Dark Matter in Many Forms

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Since ordinary matter constitutes about 4% of the closure density of the Universe while dark matter constitutes about six times as much, it is urged that searches for dark matter consider that it may exist in several forms. Implications for detection and hadron and e^+e^- colliders are discussed.

1. INTRODUCTION

Ordinary matter constitutes about 4% of the closure density of the Universe, while dark matter is responsible for about five times as much: $\Omega_d = (23 \pm 4)\%$ [1, 2]. Ordinary matter exists in several stable forms: p, n (when incorporated into nuclei), e^-, and three flavors of neutrinos. (The lifetimes of the two heavier mass eigenstates probably exceed the age of the Universe.) We could expect dark matter to exhibit at least as much variety [3].

The observed space-time (4-dimensional) and rank (4) of the Standard Model group $SU(3) \otimes SU(2) \otimes U(1)$ is much less than the maximum number of dimensions (10 or 11) considered in superstring theories or the rank of typical groups (16) in such theories. Moreover, there are at least two well-motivated dark matter candidates already (axions and neutralinos), and several variants of supersymmetry involve long-lived next-to-lightest superpartners. Thus it behooves us to case as wide a net as possible for dark matter. (The case for weakly interacting massive particles (WIMPs) as dark matter is advanced forcefully in [4].)

In the present report I give some motivations for multiple forms of dark matter, discussing how several stable forms of ordinary matter arise (Section II) and possible forms such variety might take for dark matter (Section III). Section IV is devoted to signatures in detectors planned for the CERN Large Hadron Collider (LHC) and the International Linear Collider (ILC). It is not my intention to review signatures of all suggested dark matter candidates, but to illustrate the broad range of possibilities. For reviews of dark matter candidates, see [5].

2. STABLE OBSERVED MATTER

To describe the variety of stable forms of ordinary matter, I begin with the simplest grand unified theory in which all fermions of a family belong to a single representation, the group SO(10) [6]. The baryon number B and the lepton number L are combined in a single charge $B - L$ conserved in the SO(10) limit; quarks have $B - L = 1/3$ while leptons have $B - L = -1$. No separate labels exist for B and L. The existence of stable qqq configurations is due to color SU(3). Protons (uud) are long-lived in comparison with τ(Universe) as long as SO(10) gauge bosons mediating (e.g.) $ud \to \bar{d}e^+$ are heavy enough. Nonperturbative configurations [7] enable $ud \Leftrightarrow \bar{d}e^+$ transitions but are only operative at and above electroweak temperatures.

Free neutrons are unstable ($m_e + m_{\nu_e} + m_p < m_n$), but just barely. They become stable when incorporated into some nuclei, leading to the richness of ordinary matter. The decay rates of the two heavier neutrino species in the Standard Model should be of order $G_F^2 \alpha m_\nu^3 m_\ell^2 / 16\pi^2$, which is much larger than τ(Universe). One could not have anticipated three quasi-stable neutrino species without understanding the existence of quark-lepton families. Neutrinos do contribute a non-dominant amount to the dark matter of the Universe.

Thus, the variety of stable species in the Standard Model, including protons, neutrons (in nuclei), electrons, and three families of neutrino, not to forget the massless photon and graviton, stems from a number of different sources. It might be overly naïve to expect stable dark matter to exist in only one form.

3. OLD AND NEW QUANTUM NUMBERS

Imagine a TeV-scale effective symmetry SU(3) ⊗ SU(2) ⊗ U(1) ⊗ G, where G could be R-parity in supersymmetry, Kaluza-Klein parity in theories with extra-dimensional excitations, T-parity in little Higgs models [8], Technicolor, or some other group. We can classify the possible types of matter from this standpoint as follows:

Type of matter	Std. Model	G	Example(s)
Ordinary	Non-singlet	Singlet	Quarks, leptons
Mixed	Non-singlet	Non-singlet	Superpartners
Shadow	Singlet	Non-singlet	E'_8 of $E_8 \otimes E'_8$

Dark matter can take various forms, represented by each entry in the table.

3.1. Ordinary Matter Examples

Ordinary matter could be singlets under G even if its subconstituents were non-singlets. In some composite-Higgs models, the gauge interaction binding subconstituents implies additional baryon-like states. Thus, ordinary matter could indirectly already contain the hints of a structure which could give rise to stable dark matter. Ordinary matter could exist in unusual configurations, corresponding to an alternative vacuum [9] or to exotic states carrying baryon number [2]. These models are claimed to account naturally for the ratio of dark to ordinary matter.

3.2. Mixed Matter Examples

Many dark matter scenarios involve mixed matter, such as superpartners or particles with odd Kaluza-Klein- or T-parity. These mixed-matter scenarios may different from those conventionally discussed if G is more general than a "parity," for instance a nonabelian gauge group. In supersymmetry there arises the possibility of non-topological solitons known as "Q-balls" which have been proposed as dark matter candidates [10].

3.3. Shadow Matter Examples

Shadow matter may not interact with ordinary matter *at all* except gravitationally. Alternatively, shadow matter states may mix with those of ordinary matter. Examples may be found in the case of neutrinos. For instance, each SO(10) 16-dimensional spinor contains one right-handed neutrino which is a singlet under the Standard Model group, in additional to conventional quarks and leptons. The grand unified group E_6, which contains SO(10), has an additional sterile neutrino – a singlet under SO(10) – in each 27-dimensional fundamental multiplet, in addition to 16- and 10-dimensional multiplets of SO(10). Sterile neutrinos mixing with ordinary ones have been proposed as dark matter candidates [11].

