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Evidence for a stable supermassive gravitino with charge 2/3?

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Some time ago it was suggested that dark matter may consist in part of an extremely dilute gas of supermassive fractionally charged gravitinos [1]. This scheme makes the definite (and falsifiable) prediction that massive gravitinos are the *only* new fermionic degrees of freedom beyond the known three generations of quarks and leptons of the Standard Model of Particle Physics. In this note we re-examine one special event reported and subsequently discarded by the MACRO collaboration [2, 3] in the light of this proposal.

I. INTRODUCTION.

The nature of dark matter (DM) continues to be one of the most vexing questions of modern physics. While current DM scenarios are usually based on the assumption of ultralight constituents (such as axions) or TeV scale WIMPs, the possibility has been raised in recent work [1] that DM could consist at least in part of an extremely dilute gas of supermassive stable gravitinos with charge $q = \pm\frac{2}{3}$ in units of the elementary charge e. This proposal has its roots in Gell-Mann's old observation that the fermion content of the Standard Model of Particle Physics (SM) with three, and only three, generations of quarks and leptons (including right-chiral neutrinos) can be matched with the spin-$\frac{1}{2}$ content of the maximal $N=8$ supermultiplet after removal of eight Goldstinos [4, 5]. The only extra fermions beyond the known three generations of SM fermions would thus be eight massive gravitinos, but nothing else. Crucially, the matching of $\mathrm{U}(1)_{em}$ charges requires a 'spurion shift' of $\delta q = \pm\frac{1}{6}$ [4] that is not part of $N = 8$ supergravity and that, in terms of the original spin-$\frac{1}{2}$ fermions of $N=8$ supergravity, takes the very special form given in [6, 7]. The main new step taken in [1, 7] consisted in extending these considerations to the eight massive gravitinos which split as

$$\left(\mathbf{3}\,,\,\frac{1}{3}\right) \oplus \left(\bar{\mathbf{3}}\,,\,-\frac{1}{3}\right) \oplus \left(\mathbf{1}\,,\,\frac{2}{3}\right) \oplus \left(\mathbf{1}\,,\,-\frac{2}{3}\right) \qquad (1)$$

under $\mathrm{SU}(3)\times\mathrm{U}(1)_{em}$. All gravitinos would thus carry *fractional electric charges*. If one identifies the SU(3) in (1) with $\mathrm{SU}(3)_c$ as in [1], a complex triplet of gravitinos would be subject to strong interactions. Importantly, the $\mathrm{U}(1)_{em}$ charge assignments for the gravitinos include the spurion shift needed for matching the spin-$\frac{1}{2}$ sectors [37]. Although the combined spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ content would thus coincide with the fermionic part of the $N = 8$ supergravity multiplet, the underlying theory would need to be a very specific, but as yet unknown, extension of (gauged) $N = 8$ supergravity, which in its original form [9, 10] cannot be correct for reasons that have been known for more than 40 years.

An important consequence of (1) is that, due to their fractional charges the gravitinos cannot decay into SM fermions, and are therefore stable independently of their mass. Their stability against decays makes them natural candidates for DM [1]. While a very large mass is strongly suggested by the absence of low energy supersymmetry at LHC, an even more compelling argument for large mass is the bound on the charge q of any putative DM particle of mass m derived in [11–13]

$$|q| \;\lesssim\; 7.6\cdot 10^{-10}\left(\frac{m}{1\,\mathrm{TeV}}\right)^{\frac{1}{2}} \qquad (2)$$

which immediately shows that gravitinos with charges (1) can only be viable DM candidates if their masses are close to the Planck scale. As we argued in [1] the strongly interacting gravitinos would have mostly disappeared during the cosmic evolution (but could play a role in explaining UHECRs and the predominance of heavy ions in such events [15]). By contrast, the abundance of the color singlet gravitinos cannot be estimated since they were never in thermal equilibrium, but one can plausibly assume their abundance in first approximation to be given by the average DM density inside galaxies [14], *viz.*

$$\rho_{DM} \;\sim\; 0.3\cdot 10^{6}\,\mathrm{GeV}\cdot\mathrm{m}^{-3}\,. \qquad (3)$$

