

Contents

1	Introduction	1
2	The case for a Peccei-Quinn symmetry	3
3	Axion generalities	6
3.1	The guts of the strong CP problem	7
3.2	The axion solution	9
3.3	Constructing the axion and its effective Lagrangian	10
3.3.1	Axial basis	13
3.3.2	Mixing with mesons and the axion-photon coupling	15
3.3.3	Axion-nucleon interactions	15
3.4	The physical axion: orthogonality conditions	15
3.5	Remnant symmetry and domain-wall number	19
4	Axion properties in various $SO(10) \times U(1)_{PQ}$ models	21
4.1	Models with an axion decay constant at the electroweak scale	22
4.2	Models with axion decay constants at the unification scale	27
4.3	Models with an intermediate scale axion decay constant	29
4.3.1	Additional 45_H	29
4.3.2	Additional 45_H and extra fermions	31
4.4	Models with decay constants independent of the gauge symmetry breaking	33
5	Constraints on axion properties from gauge coupling unification	34
5.1	Running with one intermediate scale	36
5.2	Running with two intermediate scales	39
5.2.1	An extra multiplet	39
5.2.2	An extra multiplet, and additional fermions	41
5.3	Models with a scalar singlet	42
5.4	Dependence on the proton lifetime	43
6	Summary and discussion	44
A	Invariance of axion-neutral gauge boson couplings under fermionic rephasings	51
B	Roots and weights of $SO(10)$ and $4_C \times 2_L \times 2_R$	52
C	Coupling evolution	55
C.1	Model 1	58
C.2	Model 2.1. Case A: $M_{PQ} > M_{BL}$	61
C.3	Model 2.1. Case B: $M_{BL} > M_{PQ}$	63

C.4	Model 2.2. Case A: $M_{PQ} > M_{BL}$	64
C.5	Model 2.2. Case B: $M_{BL} > M_{PQ}$	64
C.6	Model 3.1	65
C.7	Model 3.2. Case A: $M_{PQ} > M_{BL}$	65
C.8	Model 3.2. Case B: $M_{BL} > M_{PQ}$	66
D	Higher dimensional PQ-violating operators	66