Gravitational matter-antimatter impact interactions

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January 17, 2024

Abstract The production of antihydrogen by several research groups provides the opportunity to measure the gravitational behaviour of antimatter in the gravitational field of the Earth. The predictions in the literature range from normal attraction to repulsion. Applying our gravitational impact model, which is of a purely phenomenological nature, we conclude that there will be neither attraction nor repulsion under the assumption of a symmetric antigraviton distribution near the antihydrogen atom. However, a very small asymmetry must be expected and could effect the conclusion. The model, in addition, predicts normal gravitation between antimatter and antimatter particles at large distances, but strong repulsion at close range for matter as well as for antimatter pairs, whereas strong attraction will result for matter-antimatter encounters. We have further refined the model assumptions in light of recent CERN ALPHA-g measurements that indicate a certain attraction of antihydrogen by the gravitational field of the Earth.

Keywords
– gravitation – matter – antimatter

1 Introduction

1.1 Matter and hypothetical antimatter

The physical processes controlling baryonic matter and photons in our Solar System environment have been identified by famous scientists, such as Galileo Galilei, Isaac Newton, James Clerk Maxwell, Roland Eötvös, Max Planck, Hendrik Lorentz, Albert Einstein, Satyendranath Bose, Enrico Fermi, Steven Weinberg, and many others.

In particular, the “Standard Model” is very successful in formulating most aspects of particle physics, cf., e.g. https://home.cern/science/physics/standard-model (last accessed September 5, 2023). Although Borchert et al. (2022) in a recent paper agree with this statement, they add in the abstract:

“The standard model of particle physics is both incredibly successful and glaringly incomplete. Among the questions left open is the striking imbalance of matter and antimatter in the observable universe1, [...]”

Note 1 refers to Dine & Kusenko (2004):

“The origin of the matter-antimatter asymmetry is one of the great questions in cosmology.”

This asymmetry is also considered as severe problem by other authors, for instance, by Morrison (1958):

“Matter made of particles, protons, electrons, and neutrons, is all about, but anti-matter, made of antiparticles , is nowhere to be found. It is none the less possible to manufacture it, but only at great expense.”

Schuster (1898) asked already in 1898 in a “Holiday Dream”:

“We know positive and negative electricity, north and south magnetism, and why not extra terrestrial matter related to terrestrial matter […], gravitating towards its own kind, but driven away from substances of which the solar system is composed. […]. The fact that we are not acquainted which such matter does not prove its non-existence; […].’
He called this “extra terrestrial matter” anti-matter.

Dirac (1928) discussed a hypothetical positive electron in 1928.

1.2 Discovery of antimatter

The “positive electron” with a mass comparable to an electron was detected 1932 in cosmic ray showers by Anderson (1932, 1934). It was the first experimental proof that antimatter exists.

In his Nobel Lecture 1933 Paul Dirac elaborated on the positron concept:

“[...], any unoccupied negative-energy state, being a departure from uniformity, is observable and is just a positron. An unoccupied negative-energy state, or hole, as we may call it for brevity, will have a positive energy, since it is a place where there is a shortage of negative energy. A hole is, in fact, just like an ordinary particle, and its identification with the positron seems the most reasonable way of getting over the difficulty of the appearance of negative energies in our equations. [...].”

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

Not only Dirac assumed that “negative protons and positrons” would emit the same spectra in stars as atoms in normal stars, but also Alfvén & Klein (1963) and Vlasov (1956). Alfvén (1965) postulated that:

“Such antiatoms should have the same properties as ordinary atoms. For example they could build up chemical compounds similar to ordinary chemical compounds, and they should emit spectral lines of exactly the same wavelengths as ordinary atoms.”

1.3 Production of antimatter

Modern experiments can now produce antimatter and have confirmed with high accuracy that antihydrogen emits indeed the same spectral lines as hydrogen in our Earth environment (Parthey et al. 2011; Amole et al. 2012; Ahmadi et al. 2017, 2020). These results imply that hydrogen would emit the same spectra in an antimatter environment and, of course, antihydrogen as well.

