Experimental test of the equivalence principle: Result of studying free fall of a metal disk and a helium balloon in a vacuum (low vacuum)

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Abstract

The equivalence principle states that gravitational mass and inertial mass are two equivalent quantities, that in a gravitational field all bodies fall at the same rate during free fall in a vacuum regardless of their mass and composition. In the past, the free fall of bodies has been studied multiple times and the equivalence principle has always been confirmed so far. However, mainly solid bodies and liquids were used as test bodies in the experiments. In this experiment, in addition to a pure solid body, namely a metal disk, a solid body in hollow form filled with gas, specifically a helium balloon, has been studied during free fall in a vacuum (low vacuum). The analysis of the measured data shows a clear deviation of the measured values from the expected nominal values according to Galileo's law of falling bodies during free fall of the helium balloon and thus a violation of the equivalence principle.

Introduction

In modern physics, gravity is one of the four elementary forces. It is the longest known and at the same time the most mysterious of all elementary forces. Of the three other forces, namely the electromagnetic force, the weak and the strong nuclear force, we have a good understanding by now, but gravity remains a conundrum, a great mystery of physics. To understand the universe better or to get a coherent picture of it, it is essential to learn to understand gravity better. So, it makes sense to look at the elementary force of the cosmos in a little more detail and to ask elementary questions in this regard. What do we know for sure? Or what do we believe to know for sure? Are the basics still correct? Or could it be that a good reason for the issues in the theory of quantum gravity, which tried so far unsuccessfully to unite the quantum theory and the general theory of relativity, is, that there is something wrong with the last mentioned theory, which is generally accepted as theory of gravitation? In order to be able to answer these questions satisfactorily at some point, it would be advisable to first take stock and to put the mentioned generally recognised theory of gravitation, namely the general theory of relativity, to the test [1]. This builds on the validity of the equivalence principle, which states that the gravitational mass and the inertial mass are two equivalent quantities, that in a gravitational field all bodies fall equally fast during free fall in vacuum independent of their mass and composition. The assumption that all bodies are accelerated equally fast during free fall was already made by Galileo Galilei and Isaac Newton. And it was Galilei who was the first to scientifically formulate a law of falling bodies named after him from this thesis and who published it in 1638 [2]. If the equivalence principle should be violated in any way, this would certainly change our world view of physics permanently and the general theory of relativity would not be as fundamental as largely assumed so far. But first of all, it must be stated that the equivalence principle has passed all known tests impressively. A good example for this was recently given by the MICROSCOPE satellites [3]. However, in the past, the test bodies to help verify the validity of Galileo's law of falling bodies and Einstein's equivalence principle that later followed from it were mainly solids or liquids [3,4]. But the equivalence principle includes all bodies, thus also the gaseous body. Therefore, in this experiment, in addition to a pure solid body, a metal disk, a solid body in hollow form, which is filled with gas, namely a helium balloon, is to be studied more closely during free fall in a vacuum (low vacuum), in order to answer the question of whether all bodies really fall at the same rate in a vacuum and whether the equivalence principle is still valid in this form. The values measured in the process are compared with the nominal values according to Galileo's law of falling bodies. This introduction is followed by the main part with a detailed description of the experimental setup, the execution of the experiment and the subsequent observation of the experiment. The conclusion contains a short result, a summary and a small outlook.

Experimental setup

Vacuum chamber (Fig.1) with integrated hand pump, consisting of a transparent plastic bell, an integrated vacuum manometer with a scale corresponding to 600 mm Hg and a double vent valve. The vacuum chamber sits on a suitable air pump plate in which the hand pump is installed. Total height: 34 cm. Diameter of the bell: 20 cm. Plastic bell height: 30 cm.

