Cosmic Electroweak Monopole

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Motivation

Q: Which monopole exists in nature, and how can we detect it?

- **The electroweak monopole!**

  1. The standard model predicts it, so that it must exist if the standard model is correct.

  2. It is the electroweak generalization of the Dirac monopole. So it is this monopole, not the Dirac monopole, which exists in nature.

  3. It is different from the Dirac monopole. The magnetic charge is twice bigger.

- **How can we detect it?**

1. The mass is expected to be 4 to 10 TeV, and the 13 TeV LHC at CERN might have reached the production threshold.

2. If LHC can produce the monopole pair, the MoEDAL (Monopole and Exotics Detector at LHC) has a best chance to detect it.

3. But if the mass is bigger than 6.5 TeV, we should look for the remnant monopoles in the universe, and IceCube and similar experiments could play important role.

Two track strategy

- Physical Implications

1. The detection of the electroweak monopole, not the Higgs particle, becomes the final and topological test of the standard model.

2. If detected, it will become the first stable topological elementary particle, the true God's particle, in human history.

3. It could play important roles in cosmology, in particular the formation of the large scale structures, intergalactic magnetic field, and the baryogenesis.

- Issues to be resolved

1. To detect the monopole, we have to understand the monopole production mechanism, in particular the cosmic production of the electroweak monopole during the electroweak phase transition.

2. To find the density of the monopoles in the present universe we must study the cosmic evolution of the monopole.

3. We estimate that there could be as much as 10^7 (and as low as 10^2) monopoles in every volume of earth in the present universe, not much to be the dark matter but enough to be detected.

- **Contents**

A. History

- Ever since Dirac predicted the Dirac monopole in 1931, the monopole has become an obsession, theoretically and experimentally.
- After Dirac we have had Wu-Yang (1969), 'tHooft-Polyakov (1974), and grand unification (Dokos-Tomaras; 1980) monopoles. But it has been asserted that the standard model has no monopole.
- In 1997, however, the existence of the electroweak ("Cho-Maison") monopole was established.

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Monopole configuration in Weinberg-Salam model

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Abstract

We present a new type of spherically symmetric monopole and dyon solutions with the magnetic charge $4\pi/e$ in the standard Weinberg-Salam model. The monopole (and dyon) could be interpreted as a non-trivial hybrid between the abelian Dirac monopole and non-abelian 't Hooft-Polyakov monopole (with an electric charge). We discuss the possible physical ...tions of the electroweak dyon.

B. Explicit solution: A Review

- Start from the Weinberg-Salam Lagrangian

$$\mathcal{L} = -|\mathcal{D}_\mu \phi|^2 - \frac{\lambda}{2}\big(\phi^\dagger \phi - \frac{\mu^2}{\lambda}\big)^2 - \frac{1}{4}\vec{F}_{\mu\nu}^2 - \frac{1}{4}G_{\mu\nu}^2,$$

$$\mathcal{D}_\mu \phi = \big(\partial_\mu - i\frac{g}{2}\vec{\tau}\cdot\vec{A}_\mu - i\frac{g'}{2}B_\mu\big)\phi = \big(D_\mu - i\frac{g'}{2}B_\mu\big)\phi,$$

and choose the spherically symmetric ansatz

$$\phi = \frac{1}{\sqrt{2}}\rho(r)\ \xi, \quad \xi = i\begin{pmatrix} \sin(\theta/2)\ e^{-i\varphi} \\ -\cos(\theta/2) \end{pmatrix},$$

$$\vec{A}_\mu = \frac{1}{g}A(r)\partial_\mu t\ \hat{r} + \frac{1}{g}(f(r)-1)\ \hat{r}\times\partial_\mu\hat{r}, \quad (\hat{r} = -\xi^\dagger\vec{\tau}\ \xi)$$

$$B_\mu = \frac{1}{g'}B(r)\partial_\mu t - \frac{1}{g'}(1-\cos\theta)\partial_\mu\varphi.$$

- Notice that

1. ϕ and B_μ have the string singularity along the negative z-axis, and $\vec{A}_\mu$ has the Wu-Yang singularity $-\frac{1}{g}\hat{r} \times \partial_\mu \hat{r}$ at the origin. But the string singularity can be removed making $U(1)_Y$ non-trivial.

2. $\vec{A}_\mu$ and B_μ contain the electric potentials A and B. So the ansatz describes the electroweak dyon which carries the electric (as well as the magnetic) charge.

