EMPIRICAL LIMITS TO ANTIGRAVITY

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ABSTRACT

An upper bound of one part in 10^6 - 10^7 is derived for the violation of the equivalence principle for antimatter in the form of antiprotons based on existing data for bulk matter, electrons, positrons, neutrons and protons.

INTRODUCTION. The possibility that the gravitational mass of the antiproton could be different from that of the proton is a fascinating possibility, which has caught the public interest in its most extreme form as 'anti-gravity'. Such a difference remains a possibility within the present theoretical framework^{1,2}. A possible way for it to arise can be visualized in terms of a close analogy to the usual Coulomb interaction, which changes sign from attraction to repulsion on changing a charged particle into its antiparticle. This is due to the vector nature of the photon exchange. Similarly an anomalous gravitational interaction associated with vector exchange ('gravi-photon') leads to a 'gravi-Coulomb' potential. The corresponding 'gravi-charge', and therefore the interaction, changes sign on changing a particle into its antiparticle. Such a coupling is quite possible within the framework of supersymmetric theories as has been discussed by Goldman, Hughes and Nieto³. By analogy with the Coulomb potential one thus sees that an anomalous gravitational interaction may give rise to background potentials which modify the apparent mass of a particle. Will such interactions violate the equivalence principle? In a 'gravi-Coulomb' field the principle will remain valid for antiparticle-particle pairs such as $p\bar{p}$ or selfconjugate neutral mesons and thus for bulk matter. It may be individually violated for the proton or antiproton. In this case the proton and antiproton will have opposite 'gravi-charge', so that in the gravitational field a part of the gravitational mass switches sign. The very possibility that it can seriously be envisaged that the inertial and gravitational masses differ raises the question of the experimental limits to such effects. The availability of a rather abundant source of low energy antiprotons at CERN has stimulated interest in performing a direct gravity experiment. An investigation of the free fall of the antiproton in the gravitational field is presently planned at LEAR according to a suggestion by Goldman and Nieto aiming at a few % or slightly better precision⁴. In this case the antiproton will be allowed to fall freely in the Earth's gravity field, an

experiment that in all essence is a modern repetition of Galileo's demonstration in Pisa, but now carried out with antimatter. Clearly the interpretation of such an experiment is most direct and it has a considerable pedagogical appeal. In addition, it would be the first direct test of equivalence for anti-baryonic matter.

At the same time it is appropriate to ask the question whether existing experiments looked at in the right perspective already contain similar information in nearly as direct a way and, maybe, to a larger precision. This is the issue we address in the present note. We briefly explore the experimental limits for "anti-gravity" effects which can be reliably concluded from present experiments with only weak assumptions about the nature of the phenomenon.

EXPERIMENTAL LIMITS TO THE EQUIVALENCE PRINCIPLE. We now inspect the evidence for the validity of the equivalence principle in turn for bulk matter, electrons, neutrons, atoms and protons.

Consider first the case of ordinary matter in bulk. In spite of a vigorous search for the effects of a fifth force⁵ of finite range violating the equivalence principle no persuasive evidence for such an anomalous interaction has been found. As a consequence of these studies the equivalence principle is now exceedingly well established for bulk matter in a situation where the entire Earth generates the gravitational field; even if there were evidence for a fifth force, this conclusion is not much affected. By modern Eötvös-type experiments it has been established to a precision of 1.2 parts in 10^{11} that the equivalence principle holds in the gravity field here on Earth^{6,7}, i. e. over 100 times more accurately than the original experiment by Baron von Eötvös⁸ (the null experiments based on the Sun's gravitational field are of course not relevant to the present discussion⁹, since a Galileo-type of experiment is performed in the Earth's, and not in the Sun's, gravitational field).

In addition Niebauer et al.¹⁰ and Kuroda et al.¹¹ have demonstrated that bulk materials and thus atoms of different isotopic composition have identical gravitational interaction to 2 parts in 10^{11} .

At this point the issue is not so much the equivalence principle for bulk matter, which is accurately established, but whether it can be validly argued that this principle is also valid on the level of individual atoms, electrons, positrons, protons, neutrons or antiprotons.

For the electron-positron system the inertial masses are accurately the same. An upper limit for the difference between their gravitational masses of 10% (i. e. 50 keV) was directly established already some time ago¹². Below we will argue that a much lower limit is implicit in present experiments.

For neutrons, in direct experiments using the influence of gravity in neutron interferometry¹³ and on precision-determined neutron scattering lengths¹⁴ one establishes in both cases that the neutron inertial and gravitational mass are equal to at least one part in 10^3 (i.e. to 1 MeV).

