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Searching for supermassive charged gravitinos in underground experiments

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We examine possible experimental signatures that may be exploited to search for stable supermassive particles with electric charges of $\mathcal{O}(1)$ in future underground experiments, and the upcoming JUNO experiment in particular. The telltale signal would be a correlated sequence of three or more nuclear recoils along a straight line, corresponding to the motion of a non-relativistic ($\beta \lesssim 10^{-2}$) particle that could enter the detector from any direction. We provide some preliminary estimates for the expected event rates.

I. INTRODUCTION.

Recent work [1] has raised the unconventional possibility that Dark Matter (or DM, for short) 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. Perhaps the most unusual feature of this proposal is that, due to their large mass and very low abundance such DM candidates can carry electric charges of $\mathcal{O}(1)$ and are thus not dark at all, but luminous, and can escape detection only by virtue of their rare occurrence. In principle this feature makes these new DM candidates much more amenable to direct detection, provided a way can be found to overcome their low abundance. By contrast, previously considered DM candidates with masses in the TeV range can only carry very small charges ("milli-charges"), and are thus much harder to detect directly via their putative electromagnetic interactions.

In [1] we scanned through several past and currently operating WIMP and monopole searches in order to see whether such a particle might already have been sighted in a previous experiment. As it turned out, the most promising candidate for such reconsideration is the MACRO experiment [2] which was originally set up to search for magnetic monopoles, and which was terminated in 2002. While no unusual events were reported in the summary paper [2], a subsequent search for lightly ionizing particles revealed the existence of one outlier event that was subsequently discarded by the collaboration, because there appeared to be no way of deciding between two conflicting interpretations [3]. The more unusual of these interpretations corresponds to a *slow* particle (not a magnetic monopole) moving bottom up, hence having traversed a large part of the Earth, and possessing a fractional charge [3]. In [4] we re-examined this event in the light of our proposal and concluded that it, if confirmed, could support the above DM hypothesis. In spite of these hints it is clear that the issue cannot be conclusively settled on the basis of the existing MACRO data concerning this particular event, hence the need remains for an independent confirmation or refutation of the DM hypothesis proposed in [1].

Here we follow up on this observation in order to discuss new and independent tests in upcoming or planned future underground experiments, with special attention to the JUNO experiment [5] which will soon start operation with the chief aim of exploring properties of neutrinos. The JUNO detector is by far the largest underground detector ever constructed: it is a liquid scinitillator detector containing 20 000 tons of organic fluid, and the number of scintillators is twenty times bigger than in the largest instruments built so far. To eliminate the main background consisting of cosmic muons the experiment is located deep underground. In addition there is an outer water shell providing a veto to muons by the Cherenkov radiation and shielding the central detector from natural radioactivity. The experiment is thus ideally suited not only to probe neutrino physics (its main purpose) but also to search for other and different types of deeply penetrating particles.

Let us therefore briefly recall basic features of our proposal, which has its origins in Gell-Mann's observation [6] that, subject to a 'spurion shift' of the electric charges, the fermion content of the Standard Model (SM) can be matched with the spin-$\frac{1}{2}$ states of the $N = 8$ supermultiplet associated to maximally extended $N = 8$ supergravity (see also [7]). As a consequence the only extra fermions of the theory beside the 48 SM spin-$\frac{1}{2}$ fermions would be eight supermassive gravitinos. Under the $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{em}$ subgroup of the SM gauge group these split as

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

and thus all carry fractional electric charges; see [8, 9] for more detailed arguments and for a derivation of these quantum numbers. For the reasons explained in [1] we will here not be concerned with the color triplet gravitinos (see, however, [10] for possible effects in the physics of ultrahigh energy cosmic rays), but concentrate on the color singlet gravitinos carrying charge $\pm\frac{2}{3}$, which are not subject to strong interactions. Due to their fractional charges the gravitinos (1) cannot decay into SM fermions, and are therefore stable independently of their mass. Their stability against decays makes them natural DM candidates [1]. From the various bounds on the charge q of any putative DM particle of mass m derived in [11–13] we can infer that gravitinos with charges (1) can only be viable DM candidates if their mass is close to, but still below, the Planck scale.

As we explained in [1] the abundance of color singlet gravitinos cannot be determined from first principles, but one can plausibly assume their abundance in first approximation to be given by the average DM density inside galaxies. From the number given in [14] it then follows that, 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 our solar system. Nevertheless, a more accurate estimation of flux rates is hampered by important uncertainties, for instance possible inhomogeneities in the DM distribution within galaxies or stellar systems (where the gravitational attraction of the central star could lead to a local enhancement or depletion of such particles [15]). The velocity distribution is expected to be centered around the values $10^{-4} \lesssim \beta \lesssim 10^{-2}$. Indeed, from the virial theorem we expect the velocity of these particles to be $\sim 30 \text{ km} \cdot \text{s}^{-1}$ if they are bound to the Solar System, and $\sim 300 \text{ km} \cdot \text{s}^{-1}$ if they are bound to our Galaxy. However, there could be considerable deviations from these numbers.