If DM were entirely made out of nearly Planck mass particles, this would amount to $\sim 3\cdot 10^{-13}$ particles per cubic meter within galaxies (the average in the Universe is a million times smaller). Nevertheless, for the estimation of flux rates there remain important uncertainties, for instance concerning possible inhomogeneities in the DM distribution within galaxies or even stellar systems, as well as the average velocity of superheavy DM particles w.r.t. the earth.

A distinctive feature of the present proposal is that the DM gravitinos *do* participate in SM interactions. This is in contrast to other scenarios involving supermassive DM particles which are assumed to have only (super-)weak and gravitational interactions with SM matter [19–26], and which are mainly motivated by inflationary cosmology, whence the mass of those DM constituents would still be well below the Planck scale, on the order of the scale of inflation $\lesssim 10^{16}$ GeV (and thus, by (2), compatible only with milli-charged particles). By contrast the gravitinos in (1) could in principle be detected if a way could be found to overcome their low abundance. A superheavy electrically charged particle could easily pass through the earth without deflection, leaving a very straight but tiny ionized track in the earth's crust.

This leaves us basically with two options for discovery. Either one searches for such tracks in old and very stable rock with a paleodetector, or otherwise one sets up an underground detector with sufficiently large fiducial area/volume and waits for the candidate particle to come by. The paleodetector option has been tried in the past with MICA samples [27, 28], again to search for magnetic monopoles; a general difficulty here is that the tracks would have to remain unaffected by geological processes over very long times, and the detection technique must be such as not to destroy the tracks (this favors MICA which comes with a naturally layered structure). The other and perhaps more promising option is to look for ionized tracks with suitable underground detectors and time of flight measurements, focusing on *slow* ionizing particles. The main background would come from cosmic ray muons, but a possible way to rule those out would be to look for slow particles *moving bottom up* which must have traversed a substantial part of the earth before being registered by the detector. In this context, the possible relevance of the MACRO experiment [2] was already pointed out in [1] where it was suggested to have a second look at the data collected over many years. This is what we will now do, focusing on one special event.

II. THE MACRO EXPERIMENT AND A SPECIAL EVENT

The MACRO experiment [2] was originally designed to search for magnetic monopoles, finishing with a null result after several years of taking data. We refer to the summary paper [2] for a detailed description of the experiment and of what the detector was capable of doing, as well as a summary of the collected results. The search covered a large part of parameter space, including the full range of velocities from relativistic particles down to 'slow' particles with $\beta \sim 4 \times 10^{-5}$, coming in from all directions. In this way the detector was able to search not only for magnetic monopoles, but also for other, and unknown kinds of ionizing particles, including fractionally charged particles. Results of the latter search which concentrated specifically on *lightly ionizing particles* (LIPs) appeared in a separate publication [3].

While [2] mentions 40 events (out of a total of about 35 000) that were subsequently discarded as spurious and not further discussed, Ref. [3] reports one special event of a type different from an expected monopole signal. The relevant information about this event is contained in figure 3 of [3] which we here reproduce for the reader's convenience, together with its figure caption. Let us also quote the accompanying part of the text in [3] which says: “As one can see [...] there is one event (run 15871, event 5649) that appears in the signal region. It corresponds to a maximum energy loss of 0.66 MeV/cm, i.e., about 20% lower than what expected for a particle of charge $2e/3$ and about a factor of 3 higher than what expected for a particle of charge $e/3$. Three scintillator counters were involved in this trigger; the first in one of the upper vertical layers, the second in the central horizontal layer and the third in the lower horizontal layer. [...] The position along the counter for this particular box measured by the PHRASE and by the streamer tube track geometry were in agreement (within 15 cm). We have examined this event by hand relying primarily on the wave forms as recorded for all the counters involved in the trigger. The apparent amplitude of the recorded wave forms was consistent with the energy thresholds for the ERP and the PHRASE. Having three scintillator counters involved in the trigger we have checked for a consistency in the relative timing of them with the crossing of a single particle of constant velocity. The relative timing between the counter in the upper part of the detector and that in the central part was consistent with the passage of a relativistic particle coming from above while the relative timing between the box in the lower part of the detector and any of the other two hits was consistent with a slowly moving upward-going particle. We thus discarded this event from the signal region.”

