Dependence of the weight of a permanent magnet on its orientation. Experimental study

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Abstract. When weighed on different balances, the weight of neodymium bar magnets with the horizontal orientation of the magnetization axis was found to be less than in the vertical position of the axis. The relative change in weight for a neodymium bar magnet is about 8×10^{-6} and depends on the magnetization of the magnet and on its shape. The five-sigma significance level, widely considered to be the stringent threshold of a discovery in particle physics, was attained in our test. The possible interaction of the magnets with the balance mechanism was taken into account together with the influence of the terrestrial magnetic field. The variable weight of the magnets can only mean the dependence of the free fall acceleration of the magnets on their orientation. Our result shows a violation of the Weak Equivalence Principle also known as the Universality of Free Fall.

1. Introduction.

The Universality of Free Fall (UFF) states that "in a gravitational field all bodies fall with the same acceleration regardless of their mass and composition" [1-2] (in the absence of other forces). Many tests investigating possible violation of UFF have been performed and no violation has been found to the level of about 10^{-13} [3]. Nevertheless, the research persists because a confirmed violation of WEP could provide a clue to solving the mystery of dark matter [4].

In an attempt to clarify the problem, we assumed that the free-fall acceleration of atoms g depends on the angle formed by their spins with the vertical. At first glance it seems that such variations of g would have to be detected when checking the Universality of Free Fall [1], but this is not so. The scatter in values of g for individual atoms does not prevent the high-precision coincidence of the averaged free fall acceleration $\bar{g}$ of macro bodies. This is explained by the fact that the number of atoms in macroscopic bodies is enormous.

According to the law of statistics [5], if σ_{atom} is the population standard deviation of the gravitational acceleration g for atoms, then the standard error of the mean $\bar{g}$ for N atoms will be $\sqrt{N}$ times smaller: $SE_{\bar{g}} = \sigma_{atom} / \sqrt{N}$, regardless of the base distribution.

To estimate the effect of decreasing the scatter of the mean value, let us choose Avogadro's number $N_A = 6 \times 10^{23} mol^{-1}$, the number of atoms or molecules in one mole of a substance. Then for this number $SE_{\bar{g}} \simeq \sigma_{atom} 10^{-12}$ which means that the scatter of $\bar{g}$ for one mole of a substance is approximately 10^{12} times less that the scatter of g for one atom.

For individual atoms, the smallness of σ_{atom} compared to $\bar{g}$ among subatomic particles can be judged from the results of experiments based on atom interferometry. For instance, the fall of two Rb isotopes [6, 7] and Rb vs K [8] in the Earth's gravitational field was compared with a relative precision of about 10^{-7} (see also [9, 10]).

So far, physics is losing this competition with statistics - experiments do not reveal a difference in $\bar{g}$ for different substances.

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Our idea was that there exists coupling between the spin direction and the gravitational acceleration of particles. If so, one can change the weight of a particle by changing its spin orientation. However, to make the weight difference measurable for a macroscopic body, one should change the random distribution of the spins of its atoms to an ordered one.

Fortunately, nature has given us such an opportunity in the form of permanent magnets. In permanent bar magnets, the spins of unpaired electrons have a predominant direction along the magnetization axis [11]. Thus, a simple rotation of the magnet changes the distribution of the angles formed by the spins of the unpaired electrons with the vertical.

Although the mass of unpaired electrons is much less than the mass of protons and neutrons in the test body, nevertheless the effect of changing the magnet weight turned out to be measurable.
In our experiment, weighing neodymium magnets on three balances showed

that their weights in the horizontal orientation of the magnetization axis were less than in the vertical orientation. The relative change in the magnets weights was about 8×10^{-6}. The difference is significant at the level of 10^{-9}.

2. Factors affecting the balance readouts

First of all, the strength of Earth's gravity depends on local differences in topography (presence of mountains etc.). The centrifugal force from the Earth's rotation also varies with the latitude and affects the weight of the object. However, in our study we were not interested in the weight itself, but in its change as a consequence of the magnet orientation. The above listed factors cancel out in the final comparison of vertical and horizontal weights, as long as the location of the experiment remains the same.

The next factor acting on the magnet is the effect of Earth's magnetic field. This effect can be cancelled out by averaging two readouts made in opposite directions of the magnet's axis, if the magnet is symmetrical. This happens because if you rotate a symmetrical magnet 180°, then the action of the Earth's magnetic field changes sign. See the details below.

