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TITLE: LOOKING FOR NEW GRAVITATIONAL FORCES WITH ANTIPROTONS

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LOOKING FOR NEW GRAVITATIONAL FORCES WITH ANTIPROTONS

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ABSTRACT

Quite general arguments based on the principle of equivalence and modern field theory show that it is possible for the gravitational acceleration of antimatter to be different than that for matter. Further there is no experimental evidence to rule out the possibility. In fact, some evidence indicates there may be unexpected effects. Thus, the planned experiment to measure the gravitational acceleration of antiprotons is of fundamental importance.

Perhaps the main trust of elementary particle physics is the effort to unify in a quantum field theory what we call the four forces of nature the strong nuclear the electromagnetic the weak nuclear and the gravitational forces Of course this type of effort is not new

In the last century the experimental work of Faraday and Ørsted laid the foundation for the theoretical work of Maxwell showing that electricity and magnetism are not two separate forces but just different aspects of the same force Also the last part of Einstein's career was devoted to unsuccessfully trying to unify classical electromagnetism with classical gravity From our viewpoint he was doomed to failure because there were other forces that needed to be taken account of the strong and weak forces

The 1970's saw the next stage in this drama Weinberg Glashow and Salam devised the electroweak theory which unifies electromagnetism and the weak interactions This theory was vindicated in the discovery of the W and Z particles at CERN

Simultaneously a model of the strong force "quantum chromodynamics" or QCD was developed Therefore the next logical step was to try to unify QCD with the electroweak theory This led to the "standard model"[1] One of its main predictions is that the proton is unstable with a lifetime of order 10^{30} years This long lifetime is because the "X" particle the particle which typifies the unification mass scale is so large (10^{15} GeV) Therefore a process which would occur in the 100's of MeV region (proton decay) would be probing physics at the 10^{15} GeV scale Unfortunately proton decay has not been seen at the 10^{32} year lifetime level so this idea remains unverified

However theoretical physicists have remained undaunted and are trying to unify gravity with the other three forces even though the other three have yet to be completely unified among themselves. Such theories are called theories of "quantum gravity".[2]

As we come to in more detail below, these quantum gravity theories may show macroscopic effects at the 10^{-12} eV level due to a Planck mass (10^{19} GeV) unification scale. This is the same type of effect as was hoped for with proton decay, that it would be mediated at the X-mass unification scale. The difference is that here the energy scale stretches over an even larger regeme. In fact, it approaches the 50 orders of magnitudes of energy which defines the field of elementary particle physics. (See Fig. 1.)

In quantum theory one has to look for a new type of gravity because standard Einsteinian gravity (general relativity) cannot be quantized. The divergences obtained in trying to make Einstein's classical theory into a quantum theory are simply too severe. It is to be hoped that any new theory will be normalizeable, or perhaps even finite.

Further, one knows as a matter of principle that metric gravity must be incompatible with quantum mechanics <u>at some level</u>.[3] General relativity is a world-line (metric) theory whereas quantum mechanics is a many-path point of view.

The above all emphasizes, as we pointed out in the introduction article to this section,[4] that our ideas on gravity are really an interesting mixture of classical and quantum physics. The weak equivalence principle states that the inertial mass is equal to the gravitational mass.

