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Probing Gravitational Interactions of Elementary Particles

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Summary

The gravitational interactions of elementary particles are suppressed by the Planck scale $M_* \sim 10^{18}$ GeV and are typically expected to be far too weak to be probed by experiments. We show that, contrary to conventional wisdom, such interactions may be studied by particle physics experiments in the next few years. As an example, we consider conventional supergravity with a stable gravitino as the lightest supersymmetric particle. The next-lightest supersymmetric particle (NLSP) decays to the gravitino through gravitational interactions after about a year. This lifetime can be measured by stopping NLSPs at colliders and observing their decays. Such studies will yield a measurement of Newton's gravitational constant on unprecedentedly small scales, shed light on dark matter, and provide a window on the early universe.

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As a force between elementary particles, gravity is extremely weak. Relative to the electromagnetic, weak, and strong interactions, gravitational interactions are suppressed by E/M_*, where E is the typical energy scale of the process, and $M_* = (8\pi G_N)^{-1/2} \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck mass. Given the energies $E \lesssim$ TeV accessible now and for the foreseeable future, this is an enormous suppression. This suppression may be overcome in special cases, for example, in models with extra spatial dimensions where gravity becomes strong at the TeV scale. Barring such fortuitous scenarios, however, gravitational effects are usually expected to be completely negligible and far beyond the sensitivities of particle physics experiments.

In this essay, we note that this is not necessarily the case. In fact, in viable and well-motivated theoretical frameworks, gravitational interactions of elementary particles may be the subject of experimental study by the end of this decade. Such studies may provide new probes of gravity on the scale of elementary particles and provide crucial insights into dark matter and early universe cosmology.

The frameworks in which these gravitational studies may be done include models with supersymmetry or extra dimensions in which new particles appear at the TeV scale. We focus first on supersymmetry, a particularly well-motivated framework for new particle physics. Supersymmetry predicts that each standard model particle has a partner, its superpartner. Supersymmetry also predicts a partner for the graviton, the gravitino. If supersymmetry is to resolve the gauge hierarchy problem, the standard model superpartners should have masses around the weak scale $M_{\text{weak}} \sim$ TeV. A discrete symmetry, R-parity, assures the stability of the lightest supersymmetric particle (LSP) and thereby provides a dark matter candidate. The gauge hierarchy and dark matter problems are two of the fundamental motivations for supersymmetry, and we assume weak-scale supersymmetry with R-parity conservation below.

In supergravity models [1] where supersymmetry breaking is mediated by the known gravitational interactions, all superpartners, including the gravitino, have masses of the order of M_{weak}. The exact ordering cannot be determined theoretically. Most studies of supergravity have assumed, either explicitly or implicitly, that the LSP is a standard model superpartner. Here we explore the alternative scenario, in which the gravitino is the LSP[1].

[1] The possibility of a gravitino LSP has been considered in a number of studies, beginning with Refs. [2, 3, 4].

For concreteness, let us assume that the next-lightest supersymmetric particle (NLSP) is a charged slepton $\tilde{l}$. This slepton will be a part of the thermal bath of the hot early universe and will freeze out with its thermal relic density. Eventually, it will decay through $\tilde{l} \to l\tilde{G}$. This decay is highly suppressed, as the gravitino couples only gravitationally. On dimensional grounds, the lifetime of a weak-scale mass particle decaying through gravitational interactions is $\tau \sim M_*^2/M_{\rm weak}^3 \sim$ yr. More precisely, the decay width is given by the expression [5]

$$\Gamma(\tilde{l} \to l\tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{l}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^4 . \tag{1}$$

In the limit $\Delta m \equiv m_{\tilde{l}} - m_{\tilde{G}} \ll m_{\tilde{G}}$, the decay lifetime is

$$\tau(\tilde{l} \to l\tilde{G}) \approx 3.6 \times 10^8 \text{ s} \left[\frac{100 \text{ GeV}}{\Delta m}\right]^4 \frac{m_{\tilde{G}}}{1 \text{ TeV}} , \tag{2}$$

justifying this rough estimate. Note that the slepton's lifetime depends only on the NLSP and gravitino masses and Newton's constant G_N, as appropriate for a gravitational decay.

It was shown recently [5, 6, 7] that NLSP decays in the gravitino LSP scenario do not destroy the beautiful predictions of BBN. Some combinations of NLSP and gravitino masses are excluded, but much of the natural parameter space remains intact. In fact, the gravitino LSP may even have relic density $\Omega_{\tilde{G}} = 0.23$ and be the dominant component of dark matter without violating BBN constraints. Bounds from the black-body spectrum of the cosmic microwave background (CMB) and, in some corners of parameter space, the diffuse photon spectrum, may be even more severe than bounds from BBN, but these were also shown to be respected for superpartners with weak-scale masses [5, 6]. The possibility of a gravitino LSP in supergravity theories is therefore viable.