And the last factor: mechanisms of modern analytical balances also use magnets, so their readouts depend not only on the gravity (which is the goal of our research), but also on the interaction of the magnet with the mechanism of the balance.

The force of interaction of a magnet with the mechanism of a balance falls off rapidly with the distance h from the magnet to the balance pan. The instruction for weighing magnets states that it is enough to elevate the magnet above the pan by 10 cm in order to eliminate the interaction. In practice, this height depends on the magnet strength and on the desired precision.

The aim of our experiment was to test the main hypothesis: the weight of the magnet in the horizontal orientation of its axis differs from the vertical orientation.

Before testing this hypothesis, it was necessary to determine the critical distance above which the influence of the interaction between the magnet and the balance becomes negligible compared to the desired precision.

3. Experimental set up

The choice of a magnet is made in order to achieve the greatest possible difference between the horizontal and vertical weights of the magnet. The effect will be maximal if all unpaired electrons of the magnet are aligned along one straight line. The stronger the magnet, the greater the fraction of unpaired electrons aligned along the magnetization axis.

Today the strongest magnets are neodymium $Ne_2Fe_{14}B$. They have an adhesive force that is about 8 to 10 times higher than that of a comparable ferrite magnet.

Even with high magnetization, the desired effect can be lowered if the electrons are aligned along curved lines. This happens with short magnets but not only with these. The tests showed that magnets with a length-to-width ratio of at least 3 should be used to obtain the detectable effect. In our experiment we used one bar magnet 10 x 10 x 60 mm and also two such magnets pressed close to each other by the same poles and enclosed in a plastic box so the length-to-width ratio was 60/20 = 3.

It is necessary to warn those wishing to repeat the experiment against using two parallel bar magnets with the opposite poles facing each other. This configuration has the advantage of being symmetrical with respect to the 180° magnet flip, but at the same time the alignment of the spin directions of the electrons deteriorates and the weight difference decreases.

To exclude the influence of the magnet on the balance mechanism, 300 mm. high supports of thin plastic or cardboard (non-magnetic materials) were used. This height of the support was chosen after thousands of measurements.

We used three types of balances which we denote here by letters A, B, and C:

A - precision balance S2527 for the pilot measurements, capacity =100 g,
B - analytical balance ASB-220-C2, capacity =220 g,
C - ES 225 SM–DR 0.01/0.1 mg (semi-micro dual range), capacity =225 g.

The resolution of 0.1 mg. is sufficient, but repeatability is necessary. It is also necessary to exclude the presence of working motors in the room due to their vibration.

4. Measurements and processing of the experimental results

The magnets were weighed on three different balances when the magnetization axis is directed up, down, towards the East and West, and also towards the North and South. In all the measurements, the magnets were placed on a support 300 mm. high, in order to eliminate the interaction between the magnets and the balance mechanism.

To process the weighing results, we deduced appropriate formulas. Let us denote the free fall acceleration of an electron with the horizontal spin g_{horiz}, and with the vertical spin g_{vert}. In addition, we denote by M the mass of all unpaired electrons of the magnet. Then the sought-for difference in the weight of the magnet in the vertical and horizontal positions is

$$\Delta W = M\left(g_{vert} - g_{horiz}\right).$$

Suppose for definiteness that at our disposal there are balance readouts for the magnet position towards the East $R_{\rightarrow}$ and the West $R_{\leftarrow}$. Given the influence of the terrestrial magnetic field upon the readouts, we have

$$R_{\rightarrow} = W_{stable} + Mg_{horiz} + F_{ter}\left(East\right), \qquad (1)$$

$$R_{\leftarrow} = W_{stable} + Mg_{horiz} + F_{ter}\left(West\right), \qquad (2)$$

where W_{stable} is the total weight of protons, neutrons, and paired electrons, whose average weight variations are negligible compared to our main goal. $F_{ter}\left(East\right)$ and $F_{ter}\left(West\right)$ are the projections of the terrestrial magnetic forces on the vertical direction if the axis of magnetization is directed respectively east or west.

Figure 1 shows a bar magnet in an inhomogeneous terrestrial magnetic field. Due to the heterogeneity of the magnetic field, the vertical components of the forces acting on the south and north poles of the magnet (F_1 and F_2) do not cancel each other, so the actual weight of the magnet is not displayed on the balance display. But for a symmetrical magnet, this problem can be solved.