Figure 1. Vacuum chamber with integrated hand pump

- Helium filled latex balloon (pear shape, height approx. 15 cm, width approx. 12.5 cm) - Magnet (pot magnet with threaded pin, diameter 2.5 cm) - Metal disk (button cell battery, diameter 2 cm) - iPhone, Phyphox app, video capture device - Desktop PC with speaker boxes, video player software (VLC Plus Player, Media Player Classic) - Ruler, spirit level, felt-tip pen (wipeable)

Experimental procedure

The first body to be examined in vacuum during free fall is the metal disk. A constant height of 25 cm is set, at the top of the bell (where the bell is curved). The height is measured with a ruler and a spirit level. The ruler is placed on the floor next to the vacuum chamber, and with the help of the spirit level, which together with the ruler forms a right angle, the height is measured. This is marked by reproducing the metal disk inside the bell on the plastic housing at the specified height based on the known measurements or by drawing it with the felt pen, respectively. Then, inside the bell, the metal disk is simply placed on the graphic copy and fixed with the help of the magnet, which is located outside on the bell, by means of the magnetic force. After that, the bell is placed on the plate, the air in the bell is evacuated using the hand pump and a low vacuum of approx. 330 mbar (relative value) is generated. The magnet is then abruptly removed from the bell and the metal disk falls and hits the bottom of the air pump plate. The free fall is recorded by video. The video is then played back on a desktop PC connected to loudspeakers using a video player (VLC Plus Player). The fall time is measured using the acoustic stopwatch of the Phyphox app, which is operated via the iPhone. The iPhone is positioned lengthwise in the correct position (home button down, camera up) about 30 cm in front of the speaker box. The stopwatch starts the measurement at the sound that occurs when the magnet is removed from the bell and stops the measurement at the sound that occurs when the metal disk hits the bottom of the air pump plate. The stopwatch is set to a threshold of 0.1 and a minimum delay of 0.1 s via the Phyphox app. The advantage of this type of measurement is that you can set the volume of the speakers accordingly to ensure that the built-in microphone of the iPhone receives the sounds without any problems. The second body to be examined in a vacuum is the balloon filled with helium (He $>$ 95 vol %). This is inserted into the bell jar, the air in the bell jar is evacuated with the aid of the hand pump and a low vacuum of approx. 520 mbar (relative value) is created. This millibar range ensures that the balloon, which is floating in the upper area of the bell, falls to the bottom of the plate. The drop height is again measured with the ruler and with the spirit level. Before the experiment was carried out, several helium-filled balloons, each with a different volume, were measured in terms of height and width, and for each helium balloon the drop height and pressure at which the balloon begins to fall in the vacuum bell jar were examined. The examinations in advance were very time-consuming, but very helpful for the later actual measurement, because it was possible to estimate well which balloon with which measures at which pressure and which height of fall in the vacuum bell begins to fall. For the actual measurement, a constant drop height of 7 cm was thus determined. The timing is again done with the Phyphox app. Visual judgement is used to observe when the balloon starts to fall and when it hits the ground of the air pump plate. At the moment when the helium balloon in the bell starts to fall, a loud noise is generated with the voice 30 cm above an iPhone, which is located close to the vacuum chamber, and the timing starts and is stopped again at the sound generated with the voice, at the moment when the helium balloon touches the bottom of the air pump plate. The free fall is again recorded by video and later played back on the PC to check the fall times with a video player (Media Player Classic). This shows the precise time in milliseconds, and with the time lapse function it can be accurately observed when the helium balloon starts to fall and when it hits the bottom of the air pump plate.

Experimental observation

For the first falling object, the metal disk, the fall time t is determined from n=10 individual measurements at the fixed drop height h. h = 25 cm

n	t(s)
1	0.199
2	0.19
3	0.203
4	0.246
5	0.232
6	0.248
7	0.202
8	0.238
9	0.2
10	0.239

Table 1. Measurement series of the fall time t (metal disk)

The statistical uncertainty of measurement is calculated using the following formula:

$$\Delta x_{\text{stat}} = t.\frac{s}{\sqrt{n}} \qquad (1)$$

Δx_{stat} = statistical uncertainty of

measurement

t = parameter (confidence level)

s = standard deviation

n = number of measurements

Based on the measured values, a statistical measurement uncertainty of 0.219 ±0.013 s is obtained with 95 % statistical certainty. In addition, there is a systematic measurement uncertainty of $\Delta x_{\text{sys}} = 0.01$ s. The total measurement uncertainty $\Delta x = \Delta x_{\text{stat}} + \Delta x_{\text{sys}} = 0.013 + 0.01 = 0.023$ s. This results in a measurement uncertainty of 0.219 ±0.023 s with a statistical certainty of 95 %. Based on the given fall distance h, the fall time t is calculated according to Galileo's law of falling bodies (nominal value) using the following formula:

$$t = \sqrt{\frac{2h}{g}} \qquad (2)$$

t = fall time

h = drop height

$g = 9.837$ m/s^2 (acceleration due to gravity; measuring location Duisburg, Germany). The formula results in a nominal value of 0.225 s. The measured values and the nominal value according to Galileo's law of falling bodies are shown below in a path-time diagram (Fig.2).

