Letter

Superconducting strings in E_6

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We discuss the appearance of superconducting strings in E_6 grand unification, keeping track of the magnetic monopole flux that precedes the formation of the string flux tube. This flux matching ensures compatibility with the quantum tunneling of a monopole-antimonopole pair on a metastable string. We identify two realistic E_6 models with superconducting (metastable) strings that also carry zero modes of the right-handed Majorana neutrinos and dark matter particles. Depending on the symmetry breaking scale associated with the strings, the latter could be a source of observable gravitational waves, intermediate scale dark matter, and the observed baryon asymmetry via leptogenesis. Topologically stable superconducting strings also appear if the E_6 symmetry breaking leaves unbroken the Z_2 subgroup of Z_4, the center of SO(10). The zero modes of the Standard Model fermions are the charge carriers in this case. Finally, the flux matching condition ensures that the Aharonov-Bohm phase change in going around the metastable strings is an integer multiple of 2π for all fields. The fields in the spinorial representation of SO(10) acquire a phase change of $\exp(\pm i\pi)$ if taken around the topologically stable Z_2 string.

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Introduction. Cosmic strings arise in realistic extensions of the Standard Model (SM) with the first [1], and so far the only known example, of topologically stable strings discovered in models based on SO(10) grand unification. On the other hand, metastable strings, which are susceptible to breaking via quantum mechanical tunneling of monopole-antimonopole pairs, are far easier to identify in realistic models. In a pioneering paper [2], Witten argued that metastable strings in E_6 grand unification can be superconducting. For recent discussions of topological structures in the E_6 and SO(10) models, see Refs. [3–8]. Metastable [9] and quasistable [10,11] cosmic strings have in recent years acquired a fair amount of attention, especially if they are superheavy, with a dimensionless string tension $G\mu \sim 10^{-6}$. It has been shown [6,12–30] that the emission of gravitational waves by such superheavy metastable or quasistable strings provides a plausible explanation of the stochastic gravitational wave detected by the Pulsar Timing Array (PTA) experiments [31–34]. Gravitational wave emission from metastable strings carrying zero modes of the right-handed Majorana neutrinos has also been recently discussed [5].

In this Letter, we provide a unified discussion of metastable and topologically stable superconducting strings in E_6 models. We identify two distinct E_6 models that yield superconducting metastable strings [2]. In our discussion, we keep track of the magnetic monopoles whose nucleation on the string makes the latter unstable. We refer to it as the "flux matching condition." Following Ref. [3], the magnetic flux of the minimally charged magnetic E_6 monopole that is associated with the string contains a mixture of $\mathrm{U}(1)_\psi$ and SO(10), which is precisely determined by topological considerations. Here we are assuming that E_6 is broken via $\mathrm{SO}(10) \times \mathrm{U}(1)_\psi$, which yields the desired magnetic monopole. Taking this into account allows us to identify the magnetic flux tube subsequently carried by the string. The breaking of $\mathrm{SO}(10) \times \mathrm{U}(1)_\psi$ symmetry to the SM symmetry can proceed in more than one way, which we briefly describe. In particular, we identify an E_6 model that yields superconducting metastable strings that also carry zero modes of the three right-handed Majorana neutrinos and the dark matter particle [an SO(10) singlet fermion]. If the string is relatively light, namely, if the U(1) symmetry breaking scale is on the order of 10 TeV or so, this string can also be a source of eV mass sterile neutrinos. However, if the string is superheavy, which also leads to much heavier dark matter in the model, the gravitational wave emission from the

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string can be detected by the ongoing and future PTA measurements.

For completeness, we show how a topologically stable superconducting string appears in E_6 if the symmetry breaking to $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}}$ also preserves a Z_2 gauge symmetry, which is contained in the center Z_4 of SO(10). Finally, the flux matching condition also ensures compatibility with the Aharonov-Bohm (AB) requirement that the phase change of all matter and Higgs fields upon circling the metastable strings is an integral multiple of 2π. An exception arises for the fields in the spinorial representation of SO(10) in the presence of a topologically stable Z_2 string associated with an unbroken Z_2 gauge symmetry.