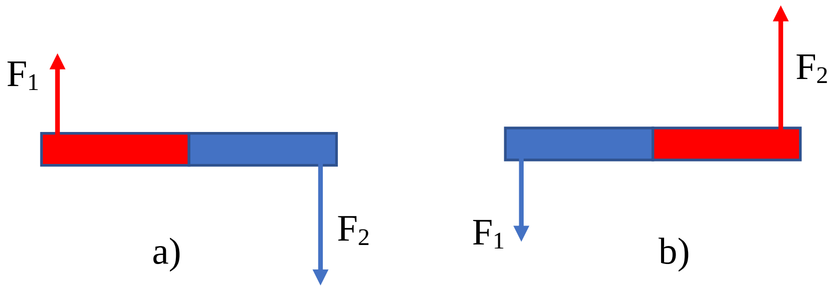

FIG. 1: Influence of an inhomogeneous terrestrial magnetic field on a bar magnet in two opposite orientations: a) the magnetization axis is directed to the East; b) the magnetization axis is directed to the West.

In Figure 1a the axis of the magnet points to the east and $F_{ter}\left(East\right)=\vec{F}_1+\vec{F}_2$. If you rotate the magnet so that its north pole points to the west (Fig.1b), then the directions of forces $\vec{F}_1,\vec{F}_2$ are reversed, hence $F_{ter}\left(West\right)=-F_{ter}\left(East\right)$.

Now, when Eqs (1) and (2) are added, the magnetic forces with the opposite magnet orientations cancel each other out, and we get

$$W_{horiz}=W_{stable}+Mg_{horiz}=\left(R_{\rightarrow}+R_{\leftarrow}\right)/2 \qquad (3)$$

That is, the horizontal weight of the magnet is obtained by averaging the two readings of the weights for opposite horizontal directions of the magnet axis.

Similarly, for the two vertical directions of the magnetization axis, the following two equations can be written:

$$R_{\uparrow}=W_{stable}+Mg_{vert}+F_{ter}\left(Up\right),$$

$$R_{\downarrow}=W_{stable}+Mg_{vert}+F_{ter}\left(Down\right),$$

where $R_{\uparrow}$ and $R_{\downarrow}$ denote two readouts of a balance in the two opposite vertical directions of the axis of a symmetrical magnet.

Then averaging the two measurements excludes the Earth's magnetic field force:

$$W_{vert}=W_{stable}+Mg_{vert}=\left(R_{\uparrow}+R_{\downarrow}\right)/2 \qquad (4)$$

It is important to emphasize here that we use the same weight W_{vert} for the axis directions up and down. We do this on the basis of the experiment [12], comparing the gravity acceleration of the ^{87}Rb atoms in two positions of which the corresponding spin vertical orientations are opposite. The equivalence of the accelerations of the atoms in the two positions were confirmed to a precision of 10^{-7}. And this was done for atoms whose number of subatomic particles is much smaller than the Avogadro number.

Finally, subtraction Eq. (3) from Eq. (4) yields

$$W_{vert} - W_{horiz} = \left(R_{\uparrow} + R_{\downarrow}\right)/2 - \left(R_{\rightarrow} + R_{\leftarrow}\right)/2 \qquad (5)$$

We see that W_{stable} has disappeared from the final formula just as any systematic errors will do if they occur.

Equation (5) can be written differently

$$2\Delta W = \left(R_{\uparrow} - R_{\rightarrow}\right) - \left(R_{\leftarrow} - R_{\downarrow}\right) \qquad (6)$$

This expression helps reduce the drift influence. Let a and b denote two weights whose difference is to be measured. By weighing in pairs we obtained a series of readings $a_i,\ b_i,\ a_{i+1},\ b_{i+1},\ ...$ If we assume that drift changes linearly from measurement to measurement, then to calculate $\Delta w = b - a$ at the same value of the drift the following expressions are suitable:

$$\Delta w = b_i - \frac{a_i + a_{i+1}}{2} \quad \text{and} \quad \Delta w = \frac{b_i + b_{i+1}}{2} - a_{i+1} \qquad (7).$$

In between the weighing of the magnet, the weight of the support was recorded to monitor the drift.