- With

$$\begin{pmatrix} A_\mu^{(\mathrm{em})} \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_{\mathrm{w}} & \sin\theta_{\mathrm{w}} \\ -\sin\theta_{\mathrm{w}} & \cos\theta_{\mathrm{w}} \end{pmatrix} \begin{pmatrix} B_\mu \\ A_\mu^3 \end{pmatrix},$$

we have

$$\begin{aligned} \mathcal{L} = &-\frac{1}{2}(\partial_\mu\rho)^2 - \frac{\lambda}{8}\big(\rho^2-\rho_0^2\big)^2 - \frac{1}{4}F_{\mu\nu}^{(\mathrm{em})\,2} - \frac{1}{4}Z_{\mu\nu}^2 \\ &-\frac{1}{2}|(D_\mu^{(\mathrm{em})}W_\nu - D_\nu^{(\mathrm{em})}W_\mu) + ie\frac{g}{g'}(Z_\mu W_\nu - Z_\nu W_\mu)|^2 \\ &+ieF_{\mu\nu}^{(\mathrm{em})}W_\mu^* W_\nu + ie\frac{g}{g'}Z_{\mu\nu}W_\mu^* W_\nu - \frac{g^2}{4}\rho^2|W_\mu|^2 - \frac{g^2+g'^2}{8}\rho^2 Z_\mu^2 \\ &+\frac{g^2}{4}(W_\mu^* W_\nu - W_\nu^* W_\mu)^2, \quad D_\mu^{(\mathrm{em})} = \partial_\mu + ieA_\mu^{(\mathrm{em})}. \end{aligned}$$

- In the physical fields the ansatz becomes

$$A_\mu^{(\rm em)} = \frac{e}{gg'}\big(\frac{g'}{g}A(r) + \frac{g}{g'}B(r)\big)\partial_\mu t - \frac{1}{e}(1-\cos\theta)\partial_\mu\varphi,$$

$$W_\mu = \frac{i}{g}\frac{f(r)}{\sqrt{2}}e^{i\varphi}(\partial_\mu\theta + i\sin\theta\partial_\mu\varphi),$$

$$Z_\mu = \frac{e}{gg'}\big(A(r) - B(r)\big)\partial_\mu t, \quad e = \frac{gg'}{\sqrt{g^2+g'^2}}.$$

- With this we have the equations of motion

$$\ddot{\rho} + \frac{2}{r}\dot{\rho} - \frac{f^2}{2r^2}\rho = -\frac{1}{4}(A-B)^2\rho + \frac{\lambda}{2}\big(\rho^2 - \frac{2\mu^2}{\lambda}\big)\rho,$$
$$\ddot{f} - \frac{f^2-1}{r^2}f = \big(\frac{g^2}{4}\rho^2 - A^2\big)f,$$
$$\ddot{A} + \frac{2}{r}\dot{A} - \frac{2f^2}{r^2}A = \frac{g^2}{4}\rho^2(A-B),$$
$$\ddot{B} + \frac{2}{r}\dot{B} = -\frac{g'^2}{4}\rho^2(A-B).$$

This has the point monopole solution which has $q_m = 4\pi/e$

$$\rho = \rho_0 = \sqrt{2\mu^2/\lambda}, \quad f = 0, \quad A = B = 0,$$
$$A_\mu^{(\mathrm{em})} = -\frac{1}{e}(1-\cos\theta)\partial_\mu\varphi.$$

- With the boundary condition

$$\rho(0) = 0, \quad f(0) = 1, \quad A(0) = 0, \quad B(0) = b_0,$$
$$\rho(\infty) = \rho_0, \; f(\infty) = 0, \; A(\infty) = B(\infty) = A_0,$$

we have the dyon solution which has the asymptotic behavior,

$$\rho \simeq \rho_0 + \frac{\rho_1}{r} \exp(-M_H \; r),$$
$$f \simeq f_1 \exp(-\sqrt{1 - (A_0/M_W)^2} \; M_W \; r),$$
$$A \simeq A_0 + \frac{A_1}{r}, \quad B \simeq A + \frac{B_1}{r} \exp(-M_Z \; r),$$
$$M_H = \sqrt{\lambda}\rho_0, \quad M_W = g\rho_0/2, \quad M_Z = \sqrt{g^2 + g'^2}\rho_0/2.$$

