t_\infty} \tag{11.08}$$

In Fig 10.4 the results for different velocities for the signal and the used reference systems are presented. Generally, it can be stated that the speed of the system has only limited influence on the results and a noteworthy effect appears at remarkably high values. Further it becomes clear that the signal velocity of $v_E = 2c$ is already reaching half values which are calculated for $v_E \to \infty$. The relations show, that it is not necessary to suppose signal velocities of extreme magnitude because the sensitivity of the measurement is extraordinarily strong.

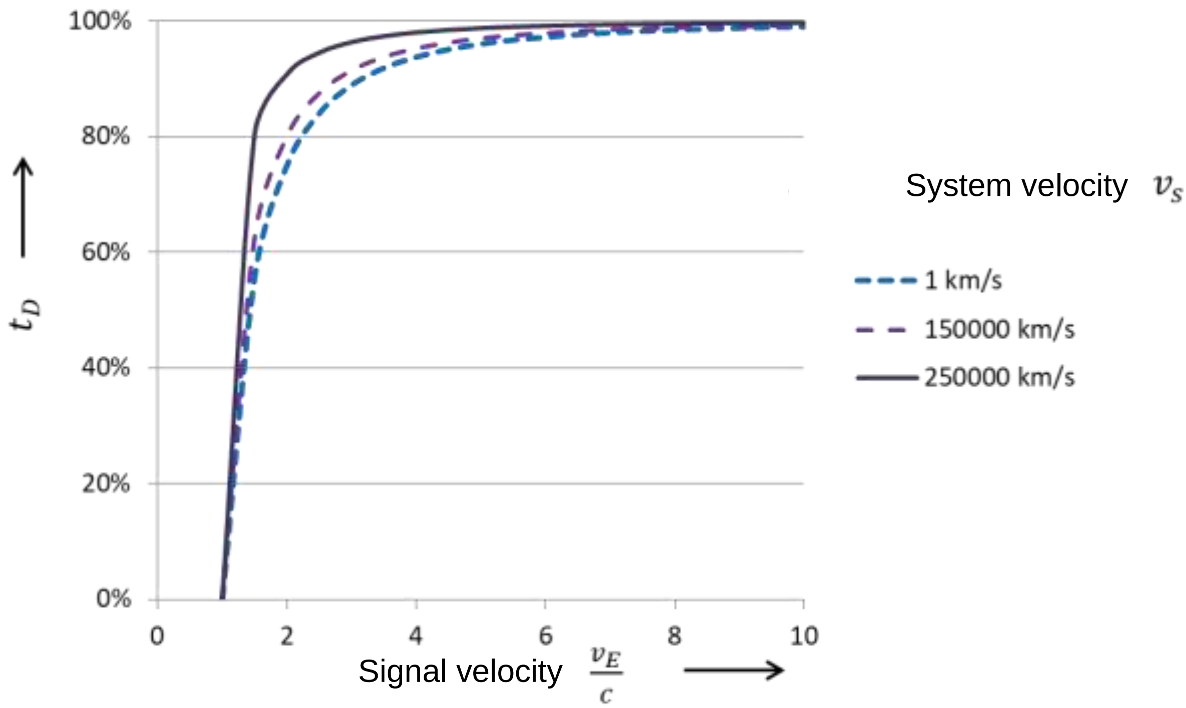

Fig. 11.4: Expected measuring effect t_D in relation to signal velocity v_E and system velocity v_S

Further additional considerations concerning the existence of superluminal velocities exist, where it is assumed that in this case the principle of causality would be violated [63]. Other publications are denying effects like this [64,65].

In general, the violation of the principle of causality would stand for the fact, that an incoming signal would be received earlier than the outgoing signal. This would mean that a negative time must be assumed, for which no experimental evidence exists. It is clear, however, that inside a system with high velocity compared to a system at rest (as shown at the right-hand side of Fig. 11.2) the incoming signal will arrive earlier (case B → A → B) or later (case B → C → B) as expected according to the synchronization procedure before. In this case no violation of the principle of causality will occur because the signal measured is earlier or later (depending on the speed of the system) than expected due to synchronization but in no case before the start of the procedure.

It shall be mentioned that the existence of superluminal velocities for the transport of signals would lead to severe conflicts with the principle of relativity which cannot be solved. Differences in measurements between systems would occur, which travel at different speed. An undisputed measuring effect would provide evidence that a system of absolute rest must exist. In chapter 13.1 a possible experiment to prove this will be presented and the dimensions of values which can be expected will be discussed in detail.