By using the expressions (7) we obtained two series of 30 to 40 estimations for $\left(R_{\uparrow} - R_{\rightarrow}\right)$ and $\left(R_{\leftarrow} - R_{\downarrow}\right)$ in one session. If there were zero difference between the actual vertical and horizontal weights of a magnet, then the null hypothesis $H_0 : \mu = 0$ would be true and the measured differences in the weights would be due to chance. For statistical verification of this hypothesis, the Independent samples t-Test is most suitable.

The basic results from the four tests are summarized in Table 1.

TABLE 1: The measured differences ΔW between the vertical and horizontal weights of two neodymium bar magnets and the corresponding Eötvös parameters $\eta = \Delta W / W$. Uncertainties are 1σ. Student p-values are two-tailed for the 76 g magnet and one-tailed for the 38 g one. All horizontal orientations of the magnets are East-West.

magnet weight	balance	ΔW (mg)	η (vertical-horizontal)	Student p-value	in σ
76 g	balance A	0.52 ± 0.15	(6.8 ± 2.0) ×10^{-6}	7.1×10^{-4}	3.4 σ
	balance B	0.70 ± 0.13	(9.2 ± 1.7) ×10^{-6}	8.1×10^{-7}	5.4 σ
38 g	balance B	0.24 ± 0.07	(6.3 ± 2.0) ×10^{-6}	5.0×10^{-4}	3.4 σ
	balance C	0.34 ± 0.13	(8.95 ± 3.4) ×10^{-6}	6.2×10^{-3}	2.6 σ

On balance B, we attained the five-sigma level that is widely considered to be the stringent threshold of a discovery in particle physics. This result alone refutes the Universality of Free Fall.
However, weighing the same magnet on balance A is another independent event (if H_0 is true), therefore the probability of occurrence of the two events equals $p(A)\,p(B)$, where $p(A)$ is p-value for the result obtained on balance A and $p(B)$ on balance B. Thus, we get $p(A and\ B) = p(A)\,p(B) = 5.8\times10^{-10}$ which corresponds to 6.2 sigma.

After these two tests it becomes clear that the deviation of ΔW from zero is essentially one-sided.

Table 1 presents the corresponding values of the Eötvös parameter $\eta = \Delta W / W$. These are also shown graphically in Fig. 2. The error bars refer to the statistical standard deviations. The systematic uncertainties were ruled out by differential weighing of the magnets in vertical and horizontal positions. Deviations from linearity are negligible due to the smallness of the interval of readings.