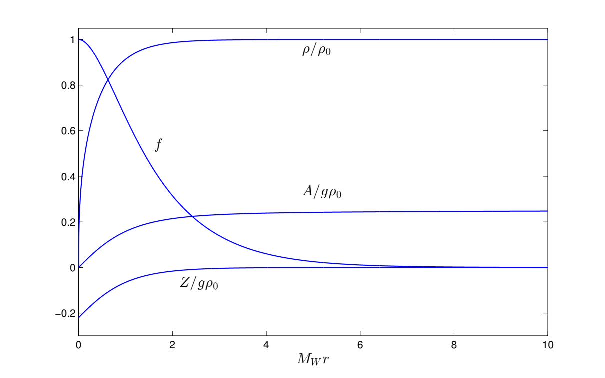

Figure : The electroweak dyon solution. Here $Z = A - B$ and we have chosen $\sin^2\theta_{\rm w} = 0.2312$, $M_H/M_W = 1.56$, and $A(\infty) = M_W/2$.

- Notice that

1. The solution has the singular monopole $-\frac{1}{e}(1-\cos\theta)\partial_\mu\varphi$ at the center, but has the non-trivial dressing of Higgs, W, and Z bosons. So it is the hybrid between Dirac and 'tHooft-Polyakov.

2. M_H, M_W, and M_Z determine the exponential damping of the weak bosons, but A has no exponential damping. So it describes the dyon with charge $q_m = 4\pi/e, \;\; q_e = 4\pi A_1/e$.

3. The dyon can be generalized to have $\pm q_e$. Moreover, we can have the anti-dyon.

C. Mass of Electroweak monopole

- The point singularity of the electroweak monopole makes the energy infinite. But, unlike the Dirac monopole, we can estimate the mass.

- There are different ways to estimate the mass, the dimensional argument, the scaling argument, and the quantum correction. All of them predict the monopole mass about 4 to 10 TeV.

- A best way to estimate the mass is to regularize the monopole with a non-trivial permittivity for the hypercharge U(1) which can mimic the quantum correction.

- Consider the effective Lagrangian of the standard model which has the electric permittivity of the $U(1)_Y$ gauge field

$$\mathcal{L}_{eff} = -|\mathcal{D}_\mu\phi|^2 - \frac{\lambda}{2}\Big(\phi^2 - \frac{\mu^2}{\lambda}\Big)^2 - \frac{1}{4}\vec{F}_{\mu\nu}^2 - \frac{1}{4}\epsilon(\phi)G_{\mu\nu}^2.$$

Notice that

1. $\mathcal{L}_{eff}$ retains the $SU(2 \times U(1)_Y$ gauge symmetry, and recover the standard model with $\epsilon \to 1$ asymptotically.

2. Moreover, with the rescaling of B_μ to B_μ/g', the $U(1)_Y$ gauge coupling g' changes to the running coupling $\bar{g}' = g'/\sqrt{\epsilon}$.

- So, choosing a proper $\epsilon(\phi)$ which can mimic the physical (real) running coupling $\bar{g}'$ of the standard model, we can implement the quantum correction.

- Moreover, we can regularize the monopole making $\epsilon(\phi)$ vanishing at the origin. Indeed, with $\epsilon = (\frac{\rho}{\rho_0})^8$, we have the regularized monopole with energy (with $A = B = 0$)

$$E \simeq 0.6526 \times \frac{4\pi}{e^2} M_W \simeq 7.19 \text{ TeV},$$

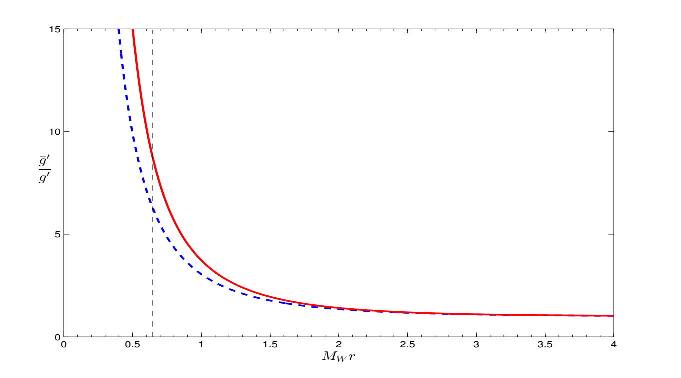

Figure : The effective coupling $\bar{g}'$ induced by $\epsilon(\phi)$ which accommodates the quantum correction. The blue curve represents $\epsilon = (\rho/\rho_0)^8$ and the red curve represents ϵ of Ellis et al. The vertical line indicates the Higgs mass.