Superconducting metastable strings in E_6. The chiral (16) and vector (10) representations of SO(10), along with an SO(10) singlet, reside in the 27-dimensional representation in E_6 grand unification. The decomposition of the E_6 representations 27 and 78 under $\mathrm{SO}(10) \times \mathrm{U}(1)_\psi$ followed by the breaking $\mathrm{SO}(10) \to \mathrm{SU}(5) \times \mathrm{U}(1)_\chi$ is as follows:

$$
\begin{aligned}
&E_6 \to SO(10) \times U(1)_\psi,\\
&27 = 16(1) + 10(-2) + 1(4), 78 \supset 1(0) + 45(0); \qquad (1)\\
&SO(10) \to SU(5) \times U(1)_\chi,\\
&16 = 10(-1) + \bar{5}(3) + 1(-5), \quad 10 = 5(2) + \bar{5}(-2),\\
&45 \supset 1(0) + 24(0); \qquad (2)\\
&SU(5) \to SU(3)_c \times SU(2)_L \times \mathrm{U}(1)_Y,\\
&10 = (3,2)(1) + (\bar{3},1)(-4) + (1,1)(6),\\
&\bar{5} = (\bar{3},1)(2) + (1,2)(-3), 24 \supset (1,1)(0). \qquad (3)
\end{aligned}
$$

The U(1) generators are normalized following Ref. [35], such that the multiplets have the minimal charges compatible with a period of 2π. With this normalization, the electric charge generator and its orthogonal broken generator are given by

$$Q = \frac{1}{2}T_L^3 + \frac{Y}{6}, \qquad \mathcal{B} = \frac{1}{2}T_L^3 - \frac{Y}{10}. \qquad (4)$$

In Table I, we summarize the relevant charges, namely, Y, ψ, and χ of the multiplets in the 27 representation, along with some other charges associated with the generators which play an important role in our analysis.

We begin with the following breaking of E_6:

$$E_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\psi. \qquad (5)$$

This breaking was discussed in Ref. [2], and it was argued that the string associated with the $\mathrm{U}(1)_\psi$ symmetry was superconducting. In our approach, as we previously mentioned, we ensure in addition, that the ψ monopole flux and the flux carried by the string are compatible with the metastable framework. We note, following Ref. [3] and Table I, that the minimally charged ψ monopole carries a flux $(\psi + \chi)/4$. This flux is compatible with the Dirac quantization condition, as shown for the 27 matter fields in Table I. Note that this flux combination comes about from the nontrivial intersection between the Z_4 symmetries in SO(10) and $\mathrm{U}(1)_\psi$.

For comparison, let us recall how the topologically stable grand unified theory (GUT) monopole emerges from the spontaneous breaking of SO(10) to $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$. A 2π rotation along Q, Eq. (4), accompanied by suitable color rotation, yields the GUT monopole that carries one unit $2\pi/e$ of Dirac magnetic charge as well as some color magnetic charge.

Returning to the ψ monopole, the breaking of $\mathrm{SO}(10) \times \mathrm{U}(1)_\psi$ to $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_\chi \times \mathrm{U}(1)_\psi$, followed by the breaking of $\mathrm{U}(1)_\psi$ and then $\mathrm{U}(1)_\chi$, can be accomplished using the SO(10) singlet Higgs field N, the SU(5) singlet Higgs field ν^c, and suitable additional Higgs fields as necessary. This yields a superconducting string in which the supercurrent is carried by the zero modes of the heavy charged fermions in the 10-plet of SO(10) (right movers) complemented by the SM down quarks and charged leptons including their antiparticles (left movers.) In addition, there will be neutral zero modes of N_i (right movers) and ν^c (left movers) arising from the dimension-five operators $F_i F^\dagger F^\dagger F_i$ with F referring to N or ν^c. The metastable monopole-string system is described in Fig. 1. Note that the inner core carries the right movers, while the zero modes of the SM fermions are in the outer core associated with the electroweak flux.

