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Axions and the dark matter of the Universe

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Spin(10) axion models are constructed which offer the intriguing possibility that axions comprise all or a significant part of the dark matter of the Universe.

Although axion models[1] can solve the strong *CP* problem, there are potential cosmological problems associated with them. One of these is the domain-wall problem.[2] A discrete subgroup of the global, anomalous Peccei-Quinn (PQ) U(1) symmetry may remain unbroken by the QCD gluon anomaly.[3] This symmetry is then broken spontaneously and domain walls are formed. A second problem of axion models has been pointed out recently.[4] This problem has to do with the fact that since the axion couplings to matter have to be weak, the axions will essentially decouple as soon as they are produced. They may then give rise to an unacceptably large energy density in the present Universe.

The analyses of Ref. 4 imply that, for axion models to be consistent with standard cosmology, the vacuum expectations value (VEV) that breaks the PQ symmetry[5] must be less than 10^{12} GeV.[6] This clearly indicates that axion models must have intermediate mass scales, and rules out the simplest axion models based on SU(5).[8]

In this Communication, we give examples of models which have PQ symmetries that are broken at an intermediate scale. These models offer the intriguing possibility that axions comprise all or a significant portion of the dark matter of the Universe.[4] They also incorporate the solution of the domain-wall problem devised in Ref. 9. The solution is to construct the PQ symmetry so that the action of the residual, discrete PQ symmetry coincides with the action of the center of the gauge group.[10] The various domains then become gauge equivalent. In the process of spontaneous symmetry breaking, *hybrid strings* form which become the boundaries of a single domain wall that terminates on them. The string and wall system rapidly decays[11] and there is essentially no effect on standard cosmology.

We now proceed to construct our models. The gauge group is Spin(10) as in Ref. 9. The fermion content is given by

$$\psi_{16}^{(i)} \ (i=1,2,3), \quad \psi_{10}^{(\alpha)} \ (\alpha=1,2) \ , \tag{1}$$

where the subscripts denote the dimension of the Spin(10) representation to which the various fields belong. The $\mathrm{U}(1)_{\mathrm{PQ}}$ transformation properties of the fermion fields are

$$\psi_{16}^{(i)} \rightarrow e^{i\theta}\psi_{16}^{(i)} \ (i=1,2,3), \quad \psi_{10}^{(\alpha)} \rightarrow e^{-2i\theta}\psi_{10}^{(\alpha)} \ (\alpha=1,2) \ , \tag{2}$$

and were chosen so that the residual, discrete PQ symmetry coincides with the center, Z_4, of Spin(10). If we had not included $\psi_{10}^{(\alpha)}$ $(\alpha=1,2)$, the residual PQ symmetry would be Z_{12}, which is, of course, too large to be embedded in Z_4.[12]

We first consider the following symmetry-breaking chain of Spin(10) (Ref. 13):

$$\mathrm{Spin}(10) \xrightarrow[M_1]{210} \mathrm{SU}_c(3)\times\mathrm{SU}_L(2)\times\mathrm{SU}_R(2)\times\mathrm{U}(1)_{B-L} \xrightarrow[M_2]{126,\,45} \mathrm{SU}_c(3)\times\mathrm{SU}_L(2)\times\mathrm{U}(1)_Y \xrightarrow[M_W]{10} \mathrm{SU}_c(3)\times\mathrm{U}(1)_{\mathrm{em}} \ , \tag{3}$$

where the Higgs fields necessary to implement this chain are as indicated. Under $U(1)_{PQ}$, the Higgs fields transform as follows:

$$\phi^{(210)}\to\phi^{(210)},\quad \phi^{(126)}\to e^{2i\theta}\phi^{(126)},\quad \phi^{(45)}\to e^{4i\theta}\phi^{(45)},\quad \phi^{(10)}\to e^{-2i\theta}\phi^{(10)}\ . \tag{4}$$

As in the fermion case, these $U(1)_{PQ}$ transformation properties ensure that the action of the residual PQ symmetry on these fields is identical to that of the center of Spin(10). Note that all Higgs fields except for $\phi^{(210)}$ are complex.