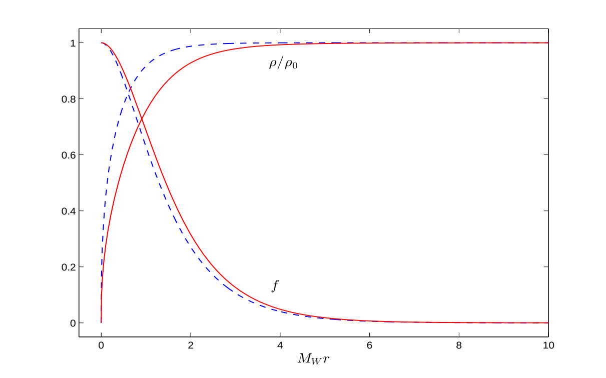

Figure : The finite energy electroweak monopole. The solid line (red) represents the regularized monopole and the dotted (blue) line represents the singular monopole.

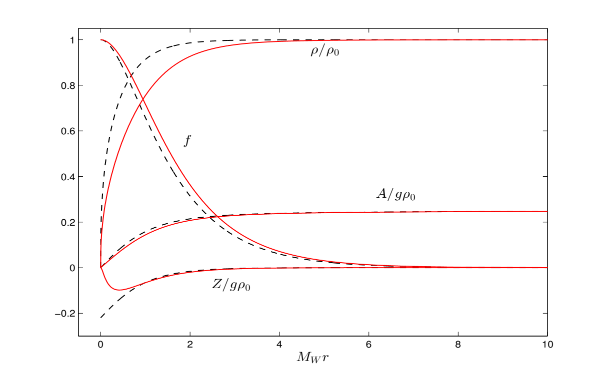

Figure : The finite energy electroweak dyon. The solid line (red) represents the regularized dyon and the dotted (blue) line represents the singular dyon.

- Adopting this approach but making $\epsilon(\phi)$ and $\bar{g}'$ more realistic, Ellis, Mavromatos, and You have recently been able to put an upper limit on the monopole mass.

- Requiring $\epsilon(\phi)$ to satisfy the experimental constraint on $H \rightarrow \gamma + \gamma$, they have shown that the monopole mass should be less than 5.5 TeV.

- This strongly implies that the present LHC could be able to produce the monopole pair, and the MoEDAL might actually detect it.

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The price of an electroweak monopole

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ABSTRACT

In a recent paper, Cho, Kim and Yoon (CKY) have proposed a version of the $SU(2) \times U(1)$ Standard Model with finite-energy monopole and dyon solutions. The CKY model postulates that the effective U(1) gauge coupling $\to \infty$ very rapidly as the Englert–Brout–Higgs vacuum expectation value $\to 0$, but in a way that is incompatible with LHC measurements of the Higgs boson $H \to \gamma\gamma$ decay rate. We construct generalisations of the CKY model that are compatible with the $H \to \gamma\gamma$ constraint, and calculate the corresponding values of the monopole and dyon masses. We find that the monopole mass could be < 5.5 TeV, so that it could be pair-produced at the LHC and accessible to the MoEDAL experiment.

Gravitating Electroweak Monopole

- Adopt the monopole ansatz and introduce the static spherically symmetric metric

$$ds^2 = -N^2(r)A(r)dt^2 + \frac{dr^2}{A(r)} + r^2(d^2\theta + \sin^2\theta d\varphi^2),$$

and find that the Einstein-Weinberg-Salam action is reduced to

$$S = \int \Big[\frac{1}{4\pi}\dot{m} - AK - U\Big] N dr,$$

$$A(r) = 1 - \frac{2Gm(r)}{r}, \qquad K = \frac{\dot{f}^2}{g^2} + \frac{r^2}{2}\dot{\rho}^2,$$

$$U = \frac{(1-f^2)^2}{2g^2r^2} + \frac{\lambda}{8}r^2(\rho^2 - \rho_0^2)^2 + \frac{\epsilon(\rho)}{2g'^2r^2} + \frac{1}{4}f^2\rho^2.$$