The phase of the scalar fields N and ν^c, respectively, change by $+2\pi$ and -2π if taken around the string in Fig. 1. Note that the -2π phase change of ν^c arises from its interactions with both the χ and ψ magnetic fluxes. Even though $\chi/4$ is not an integral multiple of the minimal magnetic flux $\chi/5$, the phase change of $\exp[-2\pi i(5/4)]$ is accompanied by an additional phase change of $\exp[2\pi i(1/4)]$ from the interaction of ν^c with the magnetic flux $\psi/4$. The overall Aharonov-Bohm phase change is therefore an integral multiple of 2π. The phase of the up-type electroweak Higgs doublet remains unchanged upon rotation around the string, while the phase of the down-type electroweak doublet changes by -2π.

At this stage, it is appropriate to discuss how the superconducting string in Fig. 1 can be a source of dark matter particles that we alluded to earlier. Let us recall that the breaking of the SO(10) symmetry to $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}}$ solely with Higgs fields in tensor representations yields an unbroken Z_2 gauge symmetry, which can make a candidate dark matter particle stable. In our case, a plausible dark matter candidate can be the lightest N_i. However, to realize the Z_2 symmetry, we should replace the vacuum expectation value (VEV) $\langle \nu^c \rangle$ with the VEV $\langle \nu^c \nu^c \rangle$ in the 126-plet of SO(10), which, in turn, is found in the $\overline{351'}$ multiplet of

TABLE I. U(1) charges Y, χ, ψ of the 27 matter fields in E_6, where i stands for the generation index. N, ν^c, and h_u, h_d denote the relevant Higgs fields in 27, and $\nu^c\nu^c$ denotes the SU(5) singlet in the 126-plet of $\overline{351'}$. Also shown are quantities that play a role in identifying the superconducting strings. $\mathcal{B} \equiv \frac{1}{2}T_L^3 - \frac{Y}{10}$ is the broken generator orthogonal to Q defined in Eq. (4), and $\chi' = \frac{3\chi-\psi}{4}$, $\psi' = \frac{\chi+5\psi}{4}$ are defined in Eq. (7). $\frac{\chi}{10} - \mathcal{B}$ is the magnetic flux carried by the stable Z_2 string. The last column shows the Z_2 charges of various fields, where $Z_2 \subset Z_4$, the center of SO(10). Note that $\chi = -5(B-L) + \frac{2}{3}Y$, where B and L denote baryon and lepton number, respectively.

	Fields	Y	χ	ψ	χ'	ψ'	$\frac{\chi'+\psi'}{4} \equiv \frac{\chi+\psi}{4}$	$\mathcal{B}$	$\frac{\chi'}{4} + \frac{\psi'}{20} + \frac{Y}{5} \equiv \frac{\chi}{5} + \frac{Y}{5}$	$\frac{\psi'}{5} - \frac{Y}{5} \equiv \frac{\psi}{4} + \frac{\chi}{20} - \frac{Y}{5}$	$\frac{\chi}{10} - \mathcal{B}$	Z_2
Matter	u_i	1	−1	1	−1	1	0	$\frac{2}{5}$	0	0	$-\frac{1}{2}$	−1
	d_i	1	−1	1	−1	1	0	$-\frac{3}{5}$	0	0	$\frac{1}{2}$	−1
	u_i^c	−4	−1	1	−1	1	0	$\frac{2}{5}$	−1	1	$-\frac{1}{2}$	−1
	d_i^c	2	3	1	2	2	1	$-\frac{1}{5}$	1	0	$\frac{1}{2}$	−1
	ν_i	−3	3	1	2	2	1	$\frac{4}{5}$	0	1	$-\frac{1}{2}$	−1
	e_i	−3	3	1	2	2	1	$-\frac{1}{5}$	0	1	$\frac{1}{2}$	−1
	e_i^c	6	−1	1	−1	1	0	$-\frac{3}{5}$	1	−1	$\frac{1}{2}$	−1
	ν_i^c	0	−5	1	−4	0	−1	0	−1	0	$-\frac{1}{2}$	−1
	H_{ui}^+	3	2	−2	2	−2	0	$\frac{1}{5}$	1	−1	0	+1
	H_{ui}^0	3	2	−2	2	−2	0	$-\frac{4}{5}$	1	−1	1	+1
	H_{di}^0	−3	−2	−2	−1	−3	−1	$\frac{4}{5}$	−1	0	−1	+1
	H_{di}^-	−3	−2	−2	−1	−3	−1	$-\frac{1}{5}$	−1	0	0	+1
	D_i	−2	2	−2	2	−2	0	$\frac{1}{5}$	0	0	0	+1
	D_i^c	2	−2	−2	−1	−3	−1	$-\frac{1}{5}$	0	−1	0	+1
	N_i	0	0	4	−1	5	1	0	0	1	0	+1
Higgs fields	ν^c	0	−5	1	−4	0	−1	0	−1	0	$-\frac{1}{2}$	−1
	N	0	0	4	−1	5	1	0	0	1	0	−1
	h_u^+	3	2	−2	2	−2	0	$\frac{1}{5}$	1	−1	0	+1
	h_u^0	3	2	−2	2	−2	0	$-\frac{4}{5}$	1	−1	1	+1
	h_d^0	−3	−2	−2	−1	−3	−1	$\frac{4}{5}$	−1	0	−1	+1
	h_d^-	−3	−2	−2	−1	−3	−1	$-\frac{1}{5}$	−1	0	0	+1
	$\nu^c\nu^c$	0	−10	2	−8	0	−2	0	−2	0	−1	+1