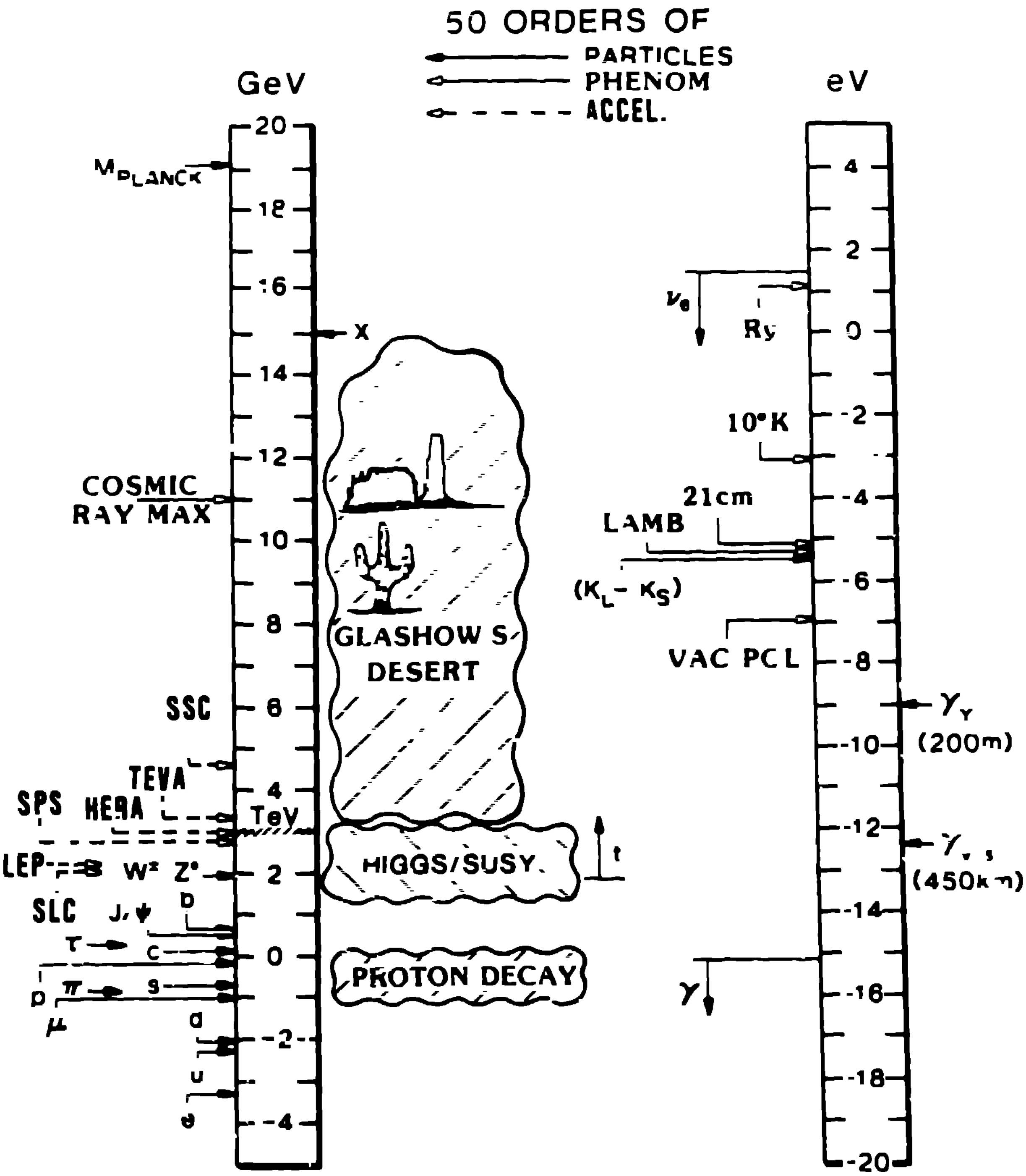

Figure 1 Physics over 50 orders of magnitude in energy Particle masses are indicated by thick lines accelerator energies by thin lines and phenomena by dashed lines The left-hand sides show established objects and concepts whereas the right-hand sides show speculated objects and concepts

$$m_I = m_G \quad . \tag{1}$$

The inertial mass is the kinematic object in Newton's law of force

$$F = m_I a \quad . \tag{2}$$

Contrariwise the gravitational mass is the charge in Newton's law of gravitation

$$F = -G m_G m'_G / r^2 \quad . \tag{3}$$

Now even though CPT tells us that the inertial mass of a particle is equal to the inertial mass of the antiparticle

$$m_I = \bar{m}_I \quad , \tag{4}$$

this does not imply that

$$m_G = m_I = \bar{m}_I \overset{?}{=} \bar{m}_G \quad . \tag{5}$$

That is $m_G \neq \bar{m}_G$ does not necessarily mean that CPT is broken.

