Single Explanation for Both Baryon and Dark Matter Densities

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(Received 4 November 1991)

It is shown that in a general class of models in which the baryon number of the Universe is created by electroweak anomalies, the energy density in dark matter may be related to the energy density in baryons as $\Omega_B/\Omega_{\mathrm{DM}} = c \times$(proton mass)/(weak scale), where the number c is order unity and calculable from the anomaly equation. The scenario unambiguously predicts charged and neutral particles with weak-scale masses which carry a new conserved quantum number and can be pair produced via the weak interactions.

PACS numbers: 98.80.Cq, 12.15.Cc, 14.80.Pb

How much matter there is in the Universe and how much of it is in the form of baryons presents an intriguing puzzle. There are three basic components to the puzzle [1]: (i) The energy density in luminous baryons (compared to the critical density) is observed to be $\Omega_B \simeq 0.1$, while conventional nucleosynthesis arguments constrain the total energy density in baryons to lie in the range $0.015 \lesssim \Omega_B \lesssim 0.16$; (ii) galactic halos contain lots of dark matter, allowing one to conclude that $\Omega_{\mathrm{DM}} \gtrsim 0.1$; and (iii) the baryon to entropy ratio today is observed to be $n_B/s \simeq 10^{-10}$.

The first striking feature about these observations is that Ω_B and Ω_{DM} are both rather close to unity—a feature explained in part by inflation [2], which predicts the sum $\Omega_{\mathrm{tot}} \equiv \Omega_B + \Omega_{\mathrm{DM}} = 1$. Combined with the constraints on Ω_B from conventional nucleosynthesis, the value $\Omega_{\mathrm{tot}} = 1$ implies

$$0.01 \lesssim \Omega_B/\Omega_{\mathrm{DM}} \lesssim 0.2 . \qquad (1)$$

Both this ratio and the value of n_B/s should be explicable in terms of fundamental particle interactions. There have been innumerable suggestions for how to generate n_B/s, as well as suggestions for dark matter candidates [1]. In most models, however, the value for the ratio (1) is fortuitous, and could be made either exponentially big or exponentially small by changing various parameters that are at best weakly constrained. In most scenarios the dark matter is comprised of relic particles that failed to completely annihilate before decoupling, and the ratio (1) depends sensitively on both the mass and decoupling temperature of the particle.

An interesting exception that motivated the present work is a paper by Barr, Chivukula, and Farhi (BCF) [3]. In that paper, an asymmetry in charges that are exactly conserved at low energy is assumed to have been generated by unstated processes far above the weak scale. For example, there could be asymmetries in $B-L$ and an anomaly-free linear combination of baryon and technibaryon number. Electroweak anomalies then equilibrate the baryon and technibaryon number densities (in a calculable way) to the values that minimize the free energy, subject to the constraint that the conserved charge asymmetries maintain their initial values.

However, the drawback of this scenario is that the equilibrated baryon and technibaryon densities will depend independently on the initial conditions. Thus their ratio cannot actually be computed without understanding the high-energy process that gave rise to the charge asymmetries in the first place, even though for "generic" initial charge asymmetries, one might expect the final baryon to technibaryon densities to be of the same order of magnitude.

The ratio (1) can be easily understood if asymmetries in both baryons and dark matter particles were produced in the same microphysical process, such as that suggested in Ref. [4]. In this Letter I show that in theories of electroweak baryogenesis (EWB), the mechanism of anomalous baryon/dark-matter equilibration envisioned by BCF may occur without having to assume any initial charge asymmetries generated far above the weak scale. During EWB, if there exists an unbroken $\mathrm{U}(1)_X$ symmetry with a weak anomaly, then dark matter in the form of stable neutral particles carrying X charge will be produced in the same anomalous process as the baryon number. Therefore not only is the baryon to entropy ratio $n_B/s \simeq 10^{-10}$ explained, but also the ratio

$$\Omega_B/\Omega_{\mathrm{DM}} = cM_p/M_X \qquad (2)$$

is predicted. In the above equation, M_p is the proton mass, M_X is the mass of the dark matter particle, and c is a number that may be computed from the anomaly equation and is typically between 1 and 10.

The $\mathrm{U}(1)_X$ symmetry can only have a weak anomaly if there are fermions which carry X charges that forbid an $\mathrm{SU}(2)\times\mathrm{U}(1)$-preserving mass term. Thus the X fermion's mass must arise from $\mathrm{SU}(2)\times\mathrm{U}(1)$ symmetry breaking and is naturally the size of M_W, but cannot be very much larger. The ratio in Eq. (1) is therefore simply explained as the ratio of the strong interaction to the weak interaction mass scales.

This scenario has definite consequences for terrestrial accelerator experiments: There must exist exotic fermions that can be pair produced via weak interactions and which have a neutral, stable decay product with a weak-scale mass. If the charged components have $M \lesssim M_W$, then the CERN e^+e^- collider LEP II will be able to produce them, and they will decay into leptons and missing energy (the dark matter particle) with large invariant mass. If only the neutral particle has mass $M \lesssim M_W$, then it could be detected in $e^+e^- \to \gamma$ plus missing energy.