The important progress achieved, in particular, by the CERN Collaborations:

1. ALPHA (Antihydrogen Laser Physics Apparatus) (cf., e.g. Amole et al. 2014; Bertsche 2018; Ahmadi et al. 2018a, b).
2. AEgIS (Antimatter Experiment: gravity, Interferometry, Spectroscopy) (cf., e.g. Kellerbauer et al. 2012; Testera et al. 2015; Brusa et al. 2017; Amsler et al. 2021), and
3. GBAR (Gravitational Behaviour of Antihydrogen at Rest) (cf., e.g. Perez et al. 2013; Mansoulid 2019; Crivelli & Kolachevsky 2020)

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Nieto & Goldman (1991) considered many arguments against “Antigravity” and discussed, in particular, arguments of Morrison (1958), Schiff (1959), and Good (1961). In the conclusion section, they mention that a consensus exists that an antiproton gravity experiment is important and further point out:

“Somewhat paradoxically, it turns out that the more precisely anomalous gravitational effects are ruled out in earth-based matter-matter experiments, the more unrestricted is the possibility that there can be a significant anomalous gravitational acceleration of antimatter.”

One of the arguments taken from Morrison (1958) assumes that a photon is blue-shifted when it falls in a gravitational field. Okun (2000) made the following statements in Chapter 6 of “Photons and static gravity”: The frequency and energy of a photon in a static gravitational field are constant, however, the momentum and the wavelength change, see also Okun, Selivanov & Teleedi (2000); Wilhelm & Dwivedi (2019). Morrison assumed that a red shifted photon has insufficient energy. The confusion is that red shift can refer to wavelength or frequency. Morrison obviously relates the shift to frequency, which is wrong, and it is thus questionable, whether the statement that energy is not conserved by the “antigravity” theory can be justified by this assumption.

Caldwell & Dvali (2020) expect that the experiments will show that antimatter is attracted by matter as the interacting field in Einstein’s theory has a spin = 2, cf., e.g. Ogievetsky & Polubarinov (1963). Particle and antiparticle attraction is also predicted by Schiff (1959).

Arguments for matter-antimatter repulsion are presented, among others, by Cabboleti (2014), Villata (2011, 2013, 2015), Hajdukovic et al. (2020a, b), Hajdukovic & Walter (2021), and Chardin et al. (2021). Scherk (1979) considered “antigravity” as well as “antigravitons”.

In a paper by Anderson (1933), the editor of Physical Review suggested the name “positron” for the positive electron.

Emphasis by Dirac.
No experimental violation of the Charge, Parity, and Time theorem (CPT) has been observed in the matter-dominated Universe, cf. [Nieto & Goldman (1991)], who also state that the CPT theorem does not determine the attraction or repulsion between matter and antimatter. Therefore, a violation of the principle of equivalence is not excluded by CPT. The invariance of the CPT theorem is now also experimentally tested with antibaryons [Ahmadi et al. 2017; Borchert et al. 2022].

The Weak Equivalence Principle (WEP) [Einstein 1911; 1916] has been experimentally confirmed many times with matter particles (cf., e.g. Eötvös, Pekár & Fekete 1911, 1916) and with antimatter (Ahmadi et al. 2017; Borchert et al. 2022).

The planned experiments with antihydrogen will be of great importance to show, whether or not WEP is valid for antimatter in a matter environment [Amsler et al. 2021; Chardin et al. 2021].

Another question in relation to matter and antimatter is whether the observed asymmetry is present in the complete Universe or if this is only a local aspect. In line with Dirac’s suggestion, proposals are presented that assume a symmetric creation of the Universe. They are discussed, for instance, by Goldhaber (1956); Sakharov (1966); Kleinknecht (2001); Villata (2013); Willmann & Jungmann (2016), and Hajdukovic (2020a). The separation of the matter and antimatter could be achieved, when small density inhomogeneities are enlarged by gravitational instabilities. Goldhaber (1956) speculated that the statistical fluctuations might have produced galaxies and “antigalaxies”. Hajdukovic (2020a) summarized three models with repulsion between matter and antimatter. Matter attracts, of course, matter. The first two models, called “wild” by Hajdukovic, “assume a symmetric Universe with equal amounts of matter and antimatter”:

1. The Dirac-Milne Cosmology, cf., e.g. Benoit-Levy & Chardin (2012), with gravitational repulsion both between matter and antimatter as well as between antimatter and antimatter. This leads to a CPT violation.
2. The Lattice Universe, cf., e.g. Villata (2013), with antimatter-antimatter attraction. There is no CPT violation.
3. Quantum vacuum fluctuations and virtual gravitational dipoles (GD) (Hajdukovic 2013, 2020b; Hajdukovic & Walter 2021). Again there is attraction between antimatter and antimatter and no CPT violation. The Universe might alternate between matter and antimatter cycles.