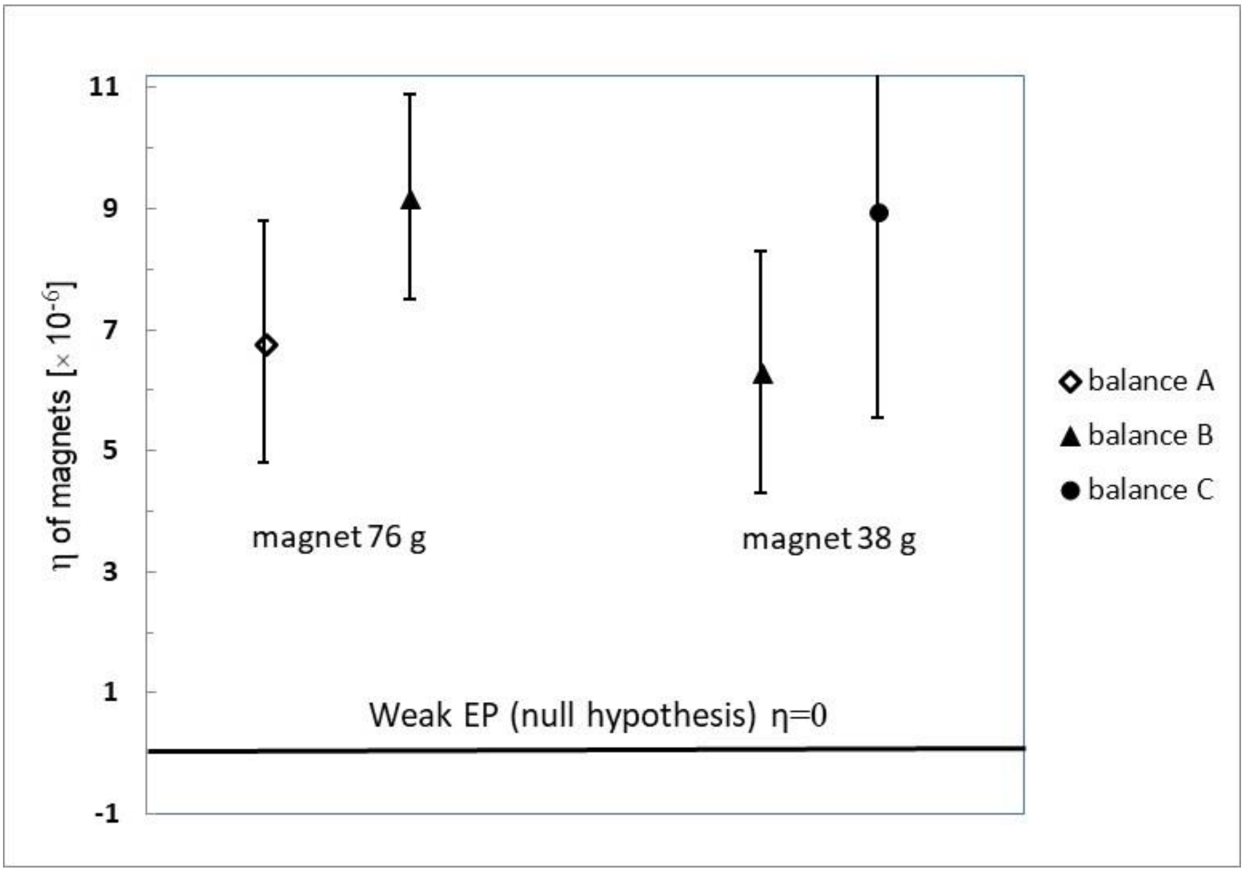

FIG. 2: The graph shows relative differences $\eta = \Delta W / W$ of the vertical and horizontal weights of two neodymium magnets. The error bars refer to the statistical standard deviations. All horizontal orientations of the magnets are East-West.

But our goal was not just to disprove the UFF and to accept the alternative hypothesis that the observations are the result of a real effect. Our statement is as follows: for each permanent magnet there is a difference between the vertical and horizontal weights and this value is the same when weighing on different balances. This is a stronger statement, and it must be verified with the help of the results obtained.

Let us verify this assertion on the 76 g magnet. There are two values ΔW measured on the balances A and B - we denote them ΔW_A and ΔW_B.

Intervals containing the true value ΔW_{true} must intersect. The intersection of the 1σ confidence intervals $\Delta W_A \pm \sigma_A$ and $\Delta W_B \pm \sigma_B$ contains points whose distances to ΔW_A and ΔW_B are less than the corresponding measurement errors σ_A and σ_B. Therefore, any value from the common segment can serve as ΔW_{true}. For our specific data, the intersection of the two 1σ confidence intervals for the weight difference is not empty. It equals $(0.57, 0.67)$ in mg. Hence the hypothesis of coincidence of the true values of ΔW_A and ΔW_B is not rejected. The same is valid for the 38 g magnet.

For all four confidence intervals of η shown in Fig.2 there is also a non-empty common interval $(7.5, 8.3)\times 10^{-6}$. The relative difference of vertical and horizontal weights η does not necessarily coincide for different magnets, nevertheless this interval may serve as an estimate of the η value for neodymium magnets.

Though we chose the East-West direction for the tests, we suppose that the horizontal weight of a magnet is independent of its specific horizontal direction. To test this hypothesis, we measured the difference between the average weights for the South-North and East-West directions of the 76 g magnet:

$$W_{South,North} - W_{East,West} = \left(R_{South} + R_{North}\right)/2 - \left(R_{East} + R_{West}\right)/2$$

The Independent samples t-Test showed that the difference between the average values lies in the interval 0.12 ± 0.125 mg., hence does not deviate significantly from zero (Student p-value = 0.36). Therefore, the hypothesis of the coincidence of the magnet weight for the selected two horizontal directions is not rejected. Of course, for a more general assertion, additional tests are required.

4. Conclusion

Lee Smolin [13] wrote: "atoms do fall, so the relationship between gravity and the quantum is not a problem for nature. If it is a problem for us, it must be because somewhere in our thinking there is at least […] one wrong assumption."

The Weak Equivalence Principle (WEP) of general relativity requires all test masses to be equally accelerated in a gravitational field. Our experiment showed that even one magnet can have different free-fall accelerations that violates the WEP. The result sharpens Smolin's question regarding the behavior of atoms in the gravitational field by providing puzzling information about it.

We hope that our study will help develop a more complete theory of gravity and dark matter.

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