11.2 Synchronization after acceleration

In the past many scientists tried to detect the one-way speed of light in a moved system in a direct way. Concerning this problem different concepts were taken into consideration; one of these is the “slow clock transport”. The principal idea in this case is that in a moved laboratory a clock is slowly transported from one end (e.g. the back end) to the other side and then compared with a second clock at that place which was synchronized before. It was already shown, that during this transport, irrespective of the chosen speed, the synchronization remains unchanged, and a zero result will be achieved (see also chapter 5).

Another possible alternative, which was first considered by E. Dewan and M. Beran [70] and later reviewed in detail by J. S. Bell [71] and also by D. J. Miller [72] and F. Fernflores [73] is the investigation of changes in systems before and after acceleration. In this case observers, which are transporting synchronized clocks, are accelerated homogenous in a way, that they show the same speed compared to each other before and after. It is required that the acceleration for all observers shall be the same; further preconditions are not necessary.

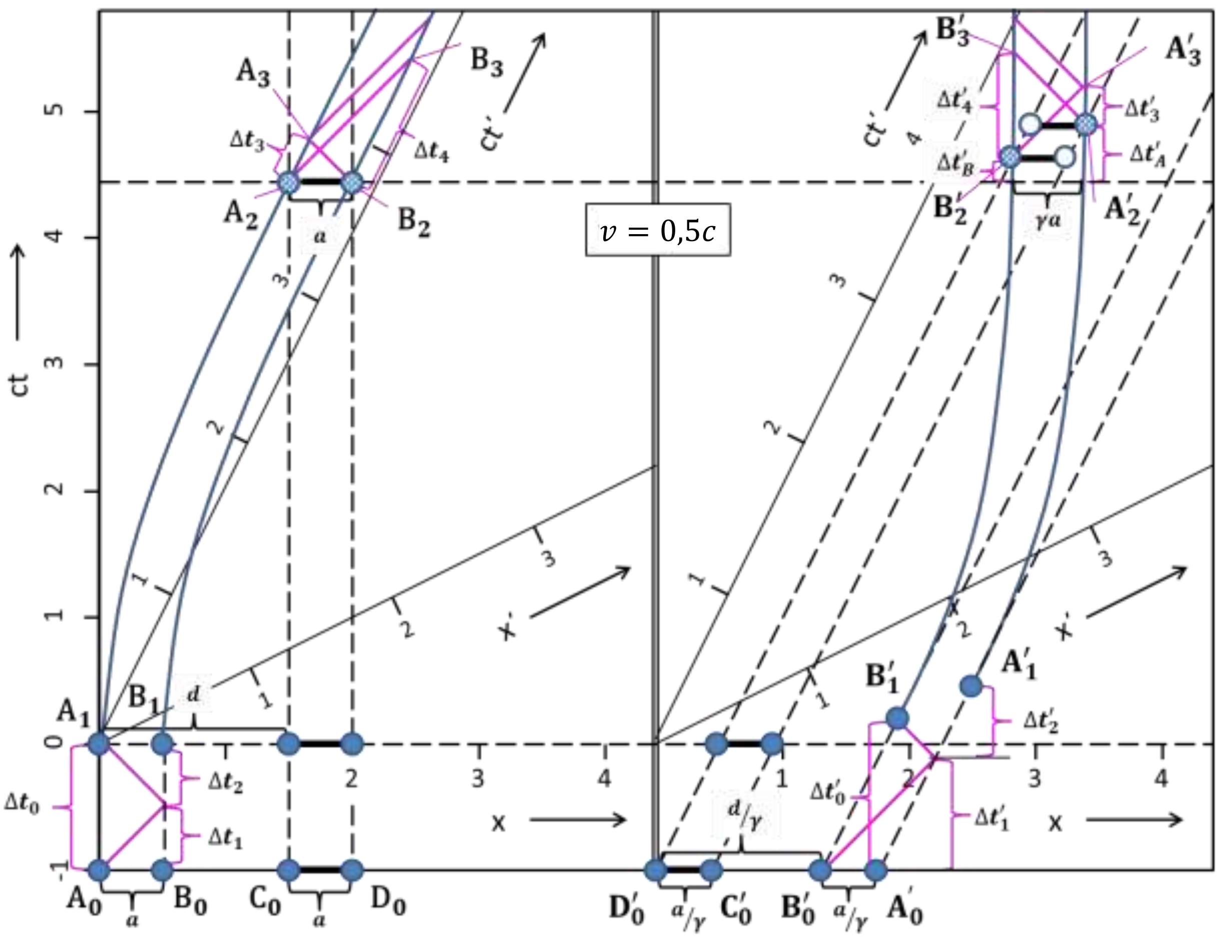

Fig. 11.5: Exchange of signals before and after an acceleration ($v = 0{,}5c$)
a) Left: System at rest to moved system
b) Right: Moved system to system at rest

At first the situation shall be examined, when the observers are lined up in direction of acceleration. The configuration of this experimental set-up is presented in Fig. 11.5.

The left-hand side is showing the case, that in a system at rest the observers A and B first synchronize their clocks and then start at the same time with acceleration. Concerning this it was determined before that A is starting directly after receiving a signal from B, but B is first calculating the starting time and takes Δt_2 for his start of acceleration (see diagram). The time Δt_2 is exactly half of the time Δt_0, that a signal is taking for travelling the distance between B and A and then back. The acceleration is running homogenously until the points C and D, which are fixed to each other, are met (A is contacting C, B reaches D). Here acceleration is stopped, and a signal is transmitted to the other observer.

A and B will now find that

1. the distance between each other has (subjectively) increased to γa,