Banik & Kroupa (2020) conclude, however, that the gravitational dipole (GD) model does not satisfy galaxy rotation curve observations and Solar System constraints, in agreement with [Iorio 2019].

Many more papers discuss the antimatter experiments and the results achieved or expected. We could only mention a small selection of them as an introduction to processes of matter-antimatter interactions based on our proposed gravitational impact model [Wilhelm, Wilhelm & Dwivedi 2013; Wilhelm & Dwivedi 2020].

### Gravitational impact model

#### 2.1 The model

Our heuristic model is based on the idea of a gravitational impact concept presented by Fatio de Duillier (1690) at the end of the seventeenth century. Small corpuscles moving with high speed interact with masses. The attraction results from a shielding effect caused by the bodies. Many objections have been raised against the shielding concept, in particular, the disturbing effect of a third body between two masses was discussed by Drude (1897). We felt that this problem can be overcome by replacing the shielding by an interaction of hypothetical massless particles with the masses. Quadrupoles are good candidates, because they have small interaction energies with positive and negative electric charges and, in addition, can be constructed with a spin of $S = \pm 2$ (Wilhelm, Wilhelm & Dwivedi 2013). We will call the quadrupoles now gravitons, cf. Footnote 3. They have no mass and a speed of light, the mean value of their energy is $T_G$ and that of the magnitude of the momentum $|p_G|$. Estimates on these quantities will be given in Subsection 3.4, but the spectral distribution is unknown.

It was, however, necessary to introduce energy and momentum losses of the gravitons during the interaction with matter, i.e. $T_G$ will be reduced to $T_G(1 - Y)$, when it is re-emitted, and $|p_G|$ to $|p_G(1 - Y)|$, where $0 < Y \ll 1$. The attraction between matter particles is accomplished by the exchange of reduced-momentum gravitons between them that do not balance the impact of the gravitons from the opposite direction. The gravitational impact interaction process is demonstrated in Figure [i] with only one of very many reduced gravitons in Input A (Path 2). In a sense, the particles will not attract each other, but are pushed together, in close analogy to Fatio’s process.

The long-range gravitational force is thus described by a heuristic impact model with hypothetical massless

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4 A proof of this theorem has been given by G. Lüders (1957).

5 Quadrupoles with two positive and two negative elementary charges have been proposed.
entities propagating at the speed of light in vacuum and transferring momentum and energy between massive bodies through interactions on a local basis. In the original publication (Wilhelm, Wilhelm & Dwivedi 2013), a spherically symmetric emission of secondary entities have been postulated. The potential energy problem in a gravitationally bound two-body system with arbitrary mass distribution has been studied in Wilhelm & Dwivedi (2015) in the framework of the impact model of gravity. This study has indicated that an anti-parallel emission of a secondary quadrupole—now called graviton—with respect to the incoming one is more appropriate, because it does not violate the energy conservation principle. It could be shown that in the latter case the difference of the potential gravitational energy during an approach of the masses corresponds to the difference of the sum of the reduced energy of the gravitons on their way between the masses. The model could successfully be applied to secular perihelion advances [Wilhelm & Dwivedi 2014] and radial accelerations of disc galaxies [Wilhelm & Dwivedi 2018a,b]. In analogy to the graviton interaction, we also formulated a heuristic model of the electrostatic forces. Repulsion of particles with the same charge and attraction of oppositely charged particles could be achieved with dipoles interacting directly or indirectly⁶ with the particles [Wilhelm & Dwivedi 2021].