If an apple falls to the earth in a certain way CPT only implies that an antiapple falls to an antiearth in the same way. CPT says nothing about how an antiapple (that is to say an antiproton or a positron) falls to an earth. Thus we see that there is nothing wrong, as a matter of quantum principle, for these new theories of quantum gravity to exhibit a violation of the principle of equivalence.

Theories of quantum gravity start from a number of different motivations, such as dimensional reduction, supersymmetry, or string theory. They remain incomplete mathematically and physically. But they do have a common generic new prediction[2,5] the spin-2 graviton has spin-1 (graviphoton) and spin-0 (graviscalar) partners. These partners are expected to have finite ranges and to couple with approximately gravitational strength to some conserved quantity such as a fundamental Fermion number. For the static case this means one would expect a phenomenological gravitational potential to be of the form[5]

$$V = - Gm_1 m_2[1 \mp ae^{-r/v} + be^{-r/s}]/r \quad . \tag{6}$$

In Eq. (6), a and v (b and s) are the coupling strength normalized to ordinary gravity and the range of the graviphoton (graviscalar). Now tensor and scalar forces are always attractive. However, spin-1 vector forces are attractive between opposite charges and repulsive between like charges. (This is familiar from electromagnetism.) Here the charges are matter and antimatter. Therefore, the (-) sign in front of the vector term of Eq. (6) represents the repulsion of matter to matter and the (+) sign represents the attraction of antimatter to matter.

These theories are saying that there are new vector and scalar gravitational forces which could be macroscopic in their effects. They could approximately cancel in the ordinary world (matter-matter interactions),[6] and so not have been noticed because there they produce very small second-order effects. However, if one were to measure the gravitational acceleration of antimatter, then the new terms would both add to the normal attraction, and thus could produce a very large first-order effect.[7]

Whether or not a large effect would ensue depends, of course, on the magnitudes of the two ranges v and s and also on the sizes of the coupling constants a and b. As to the coupling constants, they would be expected to be of order unity since they are normalized to normal gravity. A symmetry breaking could well make them slightly different.

As to the ranges, there are as yet no firm predictions. However, qualitative statements can be made. Starting with the small, even though ranges of order of the Planck length (10^{-33} cm) would produce new effects as a matter of principle, they would not produce effects which could be measured. If the ranges were on the order of 200 m, as advocates of a new "fifth-force" scenario would have,[8] then there still would be nothing to be seen in the current antiproton gravity experiment. However, in this case there might be measureable effects in precise matter-matter experiments, if the coupling constants a and b were different.

Finally, ranges on the order of many 10s to 100s of km could yield positive, unexpected results in the antiproton gravity experiment. The question is, "Are such ranges allowed by the data?" The answer, perhaps surprisingly, is, "Yes."

Many people are familiar with the work of Stacey, Tuck and coworkers analyzing gravity down mine shafts in Australia. Beginning in 1978 and cluminating in their recent RMP paper,[9] they reported an anomalous repulsion which, if analyzed in terms of a single new Yukawa potential, yielded a new term with relative coupling constant of order 0.01 and a range of order 100-1000 m.

They emphasized that their data was not precise enough to restrict the fit to a particular functional form. So, for our program, we requested that they do an analysis in terms of the two new forces predicted by quantum gravity. Stacey, Tuck and Moore[10] did this. They found that a good fit was allowed as long as (a-b) ≈ 0.01. Given this ranges up to ~450 km were allowed. This result was put into the PREM model of the earth and integrated out to see what the effect would be on the antiproton.[7] The results with a=b=1 are shown in Fig. 2.

The idealized uniform sphere earth is off by a factor of 2 essentially because of the difference in density near the surface of the earth. The real earth's curve is wavy; the waviness corresponds to the fact that you're seeing the different shells become significant. Note that at a 40 km length scale one would obtain a 1% effect in the antiproton experiment which should be measureable. At 450 km one would have a 14% effect which definitely would be measureable. This is with a=b=1, and the effect scales with a=b.

