Topologically stable, finite energy electroweak-scale monopoles

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PHENO 2020, May 4, 2020
- **ELECTROWEAK-SCALE MONOPOLE**: Monopoles whose masses \( \sim O(\text{TeV}) \) \( \rightarrow \) Accessible at the LHC
- **FINITE ENERGY**: A soliton with finite mass
- **TOPOLOGICALLY STABLE**: The monopole is stable due to a topological conservation law.
- **Who cares about monopoles?**: Dirac, Schwinger, ’t Hooft, Polyakov,...
- **For what reasons?**: Symmetry of Maxwell equations, charge quantization,..., consequences of spontaneous symmetry breaking.
A very brief history of monopoles

- **Dirac monopoles**: Just pure electromagnetism $U(1)_{em}$. Point-like monopole with a singular string attached.
- **'tHooft-Polyakov monopoles**: The singular string is gotten rid of by embedding $U(1)_{em}$ into $SO(3) \to U(1)_{em}$ with a real Higgs triplet. Energy scale $\sim M_W$. Not a realistic EW model. But it has a finite-energy, topologically stable monopole.
- **GUT monopole**: One example: $SU(5)$. It was constructed not with a monopole in mind but with gauge unification. A GUT-scale monopole comes out as a consequence of $SU(5) \to SU(3) \times SU(2) \times U(1)$.
- **Cho-Maison EW monopole**: Modification of the kinetic term of the $U(1)_Y$ gauge field $B_\mu$ in order to get a finite-energy, topologically stable electroweak monopole.
- **Topologically stable, finite energy electroweak-scale monopole**: A consequence of a model of non-sterile, electroweak-scale right-handed neutrinos.
From non-sterile EW right-handed neutrinos $\nu_R$ to EW monopoles

- There is no principle that requires $\nu_R$s to be sterile i.e. singlets of $SU(2) \times (1)_Y$
- What if $\nu_R$s are non-sterile?: e.g. a member of a doublet $l^M_R = (\nu_R, e^M_R)$ with a mirror charged lepton. (SM lepton doublet $l^L = (\nu_L, e_L)$.) The phenomenology of mirror quarks and leptons have been discussed in a series of papers. They are Long-Lived and fall into the LLP current efforts. (EW $\nu_R$ model).
- See-saw mechanism with non-sterile $\nu_R$: Usual seesaw: light mass: $m_D^2/M_R$, Heavy Majorana $\nu_R$: $M_R$.
- $m_D$ from $g_S l^M_R \phi l^M_R$; $M_R$ from $g_M l^M_R, T \sigma_2 \tau_2 \tilde{\chi} l^M_R$. $\phi$: SM singlet; $\tilde{\chi} = (\chi^0, \chi^+, \chi^{++})$: SM complex triplet. $\langle \chi^0 \rangle = v_M \rightarrow M_R = g_M v_M$
- Since $\nu_R$s are non-sterile, $M_R > M_Z/2 \Rightarrow v_M > 41 GeV$ if $g_M \sim O(1)$. Big Problems! Why?
- $M_W \neq M_Z \cos \theta_W$ at tree level VERY BADLY!
- Cure?: Introduce a real triplet $\xi (Y/2 = 0) = (\xi^+, \xi^0, \xi^-)$. Correct vacuum alignment $\rightarrow \langle \xi^0 \rangle = v_M$ Custodial symmetry is restored and $M_W = M_Z \cos \theta_W$!
- A real triplet $\xi$ of $SU(2)$ reminds us of the construction of the ’t Hooft-Polyakov monopole!
Real triplet $\xi$ and EW monopoles

To find whether or not one has a non-trivial, stable monopole with finite energy, one maps at infinity the vacuum manifold $\mathcal{M}$ onto the boundary of a 3-dimensional spatial sphere $S^2$. To make the long story short, this means that one looks at the second homotopy group $\Pi_2(\mathcal{M})$: $\Pi_2(\mathcal{M}) = 0$, no monopole; $\Pi_2(\mathcal{M}) \neq 0$, Yes there is a monopole!

**SM with only complex Higgs doublet(s):** a complex Higgs doublet has 4 real components $\Rightarrow \mathcal{M} : \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v_2^2 \Rightarrow \mathcal{M} = S^3$ (boundary of a 4-dimensional isospin sphere). Homotopy: $\Pi_2(S^3) = 0 \Rightarrow$ No topologically stable monopole in the SM!