2. time Δt_3 is larger and Δt_4 is smaller compared to Δt_2

The issue presented in point 1 is also named "Bell's Spaceship Paradox". J. S. Bell supposed the existence of a thread between these spaceships and assumed, that this would also be contracted.

In a further investigation a moved system is considered, in which the participants A and B are (from their point of view) subject to the same conditions (right side of Fig. 11.5). In this case an observer at rest will find, that Δt_1 is larger compared to the value monitored before. For this reason, A will start acceleration later than B, because he will start $\Delta t_2 = \Delta t_0/2$ after receiving the signal from A. Therefore, participant A will reach C later than B is reaching D. After the end of this trial, the distance and the times will be checked again and it will be proved, that all values are the same compared to the case looked at before. In the following the calculations of the space- and time-coordinates are presented in detail.

a) From a system at rest to a moved system

In this case the calculation is easy. Because of the accelerations running parallel it is obvious, that (from the point of view of an observer at rest) the distance a will be constant in the moved system as well. Furthermore, the following calculations apply

$$\Delta t_0 = \frac{2a}{c} \tag{11.11}$$

$$\Delta t_1 = \Delta t_2 = \frac{a}{c} \tag{11.12}$$

$$\Delta t_3 = \frac{a}{c\left(1 - \frac{v}{c}\right)} \tag{11.13}$$

$$\Delta t_4 = \frac{a}{c\left(1 + \frac{v}{c}\right)} \tag{11.14}$$

b) From a moved system to a system at rest

In this case some additional calculations are necessary.

$$\Delta t_0' = \frac{2a\gamma}{c} \tag{11.15}$$

$$\Delta t_1' = \frac{a}{c\gamma\left(1-\frac{v}{c}\right)} = \frac{a\gamma}{c}\left(1+\frac{v}{c}\right) \tag{11.16}$$

$$\Delta t_2' = \frac{a\gamma}{c} \tag{11.17}$$

$$\Delta t_B' = \Delta t_0' - \Delta t_0 + t_2 = \frac{2a}{c}(\gamma - 1) + t_2 \tag{11.18}$$

$$\Delta t_A' = \Delta t_1' + \Delta t_2' - \Delta t_0 + t_2 = \frac{a}{c}\left(2\gamma + \gamma\frac{v}{c} - 2\right) + t_2 \tag{11.19}$$

$$x(\mathrm{B}_2') = \Delta t_B' \cdot v = \left(\frac{2a}{c}(\gamma - 1) + t_2\right)v \tag{11.20}$$

$$x(\mathrm{A}_2') = \Delta t_A' \cdot v + \frac{a}{\gamma} = \left(\frac{a}{c}\left(2\gamma + \gamma\frac{v}{c} - 2\right) + t_2\right)v + \frac{a}{\gamma} \tag{11.21}$$