2.2 Matter and matter interactions

The interactions of the gravitons $\pm \mathbf{p}_G$ with masses $M$ and $m$, respectively, occur with virtual gravitons (emitted from a particle with $\pm \mathbf{p}_G$) and result in zero spin and momentum (assuming $|\mathbf{p}_G| = |\mathbf{p}_C|$) with an energy of $2T_G$ [Wilhelm & Dwivedi 2020]. The reduced energy $T_G(1 - Y)$ will liberate a virtual graviton. This process will be called a direct interaction. It is demonstrated in Figure 1 on top of Mass 2 by light shading (Input B, Path 1a) and below by dark shading (Path 1b). The momentum balance is zero in this case. If, however, a graviton with reduced momentum arrives from Mass 1 on Input A the balance is

$$-\mathbf{p}_G(1 - Y) - \mathbf{p}_G(1 - 2Y) + \mathbf{p}_G + \mathbf{p}_C(1 - Y) = +2Y\mathbf{p}_G ,$$  
(1)

for only one of the many reduced gravitons required. We assume that the total number of reduced gravitons per time interval, e.g. 1 s, is $n$ for $1 g = 9.81 \text{ m s}^{-2}$

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⁶Direct and indirect interactions are defined in the case of gravitons and antigravitons in Subsections 2.2 and 2.3 respectively, in analogy to the electrostatic situation.
gravitational acceleration of $m$ towards the Earth with mass $M$. This gives a momentum balance of $+2nYp_G$.

Gravitational processes with antimatter will require the addition of antigravitons in the next subsections.

It is assumed that the particles Mass 1 and Mass 2 are far apart relative to their sizes and thus the double-reduced graviton on the left side is not expected to interact with Mass 1. We consider subatomic particles here. Large solid bodies and the situation, when the particles approach each other, are discussed in Subsections 2.4 and 2.5.

2.3 Antimatter and antimatter interactions

The impact model has up to now only been applied to matter particles and photons. In Figure 2 the situation is shown for two antimatter bodies in the same graviton environment as in Figure 1. Antimatter is assumed to emit gravitons with opposite spin directions in their creation phase as shown in the lower part of Figure 2 for Mass 2. They will be called virtual antigravitons. In line with this definition, real antigravitons have opposite directions of spin and momentum in contrast to gravitons. The shaded area illustrates an indirect interaction caused by the fact that the interaction of $-p_G$ with $+\bar{p}_G$ in the creation phase would give a forbidden spin of $S = 4$, whereas the annihilation phase (at the bottom of Mass 2) reverses the spin direction and a total spin of zero will result. Since the indirect process is much more complicated than the direct one, we expect only a very small fraction of indirect interactions compared with direct ones. Nevertheless, these indirect interaction affect the symmetry of the graviton and antigraviton distributions and will be discussed in detail in Subsection 3.2. If Input B is replaced by Input A, the evaluation of the momentum balance is

$$-p_G(1 - Y) - p_G(1 - 2Y) + p_G - p_G(1 - Y) = -2p_G(1 - 2Y),$$

assuming $|\pm p_G| = |\pm \bar{p}_G|$.

Considering the very small value of $Y \leq 10^{-20}$, cf. Figure 3 of [Wilhelm & Dwivedi 2020], the resulting repulsion would be many orders of magnitude larger than the attraction implied by Equation (1). This might, however, be in conflict with observations referenced in Subsection 1.3 that spectral lines of antihydrogen observed on Earth are not different from corresponding hydrogen lines, because the exchange forces between the proton and electron, respectively, antiproton and positron, in hydrogen and antihydrogen would be very different and could affect the electrostatic forces. Details depend on the value of $Y$ and the uncertainties of the spectral measurements.

Fig. 2 Antimatter-antimatter interaction in a graviton environment. Both Masses 1 and 2 consist of antimatter ($\bar{M}$ and $\bar{m}$). If there is no interaction between them, they are in equilibrium, cf. Path 3a (shaded area) and a corresponding Path 3b as shown in Figure 3. If a reduced antigraviton $-\bar{p}_G(1 - Y)$ from Mass 1 is interacting with Mass 2 (Input A)–eliminating the process on Path 3a that will be called indirect interaction – the momentum balance for Mass 2 then gives in Equation (2) a momentum of $-2\bar{p}_G(1 - 2Y)$. Mass 2 is strongly repulsed. For reasons of symmetry the same is true for Mass 1. By reversing all antimatter into matter and gravitons into antigravitons, we would obtain the same result.