If you add to this the analysis of rapidly-rotating pulsars, which allows values of (a,b) up to O(100) then one can say the expected difference in g for the antiproton could be

$$\Delta g/g = a\ (0.14)\ (v/450\ \text{km}) \quad . \tag{7}$$

But that is not all the evidence. A number of other experiments have been reported, some finding anomalous results. The most illustrative, for our purposes, are the seemingly contradictory Eotvos experiments by Thieberger[11] and by Adelberger's group.[12] Thieberger found that on top of the New Jersey Palisades, a copper sphere neutrally buoyant in water is repelled outward normal to the cliff. Adelberger's group compared the differential gravitational effect of a small hill on the University of Washington campus on differing groups of two materials, and found no effect.

If one thinks in terms of a single short-ranged new Yukawa force, as in the fifth force point of view, then these two results appear

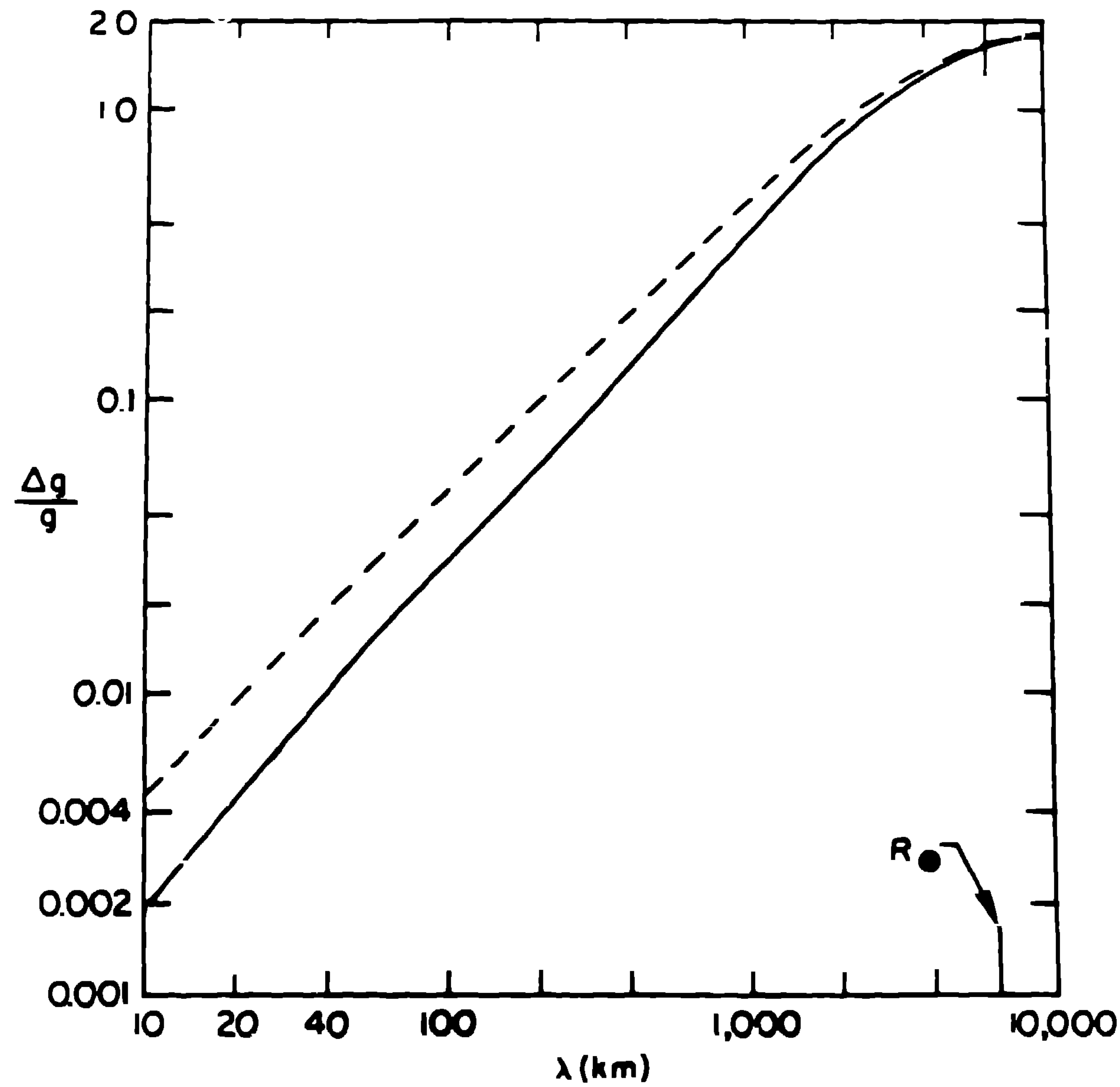

Figure 2 The size of the new effect due to the graviphoton and graviscalar interactions for antimatter as a function of the length scale v=s=λ. This result is for new coupling constants a=b=1 and scales with their values The lower, solid line is for the earth's real mass distribution whereas the dashed line is for a uniform mass distribution of the same total mass

