Topologically stable, finite energy electroweak-scale monopoles

P. Q. Hung

UNIVERSITY OF VIRGINIA

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- ELECTROWEAK-SCALE MONOPOLE: Monopoles whose masses $\sim O(TeV) \rightarrow$ 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 $SO(3) \rightarrow U(1)_{em}$ 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 $SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$.
- Cho-Maison EW monopole: Modification of the kinetic term of the $U(1)_Y$ gauge field B_μ 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 ν_R to EW monopoles

- There is no principle that requires ν_Rs to be sterile i.e. singlets of $SU(2) \times (1)_Y$
- What if ν_Rs are non-sterile?: e.g. a member of a doublet $l_R^M = (\nu_R, e_R^M)$ 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 ν_R model).
- See-saw mechanism with non-sterile ν_R: Usual seesaw: light mass: m_D^2/M_R, Heavy Majorana ν_R: M_R.
- m_D from $g_{Sl} \bar{l}_L \phi l_R^M$; M_R from $g_M l_R^{M,T} \sigma_2 \tau_2 \tilde{\chi}\ l_R^M$. ϕ: 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 ν_Rs 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 ξ of $SU(2)$ reminds us of the construction of the 't Hooft-Polyakov monopole!

. Real triplet ξ 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 $\Rightarrow \mathcal{M} : \xi_1^2 + \xi_2^2 + \xi_0^2 = v_M^2 \Rightarrow \mathcal{M} = S^2$ (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 ξ and EW monopoles

- EW-ν_R model: Higgs sector: Real triplet: ξ. complex triplet: $\tilde{\chi}$, complex doublets: $\Phi^{SM}_{1,2}$, $\Phi^{M}_{1,2}$.
- $\Pi_2(\mathcal{M}_1 \times \mathcal{M}_2) = \Pi_2(\mathcal{M}_1) \oplus \Pi_2(\mathcal{M}_1)$.
- Vacuum manifold of EW-ν_R model: $\mathcal{M} = S^2 \times S^5 \times \prod_{i=1}^{4} S_i^3$
- $\Pi_2(\mathcal{M}) = \Pi_2(S^2) = Z \Rightarrow \exists$ 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 $\xi^i \to v_M r^i/r$ as $r \to \infty$. The property of this EW monopole is similar to that of 't Hooft-Polyakov with one exception.
- If only ξ were present then $SU(2)_W \times U(1)_Y \to U(1)_W \times U(1)_Y$ (ξ 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: $W^3_{ij} = \cos\theta_W Z_{ij} + \sin\theta_W F_{ij}$ 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 ξ and EW monopoles

- Since $\tilde{\chi}$, $\Phi^{SM}_{1,2}$ and $\Phi^{M}_{1,2}$ are not parts of the EW monopole, their behaviour as $r \to \infty$ goes like $\tilde{\chi} \to v_M$, $\Phi^{SM}_{1,2} \to v_{2i}$ and $\Phi^{M}_{1,2} \to v_{2M,i}$
- Because of the fact that W_3 is a combination of Z and γ, we shall call it a γ-Z magnetic monopole.
- A summary of the properties of the γ-Z magnetic monopole is in order here.
  - The existence in the EW-ν_R model of a real Higgs triplet ξ gives rise to topologically-stable, finite-energy electroweak monopole;
  - The monopole mass, $M = \frac{4\pi v_M}{g} f(\lambda/g^2) \sim 889\,GeV - 2.993\,TeV$ is intrinsically linked to the Majorana masses of the right-handed neutrinos.
  - The monopole is a finite-energy soliton with a core of radius $R_c \sim (g v_M)^{-1} \sim 10^{-16} cm$, with virtual $W^{\pm}$ and Z inside the core.
  - This γ-Z magnetic monopole has a long-range magnetic field $B_i \approx \frac{\sin^2\theta_W}{e r^2} \hat{r}_i$ 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