E_6. The lightest N_i, presumably with an intermediate-scale mass, is stable in this case, and its zero mode resides on the superconducting string as shown in Fig. 1. Note that the presence of an unbroken Z_2 symmetry implies the existence of a topologically stable string in E_6 that we shall discuss in the next section.

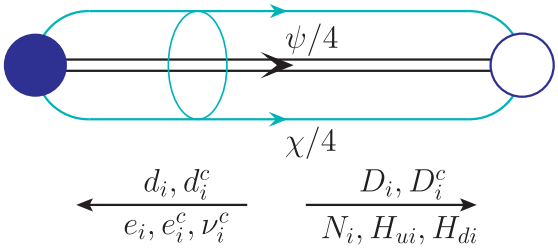


FIG. 1. ψ monopole-antimonopole pair connected by the superconducting string with magnetic flux $\psi/4 + \chi/4$. The right-moving and left-moving fermion zero modes are also shown. In the presence of an unbroken Z_2 symmetry, the lightest N_i is a plausible dark matter candidate.

For our second superconducting string, which appears in E_6, consider the following symmetry breaking:

$$E_6 \to \mathrm{SU}(5) \times \mathrm{U}(1)_{\psi'} \to \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y. \quad (6)$$

The breaking of E_6 to $\mathrm{SU}(5) \times \mathrm{U}(1)_{\psi'}$ in Eq. (6) is achieved, among other Higgs scalars, by the VEV of the field ν^c. Here, following Ref. [3], we introduce the generator ψ' and its orthogonal counterpart χ', which are linear combinations of ψ and χ and defined as follows:

$$\chi' = \frac{3\chi - \psi}{4}, \qquad \psi' = \frac{\chi + 5\psi}{4}. \quad (7)$$

From Table I, we observe that the $\langle \nu^c \rangle$ leaves $\mathrm{U}(1)_{\psi'}$ unbroken, while the broken generator is χ'. The subsequent breaking of $\mathrm{U}(1)_{\psi'}$ is achieved with the Higgs field N with

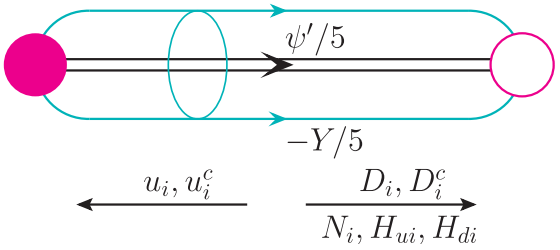


FIG. 2. ψ' monopole-antimonopole pair connected by the superconducting string carrying magnetic flux $\psi'/5 - Y/5$. The right-moving and left-moving fermion zero modes are also shown.

a ψ' charge of 5. From Table I, we conclude that $\mathrm{U}(1)_{\psi'}$ and SU(5) share in common a Z_5 symmetry. Indeed, the minimal ψ' monopole carries a magnetic flux $\psi'/5 - Y/5$, which is consistent with the Dirac quantization condition. From Table I, we can verify that the string is superconducting with the N field responsible for the right movers, and the up-type SM Higgs responsible for the left movers (Fig. 2).