Anomalous weak-scale baryogenesis (WSB) is appealing as it requires the fewest exotic particles of any baryogenesis scenario (e.g., one extra Higgs doublet), is compatible with inflation, and is predictive. The realization of WSB that I envisage is described in detail in Ref. [5]. The mechanism assumes a first-order weak phase transition, and the existence of a weak SU(2) fermion multiplet which has *CP*-violating interactions with the Higgs field(s). These interactions with the Higgs field give the fermion a complex mass whose phase changes as the fermion penetrates the phase-transition boundary. As the bubbles expand during the weak phase transition, the heavy fermions are reflected off the advancing bubble walls in a *CP*-violating way. This causes a net asymmetry in left-handed versus anti-left-handed fermions in a region preceding the wall that is typically ~100 thermal lengths thick, a nonequilibrium charge transport effect that is critical if WSB is to explain the observed value of $n_B/s \simeq 10^{-10}$; without it one tends to find too small a value [6]. In the broken phase, anomalous baryon violation is exponentially suppressed, while in the unbroken phase it is not [7]. Therefore the asymmetry in left-handed particle number produced ahead of the phase boundary in the SU(2)×U(1) symmetric region biases anomalous electroweak baryon violation in the direction of producing baryon number. These baryons then pass through to the broken phase in the interior of the bubble, where they are stable. Specific models discussed in [5] were the singlet Majoron model, where the active fermion is a ~25-GeV τ neutrino; the two-Higgs-doublet model, where the active fermion is the top quark; and the minimal supersymmetric standard model, where the Higgsino plays the leading role. Detailed numerical computations in the two-Higgs-doublet model indicate that a baryon to entropy ratio as large as 10^{-6} can be generated in this manner under optimal conditions (i.e., maximal *CP* violation, minimal reheating, etc.), and that it can easily explain the observed value of 10^{-10} under less than optimal conditions.

To explain the dark matter, I now propose that there exist additional fermions in these models with weak charges and which carry an unbroken global $U(1)_X$ symmetry with an SU(2) anomaly. While the B, L, and X symmetries are all individually violated by the weak anomaly, two linear combinations, taken to be

$$B-L, \quad B-cX, \tag{3}$$

are exactly conserved, where the number c depends on the X charges of the new fermions. If we assume for simplicity that all of the exotic fermions carry charge $X=1$, then c is an integer, and for every c units of baryon number produced by anomalous electroweak processes at the phase transition, one unit of X charge will also be produced.

The cosmology of the X fermions is not complicated. Since the X fermions can only acquire mass after SU(2)×U(1) symmetry breaking they cannot be more than several times heavier than M_W. Furthermore, measurements of the Z width from LEP show that they cannot be lighter than $\simeq 45$ GeV. The X and $\bar{X}$'s annihilate readily via Z and W exchange, by the time they go out of thermal equilibrium the temperature is well below their mass, and so the only significant energy contribution they make today is due to the particles carrying the Universe's net X charge density, which is $1/c$ times the baryon density n_B. [The calculation of X-$\bar{X}$ annihilation is similar to that for a Dirac neutrino of mass M_X (see [1,8]). Since M_X is far above the Lee-Weinberg bound of 2 GeV, the relic abundance of X's is completely determined by the $U(1)_X$ chemical potential generated at the weak phase transition.] These fermions comprise the dark matter (and hence must be electrically neutral [9]), and one finds the relation (2).

One elementary example of such a model follows from altering the two-Higgs-doublet model of Ref. [5] by adding a heavy fourth family, along with an SU(2)×U(1) singlet N which pairs up with the fourth-family neutrino to give it a Dirac mass. A global fourth-family lepton number symmetry is imposed $[\equiv U(1)_X]$, and the massive neutrino is assumed to be lighter than its charged lepton partner; fourth-family quarks are permitted to mix with the first three families. The weak anomaly for this new $U(1)_X$ is $\mathrm{Tr} X T^a T^a = 1$, while the baryon anomaly is $\mathrm{Tr} B T^a T^a = 4$. Thus $B-4X$ is exactly conserved and one heavy neutrino is produced by electroweak anomalies for every twelve quarks. As a result, the ratio today of the baryon to dark matter energy densities is given by

$$\Omega_B/\Omega_{\mathrm{DM}} = 4M_p/M_N\,. \tag{4}$$

For a fourth-family neutrino mass of size $50 \le M_N \le 400$ GeV this yields $0.01 \le \Omega_B/\Omega_{\mathrm{DM}} \le 0.1$, which lies comfortably in the range (1) which I wished to explain.

It should be evident that the scenario I am proposing is quite generic, requiring the following ingredients: (i) A first-order weak phase transition; (ii) a weak fermion multiplet whose mass develops a space-dependent phase as it penetrates the boundary separating the symmetric and broken weak phases, that arises due to *CP*-violating fermion-Higgs-boson interactions [5]; (iii) a global $U(1)_X$ symmetry with a weak anomaly; and (iv) a stable neutral particle with a weak-scale mass, which is the lightest particle carrying X charge. The first two conditions make the anomalous baryogenesis mechanism [5] possible; the last two guarantee that dark matter will be cogenerated by electroweak anomalies in a manner which explains the ratio (1). One interesting candidate for such a model is supersymmetry with exact $U(1)_R$ symmetry [10] with weak-scale Dirac masses for all of the gauginos, the photino being the lightest.