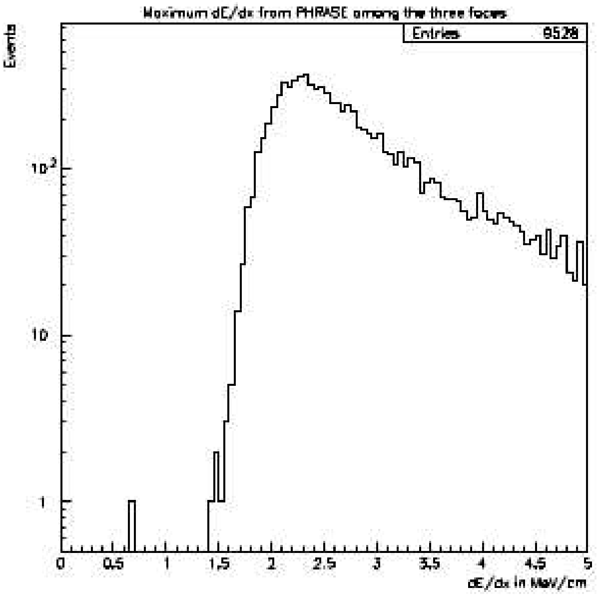

FIG. 1: Energy loss as measured by PHRASE for the LIP events that passed the track quality and geometry cuts and satisfied the requirement of a maximum energy loss rate (measured by ERP) less than 1.1 MeV/cm. [...] The signal region is in the [0, 1.35] MeV/cm interval. Figure copied from [3].

The main reason for discarding this event was therefore not some obvious instrumental glitch or any indication of a fake signal, but rather the fact that there appears to be no way to reconcile all three scintillator signals (as well as the fact that the signal does not conform with expectations for a magnetic monopole), whence one concludes that one of the three signals must be ascribed to a different origin. A crucial additional fact is that there is unmistakable and independent evidence from the streamer tubes for a single particle track running through the whole detector. The 'obvious' interpretation of this event would seem to be in terms of a relativistic particle corresponding to a cosmic ray muon coming from above, and this remains perhaps the most plausible explanation. However, this interpretation would not only require disregarding the earlier scintillator signal in the lower part of the detector, but also explaining why a third signal in the same scintillator, coincident with the central and upper scintillators, is missing. It would also require an explanation why the energy loss rate is well below the allowed minimum in Fig. 1 since the measured charge of $|q| = \frac{2}{3}$ is simply not compatible with a muon. By contrast, the alternative second interpretation with a slow particle moving upward requires only the signal in the upper scintillator to be due to some other cause. While it appears that the question cannot be finally resolved on the basis of the existing MACRO data, we here wish to raise attention to the hypothesis that it is the signal in the upper layer that was caused by a different cause, which could have masked the presumed later arrival of the slow particle in the upper detector. The event could then correspond to the passage of a 'slow' gravitino through the MACRO detector; this hypothesis is also supported by the measured low ionization pointing to charge $\pm\frac{2}{3}$. If this assumption is made we have two additional indications for the correctness of our hypothesis, as emphasized in the above quote from [3], namely

- the track as seen by the streamer tubes was consistent with the tracks in the lower and central scintillators; and
- the time of flight was consistent with the same slow particle moving bottom up in the lower and central scintillators