However a far more precise limit is obtained from Eötvös-type experiments by the following reasoning. The equivalence principle has been established for pairs of materials with varying isotopic compositions and thus varying neutron excess. Starting

from this observation it is then clear that the equivalence principle also should hold to high precision on the level of individual atoms and for nuclides. In this case the electrons and protons always come in pairs in the materials, since bulk matter is neutral. The neutron content in the observed materials can be varied and, since the neutrons are weakly bound, it is immediately possible to conclude that the equivalence principle also holds for individual neutrons. The precision of this statement is, however, a 100 times less precise than for atoms due to the relatively small number of neutrons in excess of protons in nuclei. This method establishes equivalence for the neutron on the level of a few parts in 10^9 (i.e. to 1 eV), about 10^6 times more accurately than the direct determination. Indeed, a comparison of hydrogen to deuterium in an Eötvös-type experiment would here be ideal, since then one neutron is simply added to the normal hydrogen and with an extremely small binding at that. Even in the absence of such ideal evidence the situation is very convincing.

For protons, a very direct demonstration of equivalence is obtained as follows: from the experimental fact that the e^-e^+ gravitational mass difference is less than 50 keV¹² and that atoms and neutrons behave identically in the gravity field to high precision it follows that a proton mass anomaly must exactly compensate the electron one and thus be less than 50 keV, i.e. 5 parts in 10^5 .

However, a vastly improved limit is obtained by the following plausible, but less direct argument: the neutron and proton are so similar hadronic objects that it would be most bizarre if equivalence would be a good concept for neutrons but not for protons: there is every reason to believe that the gravitational interaction has the same character in both cases. We can then conclude that the equivalence principle holds for the proton on the level of one part in 10^9 .

As a consequence, since the equivalence principle in this case holds for neutrons and protons on the level of one part in 10^9 , this gives an improved limits for electrons too, since otherwise the principle would not be valid for atoms in conflict with observation. In this case the mass effect on the electron must correspond to that of the proton so that the corresponding electron limit for equivalence is two parts in 10^6 or, alternatively, 1 eV in its gravitational mass.

Can these precise upper limits for neutrons and atoms be trusted? Further, can we trust the corresponding limits for protons and electrons obtained under the weaker additional assumption that neutrons and protons behave in the same way in the Earth's gravity field? After all, the result was deduced from the properties of bulk matter assuming that an anomalous effect on individual constituents will not be systematically shielded. Indeed, it has been stated that the validity of the principle for the individual constituents cannot be tested, since there is a background of strong electric and magnetic stray fields in a medium, far stronger than the gravitational field on individual atoms². Since the equivalence principle holds experimentally to high precision, we see no reason why the presence of such fields should be a matter of concern in the absence of any reasonable argument to the contrary. While it is certainly correct that any claim of a positive observation of an anomaly must be confronted with this possibility, we find it unreasonable to assume that stray fields would systematically lead to a null effect unless

a presently unknown symmetry principle is invoked with a reasonable degree of plausibility. In agreement with the attitude of the authors of ref. 2 we therefore completely accept that the extension to the constituents is appropriate for a null effect.

LIMITS ON THE GRAVITATIONAL MASS OF THE ANTIPROTON. Let us now turn to the relevance of these observations for the case of the antiproton.

When the proton-antiproton mass splitting is determined independently of gravity from the energy levels in antiprotonic atoms or from the e/m ratio of an antiproton in a known magnetic field, present precision measured in units of the proton mass is typically 2 parts in 10^6 with a precision of one part in 10^9 aimed for in an ongoing experiment¹⁵.

Let us next assume that the equivalence principle does not hold on some level on which we want to establish restrictions. Unless we want to make the additional very strong and *ad hoc* assumption that this happens only for antimatter in the form of antiprotons, this means that we must reasonably take it for granted that it is broken on a similar level for matter in the form of protons as well. Indeed the tighter any experimental limits for the validity of the equivalence principle can be made for protons, the more unreasonable it would become to assume that the antiproton would violate it by large amounts.

We thus see that the only reasonable way to have any substantial experimental violation of the equivalence principle would be to argue either:

1. that there are substantial violations of the equivalence principle for matter on the level of individual constituents, but that bulk matter using classical physical effects finds a way to rearrange itself in such a manner that observations give a null effect to high accuracy.

2. that the equivalence principle holds accurately for matter but not for antimatter in the Earth's gravitational field, so that there is no basic symmetry between the two.

The first of these possibilities we find highly implausible: not only does it require an initial phenomenon of uncertain and unusual nature; in addition a conspiracy to hide it is also required.