- From this we have

$$\frac{\dot{N}}{N} = 8\pi G \frac{K}{r}, \qquad \dot{m} = 4\pi(AK + U),$$

$$A\ddot{f} + \Big(\dot{A} + A\frac{\dot{N}}{N}\Big)\dot{f} + \frac{1-f^2}{r^2}f - \frac{1}{4}g^2\rho^2 f = 0,$$

$$A\ddot{\rho} + \Big(\frac{2A}{r} + \dot{A} + A\frac{\dot{N}}{N}\Big)\dot{\rho} - \frac{f}{2r^2}\rho - \frac{\lambda}{2}(\rho^2 - \rho_0^2)\rho$$
$$-\frac{1}{2g'^2 r^4}\frac{d\epsilon(\rho)}{d\rho} = 0.$$

- With the boundary conditions

$$f(0) = 1, \quad \rho(0) = 0, \quad m(0) = 0,$$
$$f(\infty) = 0, \quad \rho(\infty) = \rho_0, \quad N(\infty) = 1,$$

we have the completely regular gravitating monopole with mass $\mathcal{M}$

$$\mathcal{M} = 4\pi \int_0^\infty (K + U) e^{-P(r)} dr, \quad P(r) = 8\pi G \int_r^\infty \frac{K}{r'} dr'.$$

- Notice that the solution turns to a magnetic black hole when $\sqrt{G}\rho_0 \simeq 0.39$, which could represent the premodial black holes.

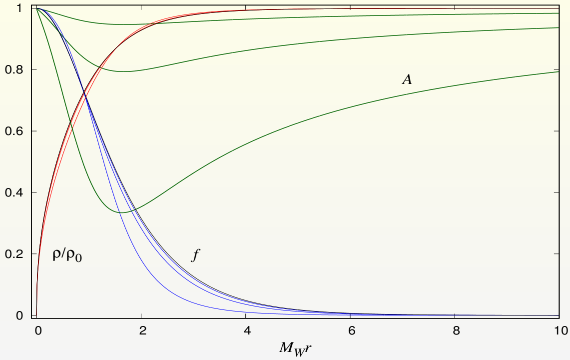

Figure : The W-boson f (blue), Higgs field ρ (red), and the metric function $A(r) = 1 - 2Gm/r$ (green) profiles of the gravitating monopole, obtained with $\rho_0/M_P =$ 0.1, 0.2, and 0.38. The black curve represents the finite energy monopole in flat space-time.

$\sqrt{G}\rho_0$	$\mathcal{M}$
0 (non-gravitating)	7.19 TeV
0.10	7.15 TeV
0.20	6.97 TeV
0.38	6.34 TeV
$(\sqrt{G}\rho_0)_{\text{max}} \simeq 0.39$	black hole

Table : The numerical estimate of ADM mass of gravitating monopole with $\epsilon = (\rho/\rho_0)^8$.

A. monopole production and Phase Transition

- The electroweak phase transition is controlled by the effective potential of the standard model

$$V_T(\rho) \simeq \frac{\lambda}{8}(\rho^2 - \rho_0^2)^2 - \frac{C_1}{12\pi}\rho^3\ T + \frac{C_2}{2}\rho^2\ T^2 - \frac{\pi^2}{90}NT^4,$$

$$C_1 = \frac{6M_W^3 + 3M_Z^3}{\rho_0^3} \simeq 0.36,$$

$$C_2 = \frac{4M_W^2 + 2M_Z^2 + M_H^2 + 4m_t^2}{8\rho_0^2} \simeq 0.36,$$

which is charactrized by three temperatures, T_2, T_c, and T_1.

1. Above $T_1 \simeq 146.7$ GeV the effective potential has only one vacuum $\rho_0 = 0$, and the theory is in the symmetric state. At T_1 the potential develops a second local minimum (unstable vacuum) ρ_+, but $\rho_0 = 0$ remains the true vacuum till the temperature cools down to $T_c \simeq 146.6$ GeV.

2. At T_c we have $\rho_+ \simeq 21.8$ GeV, and the two vacua become degenerate. But ρ_+ becomes the true vacuum below T_c, while $\rho_0 = 0$ remains an unstable vacuum till the temperature cools down to $T_1 \simeq 146.4$ GeV.