contradictory. However, if one thinks in terms of two long-ranged forces which approximately cancel, then by geologic accident the two results are consistent. As observed by Ander *et al.*[13] the Palisades cliff is the edge of a diabase sill which extends all the way into Pennsylvania. This sill has a density of 2.9 g cm^{-3} which gives a contrast of +0.2 g cm^{-3} with the other rock in the region. Taking (a-b)=0.01, this sill could account for the effect of Thieberger for a range v = 200 km.

From a preliminary version of the ideas expressed above it was proposed[14] that an experiment be done to measure the gravitational acceleration of antiprotons at LEAR (the Low Energy Antiproton Ring) at CERN. Since then a collaboration has been formed to do the experiment[15,16] and the experiment has been approved (PS 200).

Figure 3 is a schematic diagram of the experiment. The output of LEAR (antiprotons of approximate energy 2 MeV) will be decelerated either with an RFQ or by passing through a foil. Then the antiprotons will be captured, cooled, and transferred through a series of electromagnetic traps. Finally, the antiprotons, at approximastely 10 ^{o}K, will be launched up a superconducting shielded drift tube guided in the axial direction by a magnetic field.

The actual measurement is a time of flight measurement. For a given length of drift L, the arrival time of the last antiproton which has enough energy to go up a drift tube of length L is given by

$$t = (L/2g)^{1/2}. \tag{8}$$

This value of "g" for the antiproton will be compared to that of the negative hydrogen ion, a particle with the same charge and almost the