In this note we discuss the possibility of searching for supermassive color singlet gravitinos in planned neutrino experiments, pointing out distinctive features and signatures relevant for an eventual discovery, and focusing on the JUNO experiment. In the remainder we will often refer to the hypothetical supermassive gravitino simply as ‘the Particle’.

II. INTERACTIONS OF AN ELECTRICALLY CHARGED SUPERMASSIVE PARTICLE

According to (1) the DM gravitinos do participate in SM interactions, unlike for scenarios involving supermassive DM particles which are assumed to have only weak and gravitational interactions with SM matter. A supermassive electrically charged particle can easily pass through the earth along a straight track and without deflection: the kinetic energy of a (near) Planck mass gravitino with velocity $\beta \sim 10^{-3}$ is about 10^{13} GeV, so assuming a stopping power of $\lesssim 100$ MeV/cm it will lose only a tiny fraction of its energy during its passage. In fact, the actual energy loss might even be considerably less in view of the different interaction properties with ordinary matter, see below.

Due to its electric charge the Particle would thus interact electromagnetically with both electrons and nuclei. However, its large mass and non-relativistic motion necessitate a separate analysis, different from standard treatments in the literature which mostly concern relativistic particles in interaction with atoms; the interactions of ordinary ‘light’ (in comparison with Planck mass particles) objects and their ionization properties are very well understood [16]. For supermassive particles, what is required is a proper quantum mechanical treatment of a system comprising the Particle (whose mass can be taken to be infinite for all practical purposes) in interaction with an atom with six or more electrons bound to a nucleus; for definiteness, and because the detector is filled with organic fluid, we will usually have in mind a carbon atom with mass $m_C \sim 12 \text{ GeV}/c^2$. As such a calculation is currently not available (but work in progress) let us describe the situation in more qualitative terms. What would we expect this interaction to look like? There are basically three different regimes as the Particle passes through an atom. The first possibility is that the Particle simply ‘grazes’ the atom and interacts only with the outer electron(s). In the second regime the Particle passes closer to the nucleus, but still at a distance where the electric charge of the nucleus is partially shielded by the inner electrons. Finally, in the third regime the Particle passes inside the orbit of the closest electron, and in this regime the interaction effectively takes place between the Particle and the nucleus through nuclear recoils. Here it is important to note that due to its large mass, the Particle ‘can go wherever it wants to go’ within the atom, without being inhibited in any way by either the nucleus or the electron cloud. The main issue in all cases is whether the energy released in these processes via photons would be enough to excite the photomultiplier tubes (PMTs) of the detector.

For passage sufficiently far away from the nucleus the interaction is mainly between the Particle and the outer and more weakly bound electrons. A simple classical argument [4] shows that, for velocities $\beta \lesssim 10^{-3}$ the energy imparted to individual electrons by the Particle is much less than the minimum ionization energy, hence no, or not much, ionization is expected to occur, in agreement with the lower part of the Bethe-Bloch curve (Lindhard-Scharff regime) [16]. However, for a positively charged supermassive particle there is another possibility: due to the Particle’s large mass and its slow motion it can spend enough time in the electron cloud to ‘drag along’ an electron, forming a fractionally charged lightly bound state that moves along undisturbed and with unchanged speed (due to the fractional charge the binding energy would be less than for a hydrogen atom). Having removed the electron from the atom, it thus leaves behind an ion that can be detected by a streamer tube or a drift chamber. This process can be repeated any number of times along the track because the lightly bound electron can be easily stripped off the Particle again.

Closer to the center of the atom, but still sufficiently far away from the nucleus the Particle can induce electronic transitions in the inner shells and lift an electron to a higher excited state. This may give rise to some fluorescent light, but the light produced in the transition when the electron returns to its former state could be too faint to be observed by the PMTs. In addition, possible time delays in the fluorescent transitions could distort the time identification along the track.