3. Below T_1 the new vacuum ρ_+ becomes the only vacuum, which approaches to the Higgs vacuum at zero temperature.

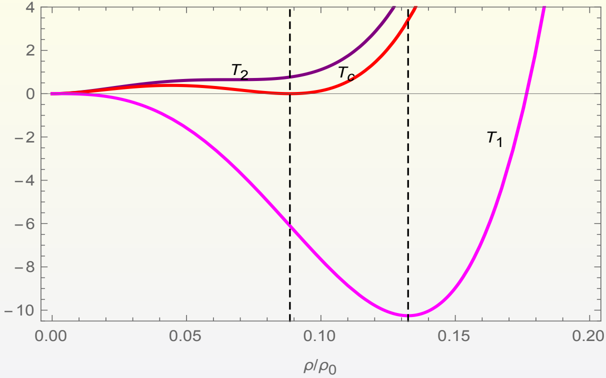

Figure : The temperature-dependent effective potential of the standard model for $T_2 = 146.7$ GeV, $T_c = 146.6$ GeV, and $T_1 = 146.4$ GeV.

- Notice that

1. The potential has a barrier between T_c and T_1, and during this period the vacuum tunneling takes place from ρ_0 to ρ_+ by the vacuum bubbles. So the phase transition is the first order.

2. On the other hand, the barrier is very small and lasts very short time. So the phase transition is very mildly the first order, almost the second order.

3. For the monopole production, the important thing is when the monopole formation takes place, and what is the production mechanism.

- The monopole production requires the change of topology, and the initial monopole density is fixed by the correlation length $\xi \simeq 1/\bar{M}_H$ determined by the Higgs mass,

$$\bar{M}_H^2 = \begin{cases} \big[(T/T_1)^2 - 1\big] M_H^2/2, & T \geq T_c, \\ \big[(\rho_+/\rho_0)^2 + 1 - (T/T_1)^2\big] M_H^2/2, & T < T_c. \end{cases}$$

  which acquires the minimum value 5.53 GeV at $T = T_c$ and becomes 11.7 GeV at $T = T_1$.

- Similarly the W-boson starts to become massive toward the value $g\rho_+(T_c)/2 \simeq$ 7.0 GeV at T_c, and acquires the mass 10.5 GeV at $T = T_1$.

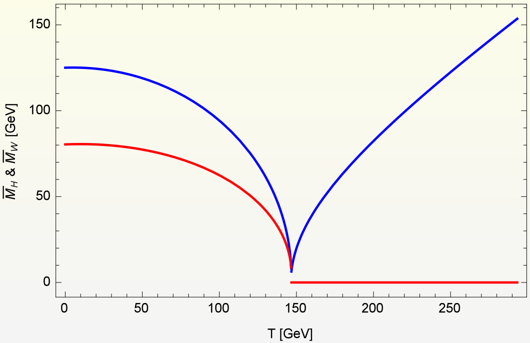

Figure : The temperature-dependent Higgs and W-boson masses. The blue and red curves represent the Higgs and W-boson masses.

- In the second order phase transition, the monopole formation takes place at T_c, but the correlation length becomes infinite. So Kibble proposed to use the horizon distance at T_c, and set the Kibble bound for the initial monopole density. This has been improved by Zurek who incorporated the relaxation time.

- In the first order phase transition, however, the monopoles are formed inside the vacuum bubbles during the phase transition. And they come to exist through the vacuum bubble collisions.

- But none of the above mechanism works for the electroweak monopole production, because the phase transition is very mildly the first order.

- Here the monopoles are produced by thermal fluctuation of the Higgs vacuum after the phase transition, not by the vacuum bubble collisions during the phase transition.

- The change of topology is induced by the zero points of $\langle \rho \rangle$, which become the seeds of the monopoles. They appear by thermal fluctuations below T_1. But this thermal fluctuation becomes insignificant below the Ginzburg temperature $T_G \simeq 57.6$ GeV.

B. Initial Monopole Density

- So the monopoles are produced between T_1 and T_G, around $T_i \simeq (T_1 + T_G)/2 \simeq 102.0$ GeV, when the correlation length becomes $\xi_i \simeq (\xi_1 + \xi_G)/2 \simeq 9.3 \times 10^{-16}$ cm.

- From this we have the initial monopole density n_i,

$$\left(\frac{n_m}{T^3}\right)_i \simeq \frac{g_P}{\xi_i^3 T_i^3} \simeq 9.1 \times 10^{-4},$$

where $g_P \simeq 0.1$ is the probability that one monopole is produced in one correlation volume.