**SU(2) with real triplet Higgs:** A real triplet Higgs has 3 real components $\Rightarrow \mathcal{M} : \xi_1^2 + \xi_2^2 + \xi_0^2 = v_1^2 \Rightarrow \mathcal{M} = S^2$ (boundary of a 3-dimensional isospin sphere). Homotopy: $\Pi_2(S^2) = Z \Rightarrow \exists$ topologically stable monopole! ('t Hooft-Polyakov)

**SU(2) with complex triplet Higgs:** A complex triplet Higgs has 6 real components $\Rightarrow \mathcal{M} : \sum_{i=1}^{6} \chi_i^2 = v_M^2 \Rightarrow \mathcal{M} = S^5$ (boundary of a 6-dimensional isospin sphere). Homotopy: $\Pi_2(S^5) = 0 \Rightarrow$ No monopole.
Real triplet $\xi$ and EW monopoles

- **EW-$\nu_R$ model**: Higgs sector: Real triplet: $\xi$. complex triplet: $\tilde{\chi}$, complex doublets: $\Phi_{1,2}^{SM}$, $\Phi_{1,2}^M$.
- $\Pi_2(\mathcal{M}_1 \times \mathcal{M}_2) = \Pi_2(\mathcal{M}_1) \oplus \Pi_2(\mathcal{M}_1)$.
- Vacuum manifold of EW-$\nu_R$ model: $\mathcal{M} = S^2 \times S^5 \times \prod_{i=1}^{4} S_i$
- $\Pi_2(\mathcal{M}) = \Pi_2(S^2) = Z \Rightarrow \exists$ topologically stable monopole because of the existence of a real Higgs triplet and is intrinsically linked to it! The non-trivial nature of this vacuum is expressed as $\xi^i \rightarrow \nu_M r^i/r$ as $r \rightarrow \infty$. The property of this EW monopole is similar to that of 't Hooft-Polyakov with one exception.
- If only $\xi$ were present then $SU(2)_W \times U(1)_Y \rightarrow U(1)_W \times U(1)_Y$ ($\xi$ carries no $U(1)_Y$ quantum number). At this stage of SSB, $W_3$ would play the role of the ”photon” of the Georgi-Glashow model. The inclusion of other Higgs fields breaks $U(1)_W \times U(1)_Y$ down to $U(1)_{em}$. The ”memory” of $U(1)_W$ is expressed in the field strength: $W_{ij}^3 = \cos \theta_W Z_{ij} + \sin \theta_W F_{ij}$ where $Z_{ij}$ and $F_{ij}$ are the Z-boson and photon field strengths respectively.
- The spectrum and interactions could be obtained by doing small perturbations in the background of the monopole.
Real triplet $\xi$ and EW monopoles

Since $\tilde{\chi}, \Phi_{1,2}^{SM}$ and $\Phi_{1,2}^{M}$ are not parts of the EW monopole, their behaviour as $r \to \infty$ goes like $\tilde{\chi} \to v_M, \Phi_{1,2}^{SM} \to v_{2i}$ and $\Phi_{1,2}^{M} \to v_{2M,i}$.

Because of the fact that $W_3$ is a combination of $Z$ and $\gamma$, we shall call it a $\gamma$-$Z$ magnetic monopole.

A summary of the properties of the $\gamma$-$Z$ magnetic monopole is in order here.

- The existence in the EW-$\nu_R$ model of a real Higgs triplet $\xi$ gives rise to topologically-stable, finite-energy electroweak monopole;
- The monopole mass, $M = \frac{4\pi v_M}{g} f(\lambda/g^2) \approx 889\,\text{GeV} - 2.993\,\text{TeV}$ is intrinsically linked to the Majorana masses of the right-handed neutrinos.
- The monopole is a finite-energy soliton with a core of radius $R_c \approx (gv_M)^{-1} \approx 10^{-16}\,\text{cm}$, with virtual $W^\pm$ and $Z$ inside the core.
- This $\gamma$-$Z$ magnetic monopole has a long-range magnetic field $B_i \approx \frac{\sin^2 \theta_W}{er^2} \hat{r}_i$ at distances larger than the core radius and looking like a Dirac monopole with a strength reduced by $\sin^2 \theta_W$. 

Production and Detection of EW monopoles

• **Production**: It has been argued that monopole production in p-p collisions is suppressed by $\exp(-1/\alpha)$. It was found later that a thermal Schwinger pair production process in heavy-ion collisions is more favorable.

• **Detection**: These monopoles are highly ionizing. There is a dedicated experiment designed to search for monopoles, especially EW monopoles. MoEDAL located at the LHCb region has 3 parts: 150 $m^2$ of plastic to make a permanent record of the path; a trap to "catch" these highly-ionizing monopoles, and the last part consists of silicon pixel chips for detecting highly-ionizing background.

• arXiv: 2003.02794