An analogous scenario is realized if there are extra spatial dimensions of size $\sim \text{TeV}^{-1}$ [8, 9, 10, 11]. Here every particle that propagates in the extra dimensions appears to the four-dimensional observer as a tower of Kaluza-Klein (KK) particles. For suitable models [11], a discrete symmetry, KK-parity, makes the the lightest KK particle (LKP) stable. In these scenarios, the lightest KK particles are nearly degenerate classically. However, quantum effects split these degeneracies. A detailed analysis [12] shows that in many such models, the lightest KK particle is the lightest KK graviton. The next-lightest KK particle (NLKP) then decays via gravitational interactions to this graviton. If the NLKP is a KK lepton, the decay width is [5, 13]

$$\Gamma(l^1 \to l G^1) = \frac{1}{72\pi M_*^2} \frac{m_{l^1}^7}{m_{G^1}^4} \left[1 - \frac{m_{G^1}^2}{m_{l^1}^2} \right]^4 \left[2 + 3\frac{m_{G^1}^2}{m_{l^1}^2} \right] \ . \tag{3}$$

Again, the lifetime depends only on the parent and daughter masses and is proportional to G_N.

Given the viability of the gravitino LSP scenario (and the KK graviton LKP scenario), what can we learn? The Large Hadron Collider (LHC) is being built at CERN in Geneva. In a few years, the LHC will collide protons with protons at center-of-mass energy 14 TeV. Weak-scale superpartners will be pair produced, and each superpartner will rapidly decay through a chain of R-parity-preserving interactions to a nearly stable NLSP. A slepton NLSP will then appear as a heavy charged particle passing through the collider detector without decaying.

These sleptons are moderately relativistic and lose energy primarily through ionization. The softer sleptons range out within several meters water equivalent of material and can therefore be stopped by placing a collector just outside an LHC detector. After a few months, this collector may then be moved to some quiet underground environment and monitored for slepton decays. The slepton mass $m_{\tilde{l}}$ may be reasonably well-constrained by standard analyses of the kinematic distributions of cascade decays. By measuring the time distribution of decays and the energy of the outgoing leptons, one may determine τ, $m_{\tilde{G}}$, and M_*, thus allowing a calculation of G_N [14].

The total superpartner event rate is highly dependent on the superpartner mass spectrum. For a light spectrum, event rates may be as large as 10^5 per LHC year, and a measurement of Newton's constant at the percent level may be possible. Such a precise measurement of the strength of gravity between fundamental particles will extend conventional measurements of G_N to unprecedentedly small scales, and provide a determination of G_N that differs in almost all ways from more conventional methods.

The studies described above determine G_N, but also have other far reaching implications. The gravitino's mass will be determined simultaneously. This implies a determination of the supersymmetry breaking scale $F \sim m_{\tilde{G}} M_*$, with implications for models of supersymmetry breaking, the mediation of supersymmetry breaking, and vacuum energy. In the case of models with extra dimensions, it may also allow us to probe the quantum effects that produce the LKP-NLKP mass difference.

A measurement of the gravitino's mass will also have important implications for dark matter. If R-parity is conserved and the gravitino is the LSP, gravitinos are necessarily a component of dark matter. Studies at future colliders will pin down supersymmetry parameters and thereby determine the slepton thermal relic density to high accuracy. Along with the gravitino's mass, this will then determine the energy density of gravitino dark matter. If the energy density is consistent with $\Omega_{\rm DM} \simeq 0.23$, such studies will have identified the main component of dark matter. We will also be confident that we understand the history of the universe back to temperatures $T \sim 10$ GeV and times $t \sim 10^{-8}$ s, when the slepton thermal relic density was established.

Finally, the observation of NLSP decays to gravitinos will affect our understanding of Big Bang nucleosynthesis. While some of the parameter space for gravitino LSPs is excluded by BBN and the CMB, much of it is allowed, as noted above. At the boundaries of the allowed region, deviations in BBN and CMB observations that are still consistent with current data are predicted. As an example, current observations of ^{7}Li are significantly lower than those predicted by standard BBN. This anomaly can be naturally explained by ^{7}Li destruction by the late decays of NLSPs for particular decay lifetimes and NLSP relic densities [5, 6]. The measurement of NLSP lifetimes and masses will therefore provide direct laboratory evidence that will clarify our understanding of BBN and the early universe.

To conclude, we have identified well-motivated scenarios in which particle physics experiments will be able to probe the M_*-suppressed gravitational interactions of elementary particles. Such studies will provide new insights into gravity at small scales, and open up a whole realm of connections between particle physics, cosmology, and gravity.

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