The same result would also be obtained for a matter-matter interaction in an antigraviton environment. If, however, an ambigraviton environment according to Subsection 2.3 is assumed, we get the configuration of Figure 1 but for antimatter.
Fig. 3 Matter-antimatter gravitation in graviton environment. With no interaction between $M$ and $\bar{m}$, the graviton $-\mathbf{p}_G$ from the background in Input B (light shading) would be compensated by $+\mathbf{p}_G$ from below. Mass 2 would be at rest. The reduced graviton $-\mathbf{p}_G(1-Y)$ arriving from Mass 1 at Mass 2 (Input A), which replaces $-\mathbf{p}_G$, cannot combine with $+\bar{p}_G$, because a spin $S = 4$ would result. The other side of Mass 2 would provide an appropriate partner in the destruction phase for an indirect interaction. The momentum balance for Mass 2 then is zero, see Equation (4). Mass 2 would be at rest in this case.

An ambigraviton environment with symmetric direct interactions of antigravitons would not change the situation. Note, however, that the discussion in Subsection 3.2 indicates a small asymmetry.

Fig. 4 Matter-antimatter gravitation in antigraviton environment. If there is no action from Mass 1 on Mass 2 (shaded area; Input B), then Mass 2 is in equilibrium. The interaction process on the opposite side, in analogy to the dark shaded area in Fig. 1 is not shown here for antimatter and antigravitons. It will result in $+\mathbf{p}_G$ and $+\bar{p}_G(1-Y)$. If a reduced graviton $-\mathbf{p}_G(1-Y)$ from Mass 1 is active (Input A) – eliminating the process in the shaded area of Path 6 – the momentum balance for Mass 2 is $+2\mathbf{p}_G(1-Y)$, see Equation (5). It is attracted by Mass 1. The inclusion of gravitons, however, would give a situation as in Figure 3.
What appears to be a severe problem for this interaction model, will eventually turn out to be extremely positive, because the assumption of a pure graviton environment in both figures was completely arbitrary and an antigraviton environment could have been added. Therefore, we agree with the statement of Alfven (1965):

“It is postulated that a cosmological theory should be matter antimatter symmetric, and introduce no ad hoc laws of nature.”

Thus we have to realize that in both figures a graviton-antigraviton environment would be appropriate (ambigravitons) to modify the expression “ambiplasma” (cf. Alfven 1965). Isolated matter and antimatter particles both experience balanced direct and indirect interactions in such an ambigraviton environment.

In Figure 2 the Input A then replaces Input B and the process on Path 4 corresponds to the inverse version of Path 2 in Figure 1 with a momentum balance of

\[
\begin{align*}
-\mathbf{p}_G(1 - Y) - \mathbf{p}_G(1 - 2Y) + \mathbf{p}_G + \mathbf{p}_G(1 - Y) &= +2Y \mathbf{p}_G , \\
&= (3)
\end{align*}
\]

which is the same as for matter-matter interactions.

2.4 Matter and antimatter interactions

The Input B in Figure 3 demonstrates on Path 3a an indirect interaction. A graviton \(-\mathbf{p}_G\) traverses \(\bar{m}\) (Mass 2) and exits as antigraviton with a momentum \(-\mathbf{p}_G(1 - Y)\). A transformation from a graviton to an antigraviton is shown, because antimatter can only emit antigravitons in our model. The impact of this traversal on \(\bar{m}\) will be balanced by the effect of the graviton \(+\mathbf{p}_G\) entering at the lower left-hand corner on Path 3b. This figure finally shows the matter-antimatter process as far as the gravitons are concerned by considering Input A. The reduced graviton indirectly interacts with Mass 2 on Path 5 and results in a momentum balance of zero:

\[
\begin{align*}
-\mathbf{p}_G(1 - Y) + \mathbf{p}_G(1 - 2 Y) + \mathbf{p}_G + \mathbf{p}_G(1 - Y) &= 0 . \\
&= (4)
\end{align*}
\]

The addition of an undisturbed antigraviton distribution also cannot provide a momentum effect on antimatter, and no attraction or repulsion is expected under these conditions. However, an indirect interaction of an antigraviton with Mass 1 will cause a disturbance. Arguments are presented in the next subsection indicating that this effect is small.