$$\Delta x\left(\frac{\mathrm{A}_2'}{\mathrm{B}_2'}\right) = \left(\frac{a}{c}\left(2\gamma + \gamma\frac{v}{c} - 2\right) + t_2\right)v + \frac{a}{\gamma} - \left(\frac{2a}{c}(\gamma - 1) + t_2\right)v$$

$$= \frac{av}{c}\gamma\frac{v}{c} + \frac{a}{\gamma} = a\gamma \tag{11.22}$$

$$\Delta t_3' = \frac{a\gamma}{c} + \Delta t_B' - \Delta t_A' = \frac{a}{\gamma c\left(1-\frac{v}{c}\right)} = \frac{1}{\gamma}\Delta t_3 \tag{11.23}$$

$$\Delta t_4' = \frac{a\gamma}{c} + \Delta t_A' - \Delta t_B' = \frac{a}{\gamma c\left(1+\frac{v}{c}\right)} = \frac{1}{\gamma}\Delta t_4 \tag{11.24}$$

These calculations show, that a, Δt_3 and Δt_4 in a moved system and a system at rest are connected by γ and that the observers A and B from their point of view cannot decide after the end of the trial whether they changed their position from a system at rest to a moved system or vice versa.

However, concerning the behavior of "Bell's thread", which is situated between the spaceships, initially a difference can be observed in the considerations between the cases a) and b). While in a) the distance and caused by this the strain on the thread increases constantly, the case b) will lead to a considerable change in the beginning of the experiment. This is caused by the fact, that observer B starts before A with the acceleration and therefore uneven strain occurs. However, this effect is only appearing seemingly and not real because the thread has a limited rigidity. Like already discussed in connection with the triggering of engines after synchronization in chapter 4.3, the strain in the thread will be transported with limited velocity and so all differences will disappear.

The validity of this argument shall be demonstrated in the following by using a simple example. The beginning of the experiment relates to the fact that in a system of absolute rest both spaceships are starting at the same time. If no total rigidity of the thread is assumed, but the transport of tension with arbitrary velocity is considered, then a thin and almost massless thread will behave like a rope and this is resulting in the fact, that a loop will be formed near the second observer. This would cause an extremely complicated situation and so a simple model is considered here instead were

1. the force will be induced into the thread not only by traction (by observer B, see Fig. 10.5) but also by compression (observer A) into a stable thread (no rope),
2. a buckling or bending of the thread will not occur.

For the start of the spaceships from the state of absolute rest it is obvious, because of symmetry conditions, that any arbitrary velocity will lead to the situation that traction and compression will reach the middle within the same time. For the moving system, the conditions already discussed in chapters 4.1 and 4.3 are valid. The relativistic addition of velocities in combination with appearing synchronization differences will also cause the effect that traction and compression will appear in the middle simultaneously. Thus, for the observers no differences will be measurable.

In publication concerning this matter different perceptions can be found, whether the thread will be contracted or not after acceleration or, in simple words, whether it is breaking or not. (This discussion for obvious reason contains the precondition that the thread is of infinite small mass and has no influence on the behavior of the spaceships). The calculations presented here lead to the clear opinion that the thread is strained, which means it will break. This is simply derived out of the fact that the acceleration phases for both spaceships can also be performed and monitored separately and in this case, when the spaceships act autonomously, the same results must appear.

Before closing the discussion, the additional issue shall be reviewed, that the observers are not lined up in acceleration direction but transverse to it. In this case the quite simple effect occurs, that during an exchange of signals after acceleration the distance between the observers is increased by the factor γ compared to the situation at rest. This must be valid because of geometrical reasons; the observer at rest will find that the signal is following a triangle with a side length larger by factor γ compared to its height. This effect is compensated exactly by the time-dilatation and so in this case no change in synchronization is observed.

Summing up the discussion two points are worth mentioning. First the chosen experimental conditions are causing tensions between two observers, which are independently accelerated under the same conditions, and this could be part of experimental observations. Obviously in this case differences in measurement results can be expected, dependent on the situation whether the observers are considered as point-shaped or spatially expanded. Second the calculations show that in case of clocks lined up in the direction of acceleration differences in synchronization will occur; this is valid for independent observers and in addition for extended spatial bodies. This effect will not be found if the observers are arranged transverse to acceleration direction. This is required by Special Relativity because of the "Relativity of Simultaneity" and represents a fundamental test regarding the principles of the theory. Details concerning this are discussed in chapter 13.2.