With these additional consistency checks let us re-iterate that a 'slow' particle moving bottom up would be difficult to explain in terms of known physics. First of all, going up, it obviously cannot be a muon. Second, it cannot be a magnetic monopole, nor a dyon, because monopoles generally are not expected to be lightly ionizing [38]; although monopoles may in principle be able to traverse the earth [29], according to [30], the energy loss in the scintillator would be ~ 1 GeV/cm for the exemplary value $\beta \sim 0.01$, and the light yield would be saturated and bigger than the observed 0.66 MeV/cm; for a dyon the energy loss would be even bigger. Third, the full track as reconstructed from the streamer tubes cannot be the result of a radioactive decay in the surrounding rock, since such products have energies of at most several MeV, so they could not penetrate the scintillator more deeply than a few centimeters. Therefore a superheavy fractionally charged particle seems to be the most plausible explanation if one adopts our hypothesis.

While [3] does not explicitly quantify what 'slow' means a more precise knowledge of the velocity would be useful as it would enable us to make a first estimate of the expected gravitino flux. A potential difficulty here is that the trigger used in [3] was sensitive only to fast lightly ionizing particles: as stated in the abstract of [3], the trigger was set for ionizing particles with velocities $\beta > 0.25$, hence any slower particle could have escaped detection without such an accompanying triggering signal, and thus possible events involving only a slow particle could have been missed. Therefore the rate of one event for the five-year cycle covered by [3] could be an underestimate of the actual abundance and flux rate for supermassive gravitinos, thus explaining why no further events of this type were observed (even taking into account the expected rarity of superheavy gravitinos). For this reason we cannot at this point reliably deduce the actual gravitino density in the vicinity of the Earth from the given data. This, as well as the confirmation (or refutation) of our hypothesis, would require a dedicated new experiment, concentrating on slow lightly ionizing particles.

III. CONCLUSIONS

Re-inspection of the special MACRO event reported in [3] has revealed the possibility of an explanation different from the 'obvious' one in terms of a cosmic ray muon, namely

- a slow particle *moving bottom up*, which thus must have traversed a substantial part of the earth; and
- the fact that this particle carries fractional charge $q = \frac{2}{3}$ within a 20% error margin.

Obviously, further and independent confirmation is needed to find out whether this is real physics or just a fluke and we hope that in the not-so-distant future some dedicated experiments will decide. We stress that the spin of the putative DM particle remains unknown, so even if the event is due to a superheavy particle it remains to determine its spin to confirm (or not) spin-$\frac{3}{2}$, as advocated in [1].

On the other hand, corroboration of our new interpretation of this event would have several implications. In particular, it would bring $N = 8$ supergravity back into focus for unification, although in an unexpected way. We emphasize that the considerations leading to (1) are so far purely kinematical, and that the dynamics underlying the present scheme remains unknown, possibly requiring a framework beyond space-time based quantum field theory. Nevertheless our findings may indicate that $N = 8$ supergravity could be closer to the truth than is widely thought (as is also suggested by the finiteness properties of the theory [32] and various anomaly cancellations

[33–36]). We also note that the spurion shift required to match the spin-$\frac{1}{2}$ sectors of the theory with three generations of quarks and leptons [4], and here extended to the gravitinos [7], appears to be incompatible with space-time supersymmetry. This could mean that, contrary to many expectations, (maximal) space-time supersymmetry might not be a relevant concept for unification after all, but, through its fermionic (spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$) content, merely a theoretical crutch to guide us to the right answer.

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[37] The explanation of how to extend the spurion shift to the gravitinos (whose U(1) charges would otherwise be $\pm\frac{1}{6}$ and $\pm\frac{1}{2}$) requires a detour via $D = 11$ supergravity [8]. The incorporation of this shift requires enlarging the SU(8) R-symmetry of $N=8$ supergravity to $K(\mathrm{E}_{10})$.
[38] In principle an electrically neutral monopole can acquire a very small electric charge proportional to the CP violating θ-angle by means of the Witten effect [31]. However, given the known upper limits on the value of θ the ionization would be dominated by magnetic interactions.