Finally, if the Particle gets sufficiently close to the nucleus, *i.e.* inside the innermost electron orbit, the collision will look more and more like a nuclear recoil, where the Particle hits the nucleus head-on. In the Particle's center of mass system, this case is very much like Rutherford scattering with an infinite mass at the center [17]. This is the process that in principle should release enough light to be be visible to the PMTs. More precisely, if the Particle's velocity is β the maximal velocity that can be imparted to the nucleus in the recoil is 2β. If the minimal energy of the recoil that can be observed is ~ 1 MeV and the recoiling object is a carbon nucleus we thus get the minimal β for the Particle to be observable

$$2m_C\beta^2 \;>\; 1\ \mathrm{MeV}/c^2 \;\Rightarrow\; \beta_{\min} \sim 6\cdot 10^{-3} \tag{2}$$

Recoil from protons would give 12 times lower recoil energy (while the recoil from electrons is negligible). The bound (2) is marginally compatible with our assumptions on the velocity distribution of supermassive gravitinos (in the sense that the velocity would have to be on the tail of the distribution). In addition, a detailed estimate on the event rates depends on the unknown abundance of such particles, but in the end this will be a matter for observation to decide.

In summary we expect three kinds of detectable interactions to take place along such a track, namely

- Ionization
- Electronic excitation without ionization
- Nuclear recoil

As we explained, not all of the interactions are expected to produce signals visible to the JUNO detectors (likewise, elastic scattering of the atom as a whole would not be expected to lead to a detectable signal). Nevertheless, these interactions will take place continually along the trajectory of the Particle, but only occasionally, such as in the case of a quasi-frontal collision with the nucleus, could there be enough light to be registered by the PMTs. In other words, we do not expect to see a continuous track, but rather only fragments of a track, with occasional flashes of light along the track.

While the qualitative picture is thus quite clear, we emphasize again that a precise calculation of the process still needs to be done. Furthermore, in the absence of such a detailed calculation the electric charge of the Particle cannot be deduced reliably. Furthermore, it is an open question whether there is any way to confirm that the particle carries spin $\frac{3}{2}$, as predicted by (1).

III. PROSPECTS FOR DETECTION

Past and present neutrino experiments have led to steadily improved measurements of the (squared) mass differences Δm^2 and the mixing angles for three neutrino species, although the absolute values of the neutrino masses remain unknown. These experiments as well as future planned measurements rely on observations of ionized short tracks produced by absorption of neutrinos by nuclei (nuclear recoil). Experiments such as Kamiokande and SuperKamiokande are based on the observation of Cherenkov radiation, while others (SNO, Argon, Xenon) are based on the observation of individual flashes produced by the nuclear recoil. JUNO will observe both anti-neutrinos from nearby nuclear reactors as well as neutrinos of astrophysical origin. The former manifest themselves via the reaction $\bar{\nu}_e + p \to n + e^+$ and the subsequent annihilation $e^+ + e^- \to 2\gamma$, while the relevant reaction in the second case is $\nu_e + n \to p + e^-$. Only the latter process produces a signal similar to the one expected with the present proposal, but the important fact is that such recoils *can* be observed by JUNO. Just like for other underground experiments, the main background consists of cosmic relativistic muons and the natural radioactivity of surrounding rocks. To eliminate this background the JUNO experiment has an outer shell consisting of a water tank that provides a veto to muons by the Cherenkov radiation and shields the central detector from the natural radioactivity.

Assuming the cross section of the nucleus to be of the order of 10^{-30} m^2 and the density of carbon atoms in the scintillator liquid to be $5\cdot 10^{28}$ m^{-3} we can estimate the number of recoils per distance as

$$P \;\sim\; 5\cdot 10^{-2}\ \mathrm{m}^{-1}. \tag{3}$$

We stress that the geometric cross section represents a very conservative estimate, which would be valid only for a short range force. This number may significantly underestimate the actual rate because electromagnetic interactions are long range. Sufficiently close to the nucleus where the nuclear charge is no longer screened by electrons we should more properly assume a Rutherford-like cross section rather than a pointlike cross section, for instance by extending the geometric cross section to a ball of the radius of the order of the innermost electron orbit. On the other hand, the momentum transfer to a nucleus can be smaller than the estimate (2). Nevertheless, already with this minimal assumption we can calculate the probability of N recoils over length L, which is given by a Poisson distribution

$$p_N \;=\; \frac{(PL)^N}{N!}\mathrm{e}^{-PL}. \tag{4}$$

For a ball of diameter R one must take into account that the length of passage decreases away from the center of the JUNO detector, so the probability of N recoils is

$$p_N(R) = \frac{1}{N!}\int_0^1 \mathrm{d}x\, 2x\,(2PRx)^N \mathrm{e}^{-2PRx}. \tag{5}$$

The JUNO detector has $R \sim 18\,\mathrm{m}$, and therefore our formula gives the following values for the probability of

N recoils for the passage of a *single* particle through the detector:

PR	N=0	N=1	N=2	N=3	N=4
0.5	0.528	0.321	0.114	0.029	0.006
1.0	0.297	0.323	0.214	0.105	0.041
1.5	0.178	0.256	0.235	0.164	0.093