- From this we have the energy density of the monopoles

$$\varrho_{mo}(T_i) = M_m (n_m)_i \simeq 9.0 \times 10^{-3}\ T_i^4\ \Big(\frac{M_m}{1\ \text{TeV}}\Big),$$
$$\frac{\varrho_{mo}(T_i)}{\varrho(T_i)} \simeq 2.5 \times 10^{-4} \Big(\frac{M_m}{1\ \text{TeV}}\Big).$$

So the universe need to consume only a tiny fraction (about $0.025\ \%$) of the total energy to produce the monopoles.

- This assures that, unlike the grand unification monopole, the electroweak monopole does not alter the standard cosmology.

Remnant Monopole Density

A. Evolution of monopole

- The cosmic evolution of the initial monopoles are described by the Boltzmann equation

$$\frac{dn_m}{dt} + 3Hn_m = -\sigma n_m^2,$$

  where H and σ are the Hubble expansion parameter and the monopole annihilation cross section.

- The annihilation cross section is affected by two factors, the mean free length l_{free} of the Brownian motion of the monopole and the capture radius r_{capt} of the monopole-antimonopole attraction.

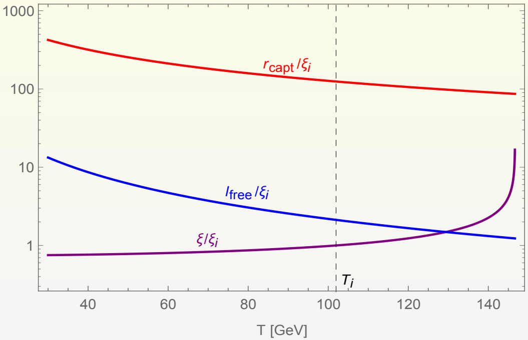

Figure : The relevant scales, ξ in purple, l_{free} in blue, and r_{capt} in red, against T. They are normalized by the correlation length ξ_i at T_i. Here we set $M_m = 5$ TeV.

- Solving the Boltzmann equation we have

$$\frac{n_m}{T^3} = \frac{1}{A(M_m/T - M_m/T_i) + B},$$
$$A \simeq \frac{0.02}{\alpha} \times \frac{m_p}{M_m}, \quad B = \Big(\frac{n_m}{T^3}\Big)_i^{-1}.$$

  The solution remains valid till the annihilation stops at T_f.

- When $T_f \ll T_i$, the final monopole density becomes independent of the initial value, and approaches to

$$\frac{n_m}{T^3} \simeq \frac{\alpha}{0.02} \times \frac{T}{m_p}, \quad (T \ll T_i).$$

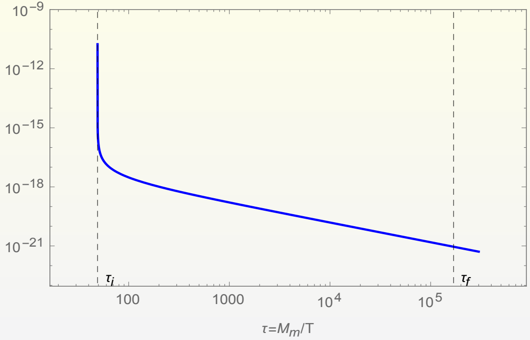

Figure : The evolution of the monopole density n_m/T^3 against $\tau = M_m/T$. The final value of the monopole density is independent of the initial value.

- Notice that most of the initial monopoles are quickly annihilated since r_{capt} becomes much bigger (by the factor 10^2) than l_{free}. This is because the monopole-antimonopole interaction is magnetic.

- The annihilation lasts very long, and stops around $T_f \simeq 29.5$ MeV when l_{free} becomes bigger than r_{capt}. The terminal density at T_f becomes

$$\left(\frac{n_m}{T^3}\right)_f \simeq 1.8 \times 10^{-22} \left(\frac{M_m}{1 \text{ TeV}}\right).$$

- The number of monopole within the comoving volume is conserved thereafter. But they still interact with the electron pairs before decouple around $T_d \simeq 0.5$ MeV, when the interaction rate becomes less than the expansion rate.