The allowed Yukawa couplings are (in schematic form)

$$\psi_{16}\psi_{16}\phi^{(10)},\quad \psi_{16}\psi_{16}\phi^{(126)\dagger},\quad \psi_{10}\psi_{10}\phi^{(45)}\ . \tag{5}$$

The allowed Higgs couplings include

$$\phi^{(210)}\phi^{(126)\dagger}\phi^{(126)\dagger}\phi^{(45)},\quad \phi^{(210)}\phi^{(126)\dagger}\phi^{(10)}\phi^{(45)},\quad \phi^{(210)}\phi^{(126)}\phi^{(10)}\ . \tag{6}$$

These couplings guarantee that $U(1)_{PQ}$ is the only global symmetry present. They also guarantee that $\phi^{(45)}\to-\phi^{(45)}$ is *not* a symmetry of the Lagrangian so that the domain-wall problems associated with this symmetry can be avoided.[16] Now $\langle\phi^{(210)}\rangle$ cannot break $U(1)_{PQ}$ since it is neutral under $U(1)_{PQ}$. Hence $U(1)_{PQ}$ is broken at the intermediate scale M_2 by $\langle\phi^{(126)}\rangle$, $\langle\phi^{(45)}\rangle$. Both of these VEV's are needed at this stage, since, if only one of them is used, then a linear combination of the $U(1)_{PQ}$ generator and B-L will remain unbroken.

We next use the one-loop renormalization-group equations for the various coupling constants to calculate M_1 and M_2 in terms of $\sin^2\theta_w(M_w)$ and $\alpha_s(M_w)$. We also include the following Higgs contributions[17]: Between M_2 and M_1 we include the (1,1,3,+1) and (1,3,1,−1) components of the $\underline{126}$, the (1,3,1,0) and (1,1,3,0) components of the $\underline{45}$, and the (1,2,2,0) components of the $\underline{10}$, where we have decomposed the Spin(10) representations under the subgroup $SU_c(3)\times SU_L(2)\times SU_R(2)\times U(1)_{(B-L)/2}$. Between M_w and M_2 we only take the contribution of a single $SU_L(2)$ doublet (the Weinberg-Salam doublet). The fermions in the $\underline{10}$ acquire masses $\sim M_2$ and so contribute to the renormalization-group equations between M_2 and M_1.

TABLE I. M_1 and M_2 as functions of $\sin^2\theta_w(M_w)$ and $\alpha_s^{-1}(M_w)$ for the chain of Eq. (3).

$\sin^2\theta_w(M_w)$	$\alpha_s^{-1}(M_w)$	M_2 (GeV)	M_1 (GeV)
0.22	7.5	3.4×10^{12}	3.4×10^{15}
0.22	8.0	4.9×10^{12}	2.1×10^{15}
0.22	9.0	1.0×10^{13}	1.0×10^{15}
0.23	7.5	1.1×10^{11}	6.0×10^{15}
0.23	8.0	1.6×10^{11}	3.7×10^{15}
0.23	9.0	3.3×10^{11}	1.4×10^{15}

We find that for $\sin^2\theta_w(M_w)\leq0.21$, M_2 is too high to comply with the constraints of Ref. 4. Table I shows how M_1 and M_2 vary as functions of $\sin^2\theta_w(M_w)$ and $\alpha_s(M_w)$. We have taken $\sin^2\theta_w(M_w)=0.22$, 0.23, and $\alpha_s^{-1}(M_w)=7.5$, 8.0, 9.0.[18]

We expect two-loop contributions to reduce M_1 and M_2 by a factor of 2–4. From Table I we see that there is a nontrivial range of values of $\sin^2\theta_w(M_w)$ and $\alpha_s(M_w)$ which are consistent with low-energy experiments *and* allow us to satisfy the constraints of Refs. 4 and 7. We also see that there are values of the parameters for which M_2/g saturates or nearly saturates its upper bound of 10^{12} GeV, where g is a typical gauge coupling constant. In this case, the axions of this model could comprise all or most of the dark matter of the Universe.[4]