Of course, in order to estimate the expected rate of events we still have to fold in the estimated flux of supermassive particles (which, as we said, is subject to a number of uncertainties). In our previous paper [1] we have estimated the flux as

$$\Phi \sim 0.03 \text{ m}^{-2}\text{yr}^{-1}\text{sr}^{-1} \tag{6}$$

With an area of $\sim \pi(18\text{m})^2 \sim 1000 \text{ m}^2$ we thus arrive at a first estimate for the number of gravitinos coming from all directions

$$\# \text{ (events per year)} \;\sim\; \mathcal{O}(100) \;\;, \tag{7}$$

again modulo the mentioned uncertainties. However, in view of the velocity bound (2) we expect only a fraction of these gravitinos to produce a visible signal. At any rate, the distinctive experimental signature would thus be a sequence of at least three nuclear recoils along a straight line, which can point in *any* direction (in particular, going bottom up), with equal calculated non-relativistic velocity between the measured subsequent points of recoil (the energies of the subsequent recoils do not have to be equal since the collisions do not have to be central). It is therefore very important to measure as precisely as possible the positions and times of the events in the detector. There is also the possibility that the drift chambers would detect the ionizing track consistent both with the straight line of nuclear recoils in the central detector (in which case two nuclear recoils would suffice) and with the reconstructed time – that would also be a very clear and unmistakable signature of a very heavy charged particle consistent with the DM gravitino proposed in [1]. For $PR \sim 1$ we would expect about one triple recoil and two double recoils per year. Statistics permitting, one might even contemplate plotting the frequency of detected directions in solar or galactic coordinates, in order to search for possible correlations.

IV. CONCLUSIONS

As we have argued, the JUNO experiment offers unique opportunities not just for neutrino physics, but also for the possible discovery of new kinds of particles of the type considered here, with the unusual property of having very large mass and carrying non-vanishing electric charge of $\mathcal{O}(1)$. As far as we are aware such searches would necessitate only relatively minor adjustments of the triggers and electronics of the JUNO detector. It goes without saying that the discovery of any such event would constitute a truly disruptive advance, in the sense that it would be a first clear *observational* indication pointing towards a novel Planck scale unification of matter with gravitation. Experimental vindication of any of the currently available approaches to quantum gravity and unification has proved elusive so far, mainly because the Planck scale is so far off that it is difficult to imagine *any* kind of conclusive test. With the Planck scale out of the reach of any conceivable accelerator experiment, underground observatories such as JUNO may offer a way out of the impasse.

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[1] K.A. Meissner and H. Nicolai, Phys. Rev. **D100** (2019) 035001

[2] M. Ambrosio et al. (MACRO coll.), Eur.Phys.J. **C25** (2002) 511

[3] M. Ambrosio *et al*, *Final search for lightly ionizing particles with the MACRO detector*, `arXiv:hep-ex/0402006`

[4] K.A. Meissner and H. Nicolai, *A stable supermassive charged gravitino?*, `arXiv: 2303.09131[hep-ph]`

[5] Fengpeng An et al. *Neutrino physics with JUNO*, J. Phys. **G43** (2016) 3,030401; `arXiv:1507.05613`

[6] M. Gell-Mann, in Proceedings of the 1983 Shelter Island Conference on Quantum Field Theory and the Fundamental Problems of Physics, eds. R. Jackiw, N.N. Khuri, S. Weinberg and E. Witten, Dover Publications, Mineola, New York (1985)

[7] H. Nicolai and N.P. Warner, Nucl. Phys. **B259** (1985) 412

[8] K.A. Meissner and H. Nicolai, Phys. Rev. **D91** (2015) 065029

[9] K.A. Meissner and H. Nicolai, Phys. Rev. Lett. **121** (2018) 091601

[10] K.A. Meissner and H. Nicolai, JCAP **09** (2019) 041

[11] S. D. McDermott, H. B. Yu and K. M. Zurek, Phys. Rev. **D83**(2011) 063509

[12] A. D. Dolgov, S. L. Dubovsky, G. I. Rubtsov and I. I. Tkachev, Phys. Rev. **D88**(2013)117701

[13] E. Del Nobile, M. Nardecchia and P. Panci, JCAP **1604** (2016) no.04, 048
[14] M. Weber and W. de Boer, Astron.Astrophys. **509** (2010) A25
[15] T. Damour and L.M. Krauss, Phys. Rev. **D59** (1999) 063509
[16] Particle Data Group, Nucl. and Part. Phys. **33** (July 2006) pp. 258-270
[17] We note that for the strongly interacting color triplet gravitinos in (1) this process could be more disruptive since the Particle could just ‘smash’ the nucleus, which is not possible with only electromagnetic interactions.