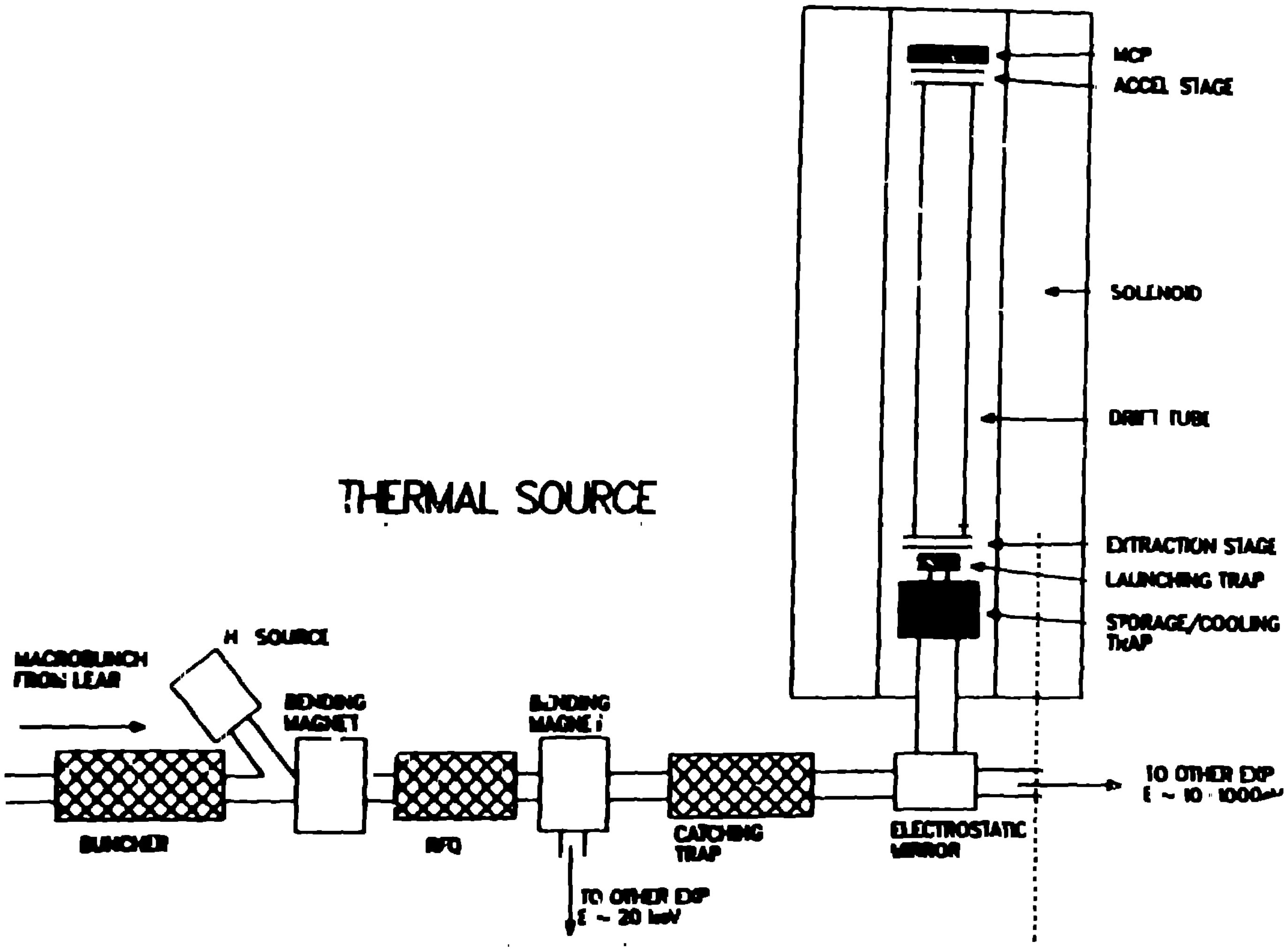

Figure 3 A possible schematic diagram[16] for the antiproton gravity experiment The diagram is not to scale The region inside the dotted lines represents a "thermnal source" of low to very low energy antiprotons that would be available for a variety of experiments

same mass as the antiproton

The drift tube used in the antiproton experiment will be an updated version of the tube used by Witteborn and Fairbank to measure the gravitational acceleration of electrons[17] In this context, we point out that Fairbank is considering doing a modern gravity experiment using positrons[18] Because such an experiment would test for anomalous gravitational coupling to lepton number instead of to baryon number (quark number), it would complementary to the antiproton experiment It is to be encouraged[19]

Ultimately, one would hope someday to be able to do a gravity experiment using neutral antimatter; more specifically, antihydrogen With electric forces neutralized, such a gravity experiment could be orders of magnitude more precise. The problem, of course, is how to make, let alone contain, antihydrogen We refer you to the article in these Proceedings by Mitchell[20] He discusses programs aimed at producing antihydrogen Once antihydrogen is made, the advent of laser storage and velocity selection techniques for single atoms and magnetic trap devices open up the possibility for doing a gravity experiment

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2 There are many people who deserve credit for the fundamental ideas in this field A few whom we mention are Fayet Fuji.. Zachos, and especially Joel Scherk Ref 5 below contains a detailed bibliography

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