From Figure 3 we find for one reduced graviton

\[
\begin{align*}
-\mathbf{p}_G(1 - Y) + \mathbf{p}_G(1 - 2 Y) + \mathbf{p}_G + \mathbf{p}_G(1 - Y) &= +2 \mathbf{p}_G(1 - Y) , \\
&= (5)
\end{align*}
\]

and a total momentum balance of \(+2n \mathbf{p}_G(1 - Y)\), cf. discussion in the context of Equation (4). Matter-antimatter gravitation in an antigraviton environment thus leads to unrealistic results for distant particles. Ambigravitons are required to avoid this situation. Input A in Figure 3 would then replace a graviton and not an antigraviton of Input B, leading to zero momentum balance as in Figure 3. It should also be mentioned that Figures 3 and 4 imply a violation of the momentum conservation principle without ambigravitons. In an ambigraviton environment, the relation between Mass \(M\) and Mass \(\bar{m}\) can be inverted without violating the momentum balance.

In discussing Figure 1 in Subsection 2.2 it has been pointed out that the interacting particles (Mass 1 and Mass 2) should be far apart. It is necessary at this stage to clarify that the interacting particles are not close together for an antimatter experiment in the gravitational field of the Earth. The emissions of virtual gravitons and antigravitons that interact in our model with real gravitons and antigravitons occur from subatomic particles, such as electrons, protons and neutrons. Larger bodies are conglomerations of these particles and are rather transparent for gravitons and antigravitons (as discussed at the end of Subsection 2.5), before an interaction with a subatomic particle happens. For a spherically symmetric body, which is a good approximation for the Earth, the gravitational attraction of a particle above the surface of the Earth is controlled by the distance to its center. Therefore, we can assume for the antihydrogen gravity experiment a mean separation of an Earth radius between the interacting subatomic particles. The result of Equation (4) with zero momentum thus is relevant for the antihydrogen experiment, assuming no indirect interactions, which would affect the symmetry of the ambigraviton environment near particles.

This surprising prediction was the reason for writing this article, since in the literature either attraction or repulsion of antimatter in the gravitational field of the Earth had been discussed. Should our prediction in future measurements be confirmed, this would support the model. If attraction or repulsion is observed, the model would have to be reconsidered.

While working on a revision of this manuscript, a Nature article was published on September 28, 2023 with ALPHA-g measurements by Anderson et al. (2023). They found that the best fit of the local acceleration of antimatter towards the Earth was 0.75 g (with relative statistical and systematic uncertainties of ±18.5 % and ±21 % as relative simulation uncertainty). The probability that the result could occur under the assumption that the gravitational field of the Earth does not act
on antihydrogen was $2.9 \times 10^{-4}$. The probability that repulsive gravity is consistent with the data is less than $10^{-15}$.

In view of these findings, modifications of our model assumptions will be discussed in Subsection 3.2.

2.5 Short range forces

If the subatomic particles are at close range, the situation is very different from the configurations discussed so far. In this context, we emphasize the prediction of Fleming (2017) (without referring to “The Matter-Antimatter Dipole” hypothesis).

“It is clear from known physics that matter and antimatter behave in such a way that matter is repelled from matter at short-range and by extension, antimatter is repelled from antimatter. It is also clear that at short-range, matter and antimatter attract.”

Is our impact model in agreement with these expectations? In Figure 1 with the assumption of ambigravity there are two effects that can be identified:

1. If the particles approach each other, the double reduced graviton $+p_G(1 - 2Y)$ on the left-hand side resulting from Path 2 will interact with Mass 1 and enlarge the attraction, because it will reduce the graviton momentum on Input A by $2Yp$. There will be a tendency of further enhancements, because the reductions at Input A will also become more important.