There are other intermediate symmetry groups that could have been used in place of $SU_c(3)\times SU_L(2)\times SU_R(2)\times U(1)_{B-L}$ in Eq. (3). One of these is the Pati-Salam subgroup[14] $SU_c(4)\times SU_L(2)\times SU(2)_R$. However, the mass scales in this case cannot satisfy the required constraints. Another subgroup is $SU_c(4)\times SU_L(2)\times U(1)_R$. In this chain, we use a combination of a real $\underline{45'}$ and a real $\underline{54}$ both with PQ charge zero to implement the first breaking (neither can do it alone). We also employ the same Higgs fields with the same PQ charges as in Eqs. (3) and (4) to implement the remaining symmetry breakings. The fermions are as in Eqs. (1) and (2), whereas the Higgs couplings include $\underline{54}\times\underline{126}^\dagger\times\underline{126}^\dagger\times\underline{45}$ and $\underline{54}\times\underline{10}\times\underline{10}\times\underline{45}$. Note that a $\underline{126}^\dagger\times\underline{126}\times\underline{45'}$ coupling exists which eliminates the domain-wall problem associated with the $\underline{45'}$ which performs the first breaking. As in the previous chain, we have used the renormalization-group equations to calculate M_1 and M_2 in terms of $\sin^2\theta_w(M_w)$ and $\alpha_s(M_w)$. We have included the following Higgs contributions: Between M_2 and M_1 we include the $(\overline{10},1,-1)$ component of $\underline{126}$, the (15,1,0) component of $\underline{45}$, and $(1,2,\frac{1}{2})$ coming from $\underline{10}$. Between M_w and M_2 we include the Weinberg-Salam doublet only. The above decompositions are with respect to $SU_c(4)\times SU_L(2)$

TABLE II. M_1 and M_2 as functions of $\sin^2\theta_w(M_w)$, $\alpha_s^{-1}(M_w)$ with $SU_c(4) \times SU_L(2) \times U(1)_R$ as the intermediate symmetry group.

$\sin^2\theta_w(M_w)$	$\alpha_s^{-1}(M_w)$	M_2 (GeV)	M_1 (GeV)
0.22	7.5	3.5×10^{11}	2.0×10^{15}
0.22	8.0	6.2×10^{11}	1.3×10^{15}
0.22	9.0	1.9×10^{12}	5.7×10^{14}
0.23	7.5	3.7×10^{9}	2.6×10^{15}
0.23	8.0	6.6×10^{9}	1.7×10^{15}
0.23	9.0	2.0×10^{10}	7.2×10^{14}

$\times U(1)_R$. Note that the fermions in the 10 contribute to the renormalization-group equations between M_2 and M_1. The results for M_1 and M_2 for this chain are given in Table II.

As in the previous case, we see that this pattern of symmetry breaking can also accommodate very nicely the bounds of Refs. 4 and 7. We also see that axions can make up most or all of the dark matter of the Universe in this scheme, too.

We now turn briefly to the phenomenology of the models discussed above. We expect that gauge-boson-mediated proton decay will occur in the model with a lifetime which can vary from $1-10^4$ times the SU(5) lifetime for the $SU_c(3) \times SU_L(2) \times SU_R(2) \times U(1)_{B-L}$ chain and from $1-10^2$ times the SU(5) lifetime for the $SU_c(4) \times SU_L(2) \times U(1)_R$ chain. We also note that if neutrinos acquire a mass through the mechanism of Ref. 19, then as M_2 varies between 10^{12} and 10^9 GeV the heaviest neutrino in our models can have a mass ranging from 0.1 to 100 eV.[20] Hence the dominant component of the dark matter of the Universe can vary from *axions* to *neutrinos* as M_2 varies between 10^{12} and 10^9 GeV, respectively. Finally, we note that the superheavy fermions $\psi_{10}^{(\alpha)}$, whose masses are of the order of M_2, might also contribute to the generation of baryon asymmetry.

To summarize, we have constructed Spin(10) axion models which are compatible with all known cosmological constraints. Moreover, they offer the possibility that the axions provide all, or a significant fraction, of the dark matter of the Universe.

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