Experimental limits on dark matter particles with couplings to nuclei like those of a Dirac neutrino with mass in the 100-GeV range [11] require that the local mass density of such a neutrino to be $\lesssim \text{few} \times 10^{-26}$ g/cm^3, which is about one-tenth the average halo density. This constraint leaves three alternatives. The first is that the lightest particle carrying X charge does not itself couple strongly to the Z. For example, in the model described above, the fourth-family neutrino could mix with a lighter weak singlet Dirac neutrino, suppressing the interaction cross section by $\sin^2\alpha$, where α is the mixing angle. A second possibility is that the local density of dark matter is significantly less than the average halo density. It has been argued that there is dynamical evidence for local dark matter [12], but the evidence has disappeared with more recent data and better statistics [13]. A third and intriguing alternative is that the galactic halo is disproportionately rich in dark baryons relative to X particles. This would require $\Omega_B \sim 0.1$ to explain the observed halo density—and hence a relatively light X particle, given Eq. (2). It would also suggest that electromagnetic phenomena such as hydrodynamic shock waves or long-range magnetic fields played a large role in structure formation; since only the baryons are charged, that might account for local enrichment of baryons relative to dark matter. An enrichment factor of ~ 100 today would be necessary to be consistent with the experimental bound [11].

I have benefited from conversations with R. S. Chivukula, G. Fuller, L. Hall, and A. Wolfe. This work was supported in part by the Department of Energy under Contract No. DE-FG03-90ER40546, by the NSF under Contract No. PHY-9057135, and by the Alfred P. Sloan Foundation.

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[1] E. Kolb and M. Turner, *The Early Universe* (Addison-Wesley, Reading, MA, 1990), and references therein.

[2] A. H. Guth, Phys. Rev. D **23**, 347 (1981); A. D. Linde, Phys. Lett. **108B**, 389 (1982); A. Albrecht and P. J. Steinhardt, Phys. Rev. Lett. **48**, 1220 (1982).

[3] S. M. Barr, R. S. Chivukula, and E. Farhi, Phys. Lett. B **241**, 387 (1990); S. M. Barr, Phys. Rev. D **44**, 3062 (1991).

[4] S. Dodelson, B. Greene, and L. Widrow, Harvard University Report No. HUTP-90-A070 (to be published).

[5] A. G. Cohen, D. B. Kaplan, and A. E. Nelson, Phys. Lett. B **245**, 561 (1990); Nucl. Phys. **B349**, 727 (1991); A. E. Nelson, D. B. Kaplan, and A. G. Cohen, University of California, San Diego, Report No. UCSD/PTH 91-20 (to be published).

[6] M. Dine, P. Huet, and R. Singleton, University of California, Santa Cruz, Report No. SCIPP 91/08, 1991 (to be published).

[7] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, Phys. Lett. **155B**, 36 (1985); P. Arnold and L. McLerran, Phys. Rev. D **36**, 581 (1987); M. Dine, O. Lechtenfeld, B. Sakita, W. Fischler, and J. Polchinski, Nucl. Phys. **B342**, 381 (1990).

[8] B. W. Lee and S. Weinberg, Phys. Rev. Lett. **39**, 165 (1977); P. Hut, Phys. Lett. **69B**, 85 (1977); K. Sato and H. Kobayashi, Prog. Theor. Phys. **58**, 1775 (1977); M. I. Vysotskii, A. D. Dolgov, and Ya B. Zel'dovich, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 200 (1977) [JETP Lett. **26**, 188 (1977)].

[9] A. de Rujula, S. L. Glashow, and U. Sarid, Nucl. Phys. **B333**, 173 (1990); R. S. Chivukula, A. G. Cohen, S. Dimopoulos, and T. P. Walker, Phys. Rev. Lett. **65**, 957 (1990); J. L. Basdevant, R. Mochkovitch, J. Rich, M. Spiro, and A. Vidal-Madjar, Phys. Lett. B **234**, 395 (1990); S. Dimopoulos, D. Eichler, R. Esmailzadeh, and G. D. Starkman, Phys. Rev. D **41**, 2388 (1990); A. Gould, B. T. Draine, R. W. Romani, and S. Nussinov, Phys. Lett. B **238**, 337 (1990).

[10] L. J. Hall and L. Randall, Nucl. Phys. **B352**, 289 (1991).

[11] S. P. Ahlen *et al.*, Phys. Lett. B **195**, 603 (1987); D. O. Caldwell, R. M. Eisberg, D. Grumm, M. S. Witherell, B. Sadoulet, F. S. Goulding, and A. R. Smith, Phys. Rev. Lett. **61**, 510 (1988).

[12] J. N. Bahcall, Astrophys. J. **276**, 156 (1984); **276**, 169 (1984); **287**, 926 (1984).

[13] K. Kuijken and G. Gilmore, Mon. Not. R. Astron. Soc. **239**, 571 (1989); **239**, 605 (1989).