2. This cycle comes, however, soon to an end, when Mass 1 prevents some antigravitons $-\bar{p}_G$ to reach Mass 2. They would have traversed $m$ on a path corresponding to Path 3a, shown in Figure 2 and Figure 3 for gravitons and $\bar{m}$, compensated by the opposite Path 3b in Figure 3. The shielding of antigravitons is accompanied by interactions of reduced gravitons from Mass 1 with Mass 2. This causes a very strong repulsion, as Path 4 in Figure 2 demonstrates for antimatter particles in a graviton environment.

In Figure 4 finally a close encounter of matter and antimatter can be set up by supposing that the antigraviton of Path 6 is indeed shielded by Mass 1 and is replaced by the reduced graviton on Path 5. This gives a very strong attraction. It can be concluded that the model yields the results as expected.

Nevertheless, at least two questions have to be answered:

1. The indirect interaction with an antiparticle (see, for instance, Path 3a in Figure 3) changes a graviton into a reduced antigraviton. An inversion from an negative antigraviton into a negative reduced graviton by Mass 1 is shown in Figure 4. The question thus is, whether in a matter dominated region all antigravitons will soon be converted to gravitons—with an opposite process in an antimatter environment?

2. The observations on Earth require that a graviton-antigraviton environment must be present in our model to avoid unusual effects, cf. Subsection 2.4. Does the Earth reverse many antigravitons?

For both questions, it has to be realized that gravitons can travel very long distances through solid bodies, before they interact with a particle. This is indicated by the small effect that multiple interactions within the Sun have on secular perihelion advances (Wilhelm & Dwivedi 2014) and that only about five interactions of a graviton on its way from the center of a disk galaxy to the boundary are expected (Wilhelm & Dwivedi 2018a,b). The expectation in Subsection 2.3 that indirect interactions are much less frequent than direct ones will be supported by the discussion in Subsection 3.2. Since we assume equal amounts of matter and antimatter in the Universe, the long travel distances will on average maintain a constant graviton-antigraviton mixture and the Earth will only convert a small fraction of antigravitons into reduced gravitons.

3 Performance of the impact model

The impact model could successfully be applied to many gravitational observations in the matter environment, cf. Wilhelm & Dwivedi (2020) and references therein. The experimental progress in the production of antihydrogen as outlined in Section 1 motivated us to expand the proposed model to antimatter problems as well.

3.1 Symmetry

The result of Equation 2 obtained from Figure 2 demonstrates that a graviton environment as assumed...
If one antigraviton in Figure 4 (Input B) is replaced by a reduced graviton (Input A), we get $+2 \bar{p}_G(1 - Y)$. The question now is what fraction of the $n$ negative antigravitons in 1 s must be replaced in Figure 3 to get accelerations of $+0.75 \, g$, $+1.04 \, g$, or $+0.44 \, g$, respectively. The answer follows from equating $+2 n \bar{p}_G(1 - Y) \times x Y$ with the result of Equation 4, which leads to a gravitational attraction of $1 \, g$, multiplied by the corresponding conversion fraction:

$$+2 n \bar{p}_G(x Y - x Y^2) = +2 n p_G(Y - x Y + 2 x Y^2) \times [0.75, \, 1.04, \, 0.44] \quad . \quad (7)$$

The quadratic terms of $Y$ can be neglected, because of the very small value of $Y$ (cf. Subsection 2.3). The evaluation then gives values of $x Y = [0.43, \, 0.51, \, 0.31] \, Y$. They can be adjusted to comply with more precise measurements in the future. The fraction is, in any case, extremely small and supports the speculations in Subsection 2.4 that only very few antigravitons would be converted by matter.

3.3 Interactions between particles at close range

The impact model thus predicts normal gravitational attraction between remote masses of matter and matter as well as of antimatter and antimatter, whereas there is no interaction between matter and antimatter in a symmetric antigraviton environment. In Subsection 2.5 processes have been discussed, if this condition is not met.

As pointed out by Fleming (2017), cf. Subsection 2.5, this behaviour changes at close range, where we find a very strong repulsion between matter and matter as well as between antimatter and antimatter, whereas a very strong attraction is characteristic for near matter-antimatter encounters.