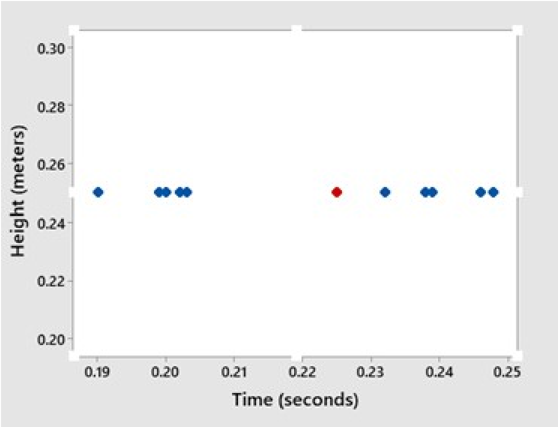

Figure 2. Path-time diagram. Free fall of the metal disk. The red dot represents the nominal value according to Galileo's law of falling bodies. The blue dots represent the measured values.

For the second fall object, the helium balloon, the fall time t is determined at the fixed drop height h from n=10 individual measurements.

h = 7 cm

n	t(s)
1	1.044
2	0.942
3	1.014
4	0.894
5	1.049
6	0.974
7	1.09
8	0.958
9	0.982
10	1.086

Table 2. Measurement series of the fall time t (helium balloon)

Based on the measured values, a statistical measurement uncertainty of 1.003 ±0.045 s is obtained with 95 % statistical certainty. In addition, there is a systematic measurement uncertainty of $\Delta x_{\text{sys}} = 0.01$ s. The total measurement uncertainty $\Delta x = \Delta x_{\text{stat}} + \Delta x_{\text{sys}} = 0.045 + 0.01 = 0.055$ s. This results in a measurement uncertainty of 1.003 ±0.055 s with a statistical certainty of 95 %. The fall times that were subsequently measured via the time specification (including milliseconds) of the video player (Media Player Classic) were all within the interval that was determined on the basis of the measurement uncertainty (1.003 ±0.055 s). Thus, it can be assumed that the true value lies within this interval with a high probability. The nominal value according to Galileo's law of falling bodies is 0.119 s. The measured values and the nominal value according to Galileo's law of falling bodies are shown below in a path-time diagram

(Fig.3).

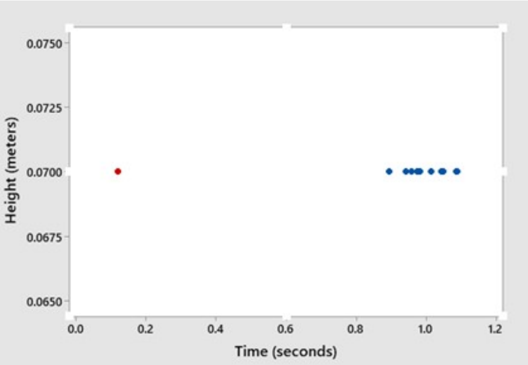

Figure 3. Path-time diagram. Free fall of the helium balloon. The red dot represents the nominal value according to Galileo's law of falling bodies. The blue dots represent the measured values.

Evaluation

First falling object:

The solid (metal disk) falls in a vacuum as expected according to Galileo's law of falling bodies. The nominal value (0.225 s) lies in the interval determined by means of the measurement uncertainty (0.219 ±0.023 s).

Second falling object:

The solid (hollow body of latex material) filled with gas (helium) does not fall in vacuum as expected according to Galileo's law of falling bodies. The nominal value (0.119 s) according to Galileo's law of falling bodies does not lie in the interval determined by means of the measurement uncertainty (1.003 ±0.055 s). The true measured value deviates significantly from the nominal value according to Galileo's law of falling bodies.