The second possibility is more interesting in view of the possibility of a cancellation between contributions from scalar and vector exchange in certain schematic models¹. The 'gravi-Coulomb' interaction is symmetric for particles and anti-particles, but for a sign change. Since the equivalence principle is accurately respected experimentally, a violating interaction needs a compensating term for interaction with matter: we need a null or nearly null effect for both electrons and nucleons separately. The theoretically possible way out would be the cancellation of a vector and scalar contribution to the interaction associated with appropriate masses; such cancellations indeed may occur in schematic supersymmetric models between equal fermions in the static limit and for mass-less exchanges¹. More precisely, the anomalous gravitational term for a static source has the schematic Yukawa form:

$$V_{an}(r) = -GM_1 M_2 [\pm a \exp(-r/v) / r + b \exp(-r/s) / \gamma_1 \gamma_2 r] ,$$

where the coefficients a, b are to be compared to unity for the normal gravitational interaction, $\gamma_{1,2}$ is the Lorenz factor of the antiproton and the Earth in this static field and v, s are the range parameters of the scalar and vector field, respectively. The searches for an anomalous gravity interaction has found no evidence for any anomaly at a vast range of distances from meters to the distance to the Sun and even so, as limits to very small contributions to the normal gravity field. This clearly implies either that a, b are extremely small or that the ranges s, t are nearly identical. Only then can it be prevented that effects do not show up already for ordinary matter. Indeed, if one plans for experiments on the antiproton on the level of a few % in the mass, one must accept that a, b are assumed to be of the order of unity, if the range of the interaction is comparable to the radius of the Earth or larger. If it is much smaller (say of the order of 1 km or less), these coefficients must be enormous so that at laboratory distances anti-gravity is far stronger than ordinary gravity in Cavendish type experiments. Thus, an additional *ad hoc* assumption of nearly identical range is required and most likely the exchanged mass needs to be of the order 10^{-8} eV or less, although a more natural mass scale would be the Planck mass 10^{19} GeV.

A more powerful restriction on the scalar interaction is imposed by the different energy dependence of the scalar and vector interaction implied by the Lorenz factor, which prevents an exact cancellation between the two. Indeed, the sensitivity of experiments is such that if the scalar field has infinite range (zero mass) the velocity effect due to the Earth's motion around the Sun would be sufficient to upset the delicate cancellation between the vector and scalar interaction. This would have been observed as a violation of the equivalence principle by the scalar field in Dicke's experiment⁹ unless its effect on the gravitational mass is smaller than one part in 10^3 .

The energy dependence can also be due to binding in the nuclear potential or in the nuclear Coulomb field. In this case the argument becomes independent of range and also far more accurate. A nucleon in the nucleus has a typical binding energy of 1% of the rest mass; the exact amount varies from nucleus to nucleus throughout the periodic system. This means that an exact cancellation for free neutrons and protons will not appear as such for bound nucleons. It might be argued that this statement is not fully exact, since the nucleons move in a mean potential (numerically more important than the binding energy), but this may in the worst case cost a magnitude in the argument and we are not short of precision. From Eötvös type experiments we can thus conclude by comparing different materials that the scalar interaction cannot contribute more than one part in 10^6 - 10^7 in order not to show up. The direct Galilean experiments^{10,11} for materials of different composition imply the same kinds of limits. In particular, this observation is a powerful argument against models in which it is proposed to realize the scalar interaction by coupling to the trace of the energy tensor and the vector interaction by coupling to baryon number.

Contrary to the belief of many the $K_0\bar{K}_0$ mass splitting of 10^{-6} eV, is not a very strong constraint on the $p\bar{p}$ mass difference¹⁶ although no more than one part of 10^3 of the observed mass splitting can be ascribed to gravity¹⁷. If we look at this system schematically as resulting from $q\bar{q}$ pairs with strangeness the vector interaction would most likely cancel out due to conserved gravitational charge, while the scalar contribution

could remain. An anomalous gravitational interaction may not couple to the strangeness; a null effect may result in this case. The limit of about one part in 10^{18} (i.e. to 10^{-9} eV) is therefore not necessarily relevant here in spite of its enormous precision. However, although nuclei and atoms are non-strange, the absence of an effect for the $K_0\bar{K}_0$ system manifestly does not favour any argument for a violation.

We therefore conclude that direct searches for gravitational mass-differences between the proton and antiproton face very dim prospects of relevance to theory unless the precision is carried to an experimental accuracy of the order of 10^6 - 10^7 , since present experiments implicitly test this level of precision. This conclusion follows quite apart from theoretical prejudice. The value of present experimental investigations should thus be viewed as purely methodological and they should not be seen as testing fundamental concepts.

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