3.4 The cosmological constant problem

The gravitation between particles and photons cannot be treated without considering the cosmological constant and the problem of a consistent interpretation within the standard model. The cosmological constant has to be many orders of magnitude smaller than predicted by the standard model. From the immense literature on this topic values of $10^{-122}$ to $10^{-166}$ can be quoted (cf., e.g. Abbott 1988; Weinberg 1989; Martin 2012; Planck Collaboration 2020). In line with our proposal, we find a suggestion by Lombriser (2019) very

\[10\] Electrostatic forces are not taken into account. Neutron and antineutron interactions could be appropriate models.
interesting that not every vacuum energy is gravitating. The gravitational impact model in Wilhelm, Wilhelm & Dwivedi (2013) had assumed in Equation 16 an emission coefficient \( \eta_G = c_0^2/(2h) \) of quadrupoles by matter (corresponding to half the intrinsic de Broglie frequency per kilogram) with \( c_0 \) the speed of light and \( h \) the Planck constant. The justification for assuming half the frequency was that two emissions of virtual gravitons are involved per graviton emission. Do we have to adjust the emission coefficient in a matter-antimatter system with ambigravitons? The answer is no, because the direct interactions (see Path 1a in Figure 1) and the indirect interactions (see Path 3a in Figure 2) equally contribute to the production of reduced gravitons in the case of matter particles and reduced antigravitons for antimatter particles. Thus the proposed interaction between matter and matter particles will not change in an ambigraviton environment and, for reasons of symmetry, we can expect the same between antimatter and antiantimatter particles.

Figure 3 of Wilhelm & Dwivedi (2020) is therefore relevant also under an ambigraviton environment, and we can obtain some estimates from it. With a value of the electron radius \( r_{G,e} = (2.43 \pm 0.39) \times 10^{-16} \text{ m} \) (smaller than or equal to the classical electron radius) and an electron mass \( m_e \), the ambigraviton density is \( \rho_G = 2.75 \times 10^{41} \text{ m}^{-3} \) and with the surface mass density \( \sigma_G = m_e/(4\pi r_{G,e}^2) \) in Equation 23 of Wilhelm & Dwivedi (2020), the Equation 28 can be written as

\[
\epsilon_G = T_G \rho_G = 2\pi G_N \sigma_G^2 / Y, \tag{8}
\]

where \( \epsilon_G \) is the undisturbed ambigraviton energy density, \( T_G \) the graviton or antigraviton energy and \( G_N \) Newton’s constant of gravity. The choice of the reduction parameter \( Y \) then determines the remaining quantities. With a value of \( Y = 10^{-20} \), we get \( \epsilon_G = 6.22 \times 10^{10} \text{ J m}^{-3} \) and \( T_G = 2.26 \times 10^{-31} \text{ J} \).

If we now consider that only the reduced portion of the ambigravitons mediates the gravitational force in the impact model, it can be concluded that the relevant gravitational energy density is

\[
Y \epsilon_G = 6.22 \times 10^{-10} \text{ J m}^{-3}, \]

corresponding to estimates of the dark energy in the literature, cf., e.g., Beck & Mackey (2007); Frieman, Turner & Huterer (2008).

4 Conclusion

From our hypothetical impact model of gravity applied to matter-antimatter configurations in Figures 1 to 4 we expect neither attraction nor repulsion between matter and antimatter bodies at large distances but an attractive force at short ranges. The gravitational forces between antimatter and antimatter particles should be the same as in matter-matter systems. These predictions are based on a symmetric antigraviton environment. Recent measurements published in Anderson et al. (2023) indicate that we must not assume a perfect symmetry of antigravitons near matter particles. The measurements could be explained by a minor adjustment of the model assumptions concerning the fraction of indirect to direct interactions.

Acknowledgements

This research has made extensive use of the Astrophysics Data System (ADS). Administrative support has been provided by the Max-Planck-Institute for Solar System Research, Göttingen, Germany. We thank two Reviewers for many constructive and valuable comments which improved the presentation of the manuscript.

Data Availability

The physical quantities discussed in Section 3.4 are taken from Wilhelm & Dwivedi (2020); DOI:10.5772/intechopen.86744.
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