To clarify the appearance of the ψ' monopole, consider the symmetry breaking

$$E_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\psi \to \mathrm{SU}(5) \times \mathrm{U}(1)_\chi \times \mathrm{U}(1)_\psi \to \mathrm{SU}(5) \times \mathrm{U}(1)_{\psi'}. \tag{8}$$

The first breaking produces the ψ monopole with flux $\psi/4 + \chi/4$, which is followed by the χ monopole in the second breaking, which carries a flux of $\chi/5 + Y/5$. In the subsequent breaking of the symmetry $\mathrm{U}(1)_\chi \times \mathrm{U}(1)_\psi$ to $\mathrm{U}(1)_{\psi'}$ with the SU(5) singlet ν^c, the ψ' monopole is realized from the merger of a ψ monopole with a χ antimonopole, as shown in Fig. 3. (Here we describe the ψ and χ monopoles in the prime notation ψ', χ'.)

These E_6 models are interesting not only because the string is superconducting, but also because they carry zero modes pertaining to the three right-handed neutrinos. Furthermore, if we require the presence of a suitable dark matter particle which, say, is the lightest SO(10) singlet fermion N_i, the string also carries the zero modes of dark matter. This is because the N_i matter fields acquire masses from the dimension-five couplings $N_i N_j \bar{N}\bar{N}$, and the lightest one is a plausible dark matter candidate (for recent discussions of dark matter candidates in E_6, see [6,36–40]).

Topologically stable superconducting string in E_6. We have focused so far on metastable strings in E_6 and emphasized the importance of matching the magnetic flux carried by the monopole and string in this setup. In order to implement this scenario, we have utilized the SU(5) singlet Higgs field ν^c contained in the 27-plet whose VEV breaks the gauge symmetry $\mathrm{U}(1)_\chi$ to Z_5.

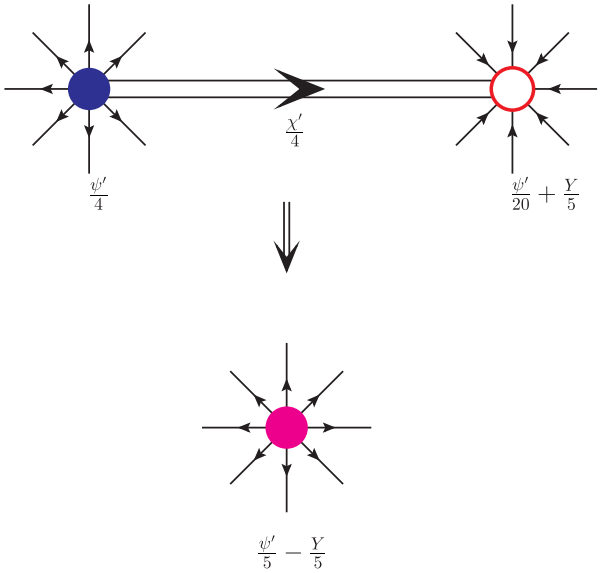


FIG. 3. A ψ monopole with flux $\psi'/4 + \chi'/4$ $(= \psi/4 + \chi/4)$ and a χ antimonopole with flux $\psi'/20 + Y/5 (= \chi/5 + Y/5)$ are connected by a $\mathrm{U}(1)_{\chi'}$ flux tube as described in the text. They merge to form a ψ' monopole. This arises from the breaking $E_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\psi \to \mathrm{SU}(5) \times \mathrm{U}(1)_\chi \times \mathrm{U}(1)_\psi \to \mathrm{SU}(5) \times \mathrm{U}(1)_{\psi'}$.

It was shown in Ref. [1] that if SO(10) is broken to $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}}$ using only scalar Higgs in the tensor representations, a discrete Z_2 gauge symmetry stays unbroken, which leads to the appearance of topologically stable strings. In SO(10) this means replacing the Higgs 16-plet with a 126-plet which, in E_6, can be found in the $351'$ multiplet.