Conclusion

As a short result it can be stated, if a falling object consists partly of gas or of a gaseous body, it can be the case that this object does not fall in the vacuum as expected according to Galileo's law of falling bodies, as the case of the helium balloon shows here. It could also be formulated like this: the gravitational acceleration of a body depends on the state of matter. In the introduction, it was made clear why the equivalence principle was checked for its validity and why a falling object was used in the experiment, which partly consists of gas. The main part then dealt with the experiment of the free fall of two test bodies in vacuum. A low vacuum was created by evacuating the air in a plastic bell jar. In the vacuum, the free fall of a metal disk and a balloon filled with helium was then examined and compared with the nominal values according to Galileo's law of falling bodies. Einstein's equivalence principle follows directly from Galileo's law of falling bodies. Therefore, if there should be a deviation between the measured values and the nominal values according to Galileo's law of falling bodies that is too large or no longer justifiable, Galileo's law of falling bodies and the equivalence principle based on this would be violated. The evaluation of the measurements made showed that the metal disk fell in a vacuum, as expected according to Galileo's law of falling bodies. The nominal value (0.225 s) was within the interval determined by the measurement uncertainty (0.219 ±0.023 s). On the other hand, the evaluation showed that the helium balloon did not fall in vacuum as expected according to Galileo's law of falling bodies. The nominal value (0.119 s) according to Galileo's law of falling bodies was not within the interval determined by the measurement uncertainty (1.003 ±0.055 s). The true measured value even deviated quite significantly from the nominal value according to Galileo's law of falling bodies. The evaluation has thus shown that not all bodies fall at the same rate in a vacuum. If this were the case, then there would not have been such a clear deviation in the measured values of the fall times of the helium balloon from the nominal values according to Galileo's law of falling bodies. The nominal value of 0.119 s means that, according to Galileo's law of falling bodies, it is expected that in this experiment, at the specified height and the selected measurement location, all objects or bodies fall at the same rate or have the same fall times, in this case 0.119 s. However, every measurement is naturally subject to an error, the measured value deviates from a mostly unknown true value of the measurand. However, if Galileo's law of falling bodies is valid, it can be assumed that the true value is identical with the corresponding nominal value. A verification of Galileo's law of falling bodies would therefore take place if the nominal value lies in an interval in which the true value also lies, in an interval which is determined by means of the measurement uncertainty. This is of course valid for all falling objects. In the case of the free fall of the helium balloon in a vacuum, however, the nominal value (0.119 s) does not lie in the interval described, it quite clearly deviates from it. And this in turn means, as already mentioned, that not all bodies fall at the same speed in a vacuum. Finally, a small outlook follows. The experiment carried out here was done with simple and modest means. No expensive measuring technique, as it is used for example in universities, was used here. This has of course the disadvantage that the measurements could not be carried out with the same accuracy as when using an expensive professional measuring technique. And this disadvantage unfortunately plays a greater role in the fall of the helium balloon than in the fall of the metal disk. Because this could be fixed at the specified height with the help of a magnet, and the fall time could be determined quite easily by means of the acoustic stopwatch, which started the measurement at the sound that was created when the magnet was removed from the bell and ended the measurement at the sound that was created when the metal disk hit the bottom of the air pump plate. In contrast, during the free fall of the helium balloon, visual judgement played a decisive role in the measurement, which naturally has a disadvantage with regard to the accuracy of the measurement. But it must be noted here that the fall times, which were subsequently measured via the time specification (including milliseconds) of the video player (Media Player Classic), were all within the interval determined on the basis of the measurement uncertainty (1.003 $\pm$0.055 s). This indicates that the measurement was carried out with a reasonable degree of accuracy. In addition, the nominal value here deviated significantly from the interval in which the true measured value lay. All this suggests that the helium balloon, i.e., a falling object consisting partly of gas or of a gaseous body, does not fall in the vacuum as expected according to Galileo's law of falling bodies. In this case, Galileo's law of falling bodies and at the same time the equivalence principle is violated. Therefore, it would be useful to conduct further research with a better quality measurement technique, with the aim to reproduce the result of this work and to study the free fall of gaseous bodies in the vacuum in more detail.

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