4. DETECTOR SIGNATURES

Given the possibilities mentioned above, how can we be prepared for them?

Axion dark matter deserves increased attention. In RF cavity searches a large range of frequencies remains to be scanned with adequate sensitivity to find axions even if they were to account for *all* the expected dark matter [12]. If they constitute only *part* of it, the searches are even more challenging. They become especially demanding at higher frequencies (above the currently-studied range of up to 4 GHz, corresponding to axions of mass greater than about 1.6×10^{-5} eV), since cavity design and tuning becomes progressively more difficult with increasing frequency.

The neutrino dark matter contribution to Ω depends on neutrinos' absolute masses, on which neutrinoless double beta decay will shed some light. We know that at least one neutrino species has a mass exceeding about 0.05 eV.

Dark matter with non-singlet Standard Model charges but more than a Z_2 (parity) symmetry in the BSM group G may exist in several stable forms. [In the Standard Model, the color-singlet qqq configuration stems from the richness of the color SU(3) group.] Even in supersymmetry there are scenarios in which the next-to-lightest superpartner decays to the lightest superpartner over a non-prompt distance (i.e., corresponding to a vertex displaced by at least a few tens of microns). Detectors need to be ready for kinks or vees with unexpected flight paths and for accumulation of high-energy stable particles produced in pairs at high energies. At the end of experiments it may be worth searching these detectors for relics of quasi-stable particles which have lodged in them and are still decaying [13].

Another interesting signature of near-stability corresponds to intermittent tracks in detectors. One could imagine charged and neutral quasi-stable particles split by so little in mass that they would repeatedly undergo charge exchange with the detector and would leave a track looking like a dashed line.

Dark matter with non-zero charges purely in the hidden sector will respond to gravitational probes. The detection of such particles in the mass range of 10^{14} to 10^{20} gm has been discussed in Refs. [14].

To summarize, exploring the full range of dark matter possibilities will test our ingenuity! I believe it is a prudent to base searches on signatures suggested by the widest possible variety of theoretical frameworks.

Acknowledgments

References

[1] D. N. Spergel *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **148**, 175 (2003); M. Tegmark *et al.* [SDSS Collaboration], Phys. Rev. D **69**, 103501 (2004); J. L. Feng, arXiv:hep-ph/0509309.

[2] G. R. Farrar and G. Zaharijas, arXiv:hep-ph/0510079.

[3] A. Bottino *et al.*, Nucl. Phys. Proc. Suppl. **113**, 50 (2002); G. Duda, G. Gelmini, and P. Gondolo, Phys. Lett. B **529**, 187 (2002); G. Duda *et al.*, Phys. Rev. D **67**, 023505 (2003); S. Mitra, Phys. Rev. D **71**, 121302(R) (2005); M. Y. Khlopov, in *Dark matter in cosmology: Clocks and tests of fundamental laws* (Moriond, January 1995), ed. B. Guiderdoni *et al.*, Editions Frontières, Gif-sur-Yvette, France, 1995, p. 133.

[4] M. Battaglia and M. E. Peskin, arXiv:hep-ph/0509135.

[5] G. Bertone, D. Hooper, and J. Silk, Phys. Reports **405**, 279 (2005); K. Freese, astro-ph/0508279.

[6] H. Georgi, AIP Conf. Proc. **23**, 575 (1975); H. Fritzsch and P. Minkowski, Ann. Phys. (N.Y.) **93**, 193 (1975).

[7] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, Phys. Lett. **155B**, 36 (1985).

[8] A. Birkedal-Hansen and J. G. Wacker, Phys. Rev. D **69**, 065022 (2004).

[9] C. D. Froggatt and H. B. Nielsen, astro-ph/0508513.

[10] A. Kusenko and M. E. Shaposhnikov, Phys. Lett. B **418**, 46 (1998); A. Kusenko *et al.*, Phys. Rev. Lett. **80**, 3185 (1998).

[11] K. Abazajian, G. M. Fuller, and M. Patel, Phys. Rev. D **64**, 023501 (2001); G. M. Fuller *et al.*, Phys. Rev. D **66**, 023526 (2002), and references therein.

[12] C. Hagmann, K. van Bibber, and L. J. Rosenberg, in *Review of Particle Physics*, Phys. Lett. B **592**, 1 (2004), pp. 394–397; L. J. Rosenberg, SLAC Summer Institute on Particle Physics (SSI04), August 2–13, 2004, publ. in Electronic Conf. Procs. eConf C040802:MOT002, 2004; P. Sikivie, arXiv:hep-ph/0509198.

[13] J. L. Feng, S. Su, and F. Takayama, Phys. Rev. D **70**, 063514 (2004); arXiv:hep-ph/0503117; A. Brandenburg, L. Covi, K. Hamaguchi, L. Roszkowski and F. D. Steffen, Phys. Lett. B **617**, 99 (2005).

[14] N. Seto and A. Cooray, Phys. Rev. D **70**, 063512 (2004); A. W. Adams and J. S. Bloom, astro-ph/0405266.