In order to identify the topologically stable string in E_6, let us begin by breaking the E_6 symmetry to SO(10) using the Higgs field N. Next, we employ the 78-dimensional representation to break SO(10) to $\mathrm{SU}(5) \times \mathrm{U}(1)_\chi$, which produces a chi monopole carrying a magnetic flux $(\chi + Y)/5$. The χ magnetic flux of this monopole is squeezed into two separate tubes by the VEV of the SU(5) singlet component of the 126-plet (in $351'$). This occurs because the χ charge of this field is -10, which means that the flux tube created from this breaking can only carry a flux $\chi/10$.

The monopole-string structure associated with the symmetry breaking $E_6 \to \mathrm{SO}(10) \to \mathrm{SU}(5) \times \mathrm{U}(1)_\chi \to \mathrm{SU}(5) \times Z_2$ is shown in Fig. 4. The string is topologically stable because of the mismatch between the monopole flux $\chi/5$ and the flux $\chi/10$ that the string can carry. Note that the string carries zero modes of the three right-handed neutrinos as well as the N_i matter fields.

The breaking of the SU(5) symmetry to the SM gauge symmetry can be carried out in the usual way using the adjoint field of E_6. The final breaking to $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}} \times Z_2$ is achieved with the SO(10) 10-plet Higgs contained in the 27-dimensional representation of E_6. This ensures that the Z_2 gauge symmetry stays unbroken and the string is topologically stable. In order to make sure that the phase change of the electroweak doublets from going

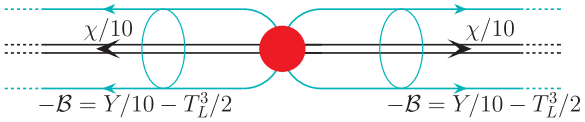


FIG. 4. Monopole-string system from the breaking $E_6 \to \mathrm{SO}(10) \to \mathrm{SU}(5) \times \mathrm{U}(1)_\chi \to \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times Z_2 \to \mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}} \times Z_2$. $\mathcal{B}$ denotes the broken electroweak generator orthogonal to Q, the electric charge. An open string is stable because of the unbroken Z_2 symmetry. The phase change of the matter fields in the spinorial representation of SO(10) is $\exp(\pm i\pi)$ if taken around this superconducting Z_2 string with magnetic flux $\chi/10 - \mathcal{B}$ (see Table I, second to last column).

around the string is an integral multiple of 2π, we should include a $-T_L^3/2$ unit of magnetic flux to the string. The combination $\mathcal{B} = T_L^3/2 - Y/10$ is the broken generator orthogonal to Q. Including the electroweak symmetry breaking, the final monopole-string configuration is displayed in Fig. 4.

A crucial thing to note is that phase change of the up-type and down-type Higgs doublets is $+2\pi$ and -2π, respectively, which means that the string is superconducting. The up-type quarks and their antiparticles are the right movers, while the down-type quarks and charged leptons, together with their antiparticles are the left movers. Furthermore, the phase change of the spinorial 16-plet of SO(10) matter fields in the 27-plet is $\exp(\pm i\pi)$, which is a reflection of the unbroken Z_2 symmetry.

Conclusions. We have shown the presence of both metastable and topologically stable superconducting strings in E_6 grand unified models. For the metastable strings susceptible to breaking via quantum tunneling of monopole-antimonopole pairs, we ensure that the monopole flux and the flux carried by the string are precisely matched. If appropriately heavy, the metastable strings seem to provide a satisfactory explanation of the stochastic gravitational background observed by the PTA experiments. In the presence of an unbroken gauge Z_2 symmetry, the superconducting metastable strings also carry zero modes of a compelling dark matter candidate in E_6. The topologically stable string whose presence is guaranteed by the unbroken Z_2 symmetry also turns out to be superconducting. Finally, the flux matching condition also ensures that the AB phase change for all matter and Higgs fields in E_6, if taken around these metastable strings, is an integral multiple of 2π. The 16-dimensional matter fields in SO(10) acquire an AB phase of $\exp(\pm i\pi)$ if taken around the topologically stable Z_2 string.

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Data availability. No data were created or analyzed in this study.

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