B. Relic monopole density

- Assuming that the expansion is adiabatic we have the current density parameter of monopole

$$\Omega_{mo}\ h^2 = \frac{\rho_{mo,0}\ h^2}{\rho_{\mathsf{c},0}} \simeq 1.2 \times 10^{-12} \left(\frac{M_m}{1\ \mathsf{TeV}}\right)^2,$$

where $\rho_{\mathsf{c},0}$ is the critical density of present universe and $h \simeq 0.678$ is the scaled Hubble parameter.

- In terms of the number density, we have about $6.1 \times 10^{-20}/\ \text{cm}^3$, or about 2.3×10^{-13} of the baryon number density. This amounts to roughly 6.6×10^7 monopoles per every volume of the earth in the universe.

- This tells that the electroweak monopole can not be the dark matter, but assures that there are enough monopoles left over in the universe that we could detect.

- When decoupled, the monopoles were non-relativistic. But the inter-galactic magnetic field makes them highly relativistic in the present universe.

C. Parker Bound

- It is well known that the universe has inter-galactic magnetic field $B \simeq 1.2 \times 10^{-9}\ T$, and the monopole traveling through the magnetic field drains the energy from the magnetic field.

- Requiring that the monopoles do not drain too much energy to sustain the magnetic field, we have the upper bound of the monopole flux in the universe, $F \leq 10^{-15}/$ cm^2 sec sr, or

$$\Omega_{mo} h^2 \lesssim 4.3 \times 10^{-17} \left(\frac{M_m}{1\ \mathrm{TeV}} \right).$$

  But our estimate of Ω_{mo} is too big (by the factor 10^5) to satisfy this bound.

- Notice, however, that not all the monopoles are free streaming.

  1. As the heaviest stable particles in the universe, many of them may have become the seed of the premodial black holes and/or large scale structures, and may have been buried in the galactic centers.

  2. The relativistic monopoles can penetrate less than 10 m in the Aluminum before trapped. So most of them may have been filtered out by the stellar objects.

  3. In fact, these buried and trapped monopoles could have been the source of the inter-galactic magnetic field.

Discussions

A. Experimental

- In spite of the huge efforts, the search for the monopolehas not been successful. Most were the blind searches in the dark room with few theoretical leads, and many were looking for the "wrong" monopoles at "wrong" places.

- Focusing on the electroweak monopole which has unique features, we could greatly enhance the probability to find the monopole.

1. A major concern at LHC has been whether it has enough energy to produce the monopole pair. But this may not be as serious problem as we thought, because the baby monopole is expected to be lighter. If so, MoEDAL has a best chance to detect it.

2. IceCube, ANTARES, Auger, and similar experiments which look for the remnant monopoles could enhance the detection efficiency focusing on the electroweak monopole. But they should look for the non-relativistic monopoles, because the monopoles loose most of the energy passing through the earth atmosphere.

B. Theoretical

- Can the monopoles indeed be the seed of the large scale structures and the source of the inter-galactic magnetic field?
- What are the new physical processes induced by the monopole? Electroweak baryogenesis?
- How can we justify the perturbative expansion in the presence of the monopole? Can we construct the quantum field theory of monopole, Quantum Electro-Magneto-Dynamics (QEMD) which generalizes QED?

C. Challenges

- As the electroweak generalization of Dirac, the electroweak monopole must exist **within** the standard model, not beyond. So we must find it.

- If detected, it will become the first stable topological elementary particle, the true God's particle, in nature. It will open the After the Monople (AM) era in physics.

New Physics!

D. Smoking Gun???

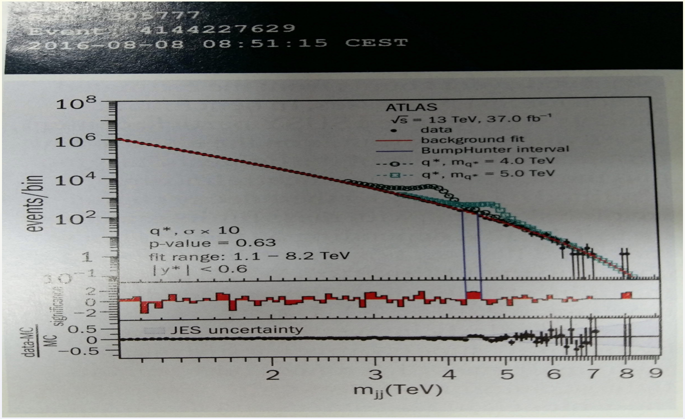

Figure : The ATLAS dijet event at 8.2 TeV.

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