Title: Electroweak Monopole - Yongmin Cho

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Abstract: <p>We propose the discovery of the electroweak monopole as the final test of the standard model. Unlike the Dirac's monopole in electrodynamics which is optional, the electroweak monopole must exist within the framework of the standard model because the $U(1)_{em}$ becomes non-trivial. We estimate the mass of the monopole to be around 4 to 7 TeV, and expect the production rate to be relatively large, $(1/\alpha_{em})^2$ times bigger than the WW production rate. This implies that the MoEDAL detector at LHC could have a real chance to detect it. </p>

Electroweak Monopole and MoEDAL

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Motivation and Plan

Q: What is the next hot subject after Higgs?

- **The electroweak ("Cho-Maison") monopole!**

  1. It is predicted by the Weinberg-Salam model. So the detection of the monopole becomes the final test of the standard model.

  2. It is the electroweak generalization of the Dirac monopole, a hybrid of Dirac and 'tHooft-Polyakov.

  3. It is the only realistic monopole we can have in nature which has huge potential applications.

- **Can we detect it?**

1. The LHC at CERN has now reached the threshold to produce the monopole, and the MoEDAL (Monopole and Exotics Detector at LHC) is actively searching for this.

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

3. But a crucial information is lacking. We need to know the mass.

Theoretical and Experimental Challenges

Cho-Maison Monopole

A) History

- Ever since Dirac predicted his monopole in 1931, the monopole has become an obsession, theoretically and experimentally.
- After Dirac we have had monopoles of Wu-Yang (1969), 'tHooft-Polyakov (1974), and Dokos-Tomaras (1980). But none (except Dirac) was realistic.
- In the realistic Weinberg-Salam model it has been asserted that the monopole does not exist.

- In 1997 the existence of the monopole topology in the standard model was proved and the electroweak monopole has been constructed numerically.

- In 1998 the mathematical existence proof was made by Yang, and the monopole was named the "Cho-Maison" monopole.

- The "discovery" of Higgs particle has made it hot again. Moreover, the LHC at CERN has finally reached the energy to produce it, and the MoEDAL ("the Magnificient Seventh") is actively searching for the monopole.

B) Cho-Maison Dyon: A Review

- Consider the Weinberg-Salam Lagrangian

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

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

- 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 $\vec{A}_\mu$ has the Wu-Yang singularity $-\frac{1}{g}\hat{r} \times \partial_\mu \hat{r}$ at the origin, but ξ and B_μ have the string singularity along the negative z-axis.

- However, the string singularity can be removed making $U(1)_Y$ non-trivial. So $U(1)_Y$ plays the crucial role to make the ansatz spherically symmetric.

- The ansatz contains the electric potentials A and B. So it can describe 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

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

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

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

Notice that A_μ^{em} contains the singular Abelian monopole.

- From this the equations of motion reduce to

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

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

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

- 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 Cho-Maison dyon which has the asymptotic behavior,

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

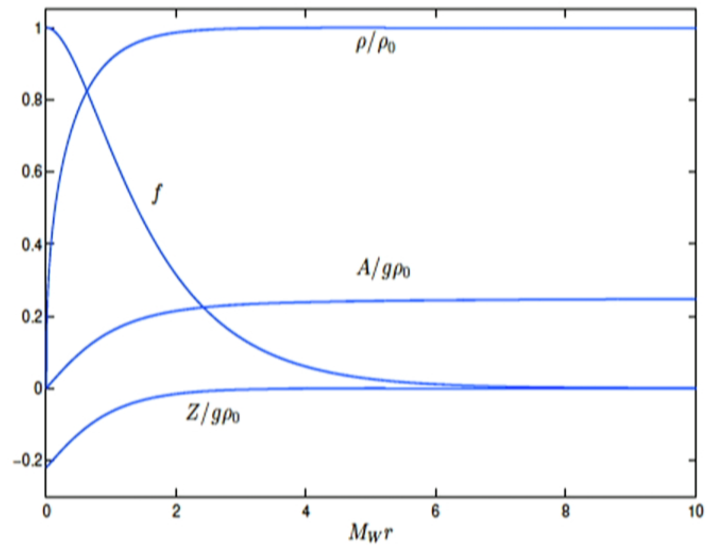

Figure : The Cho-Maison dyon solution. Here $Z = A - B$ and we have chosen $\sin^2\theta_\mathrm{w} = 0.2312$, $M_H/M_W = 1.56$, and $A(\infty) = M_W/2$.

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

- Clearly M_H, M_W, and M_Z determine the exponential damping of the Higgs, W, and Z bosons. And A_0 slows down the damping of the W boson further.

- But A has no exponential damping, and generates the electric charge. So the dyon has the electromagnetic charges

$$q_e = \frac{4\pi}{e} A_1, \qquad q_m = \frac{4\pi}{e}.$$

- Moreover, the dyons always come in pair with opposite electric charges $\pm q_e$, since the equation is invariant under the reflection $A \to -A,\ B \to -B$.

Q: But why $U(1)_Y$ has to be non-trivial?

- Notice that $U(1)_{(\mathrm{em})}$ is given by the linear combination of the U(1) subgroup of SU(2) and the hypercharge U(1). In this case the mathematical consistency requires the two U(1), and two potentials A_μ^3 and B_μ, to have the same topology. (One can not add two U(1) which have different topology!)

- But the U(1) subgroup of SU(2) is intrinsically non-trivial. So $U(1)_Y$, and consequently $U(1)_{(\mathrm{em})}$, must be non-trivial.

- But A has no exponential damping, and generates the electric charge. So the dyon has the electromagnetic charges

$$q_e = \frac{4\pi}{e} A_1, \qquad q_m = \frac{4\pi}{e}.$$

- Moreover, the dyons always come in pair with opposite electric charges $\pm q_e$, since the equation is invariant under the reflection $A \to -A, \ B \to -B$.

- Moreover, in the grand unification $U(1)_Y$ must be non-trivial because it should become an Abelian subgroup of a compact group.

- So, unlike the Dirac monopole which is optional in electrodynamics, the Cho-Maison monopole in the standard model must exist. And MoEDAL is to confirm this.

- But ultimately this question should be answered by experiment. This means that the discovery of the electroweak monopole, not Higgs, must be the final test of the standard model.

Topological Test of Standard Model

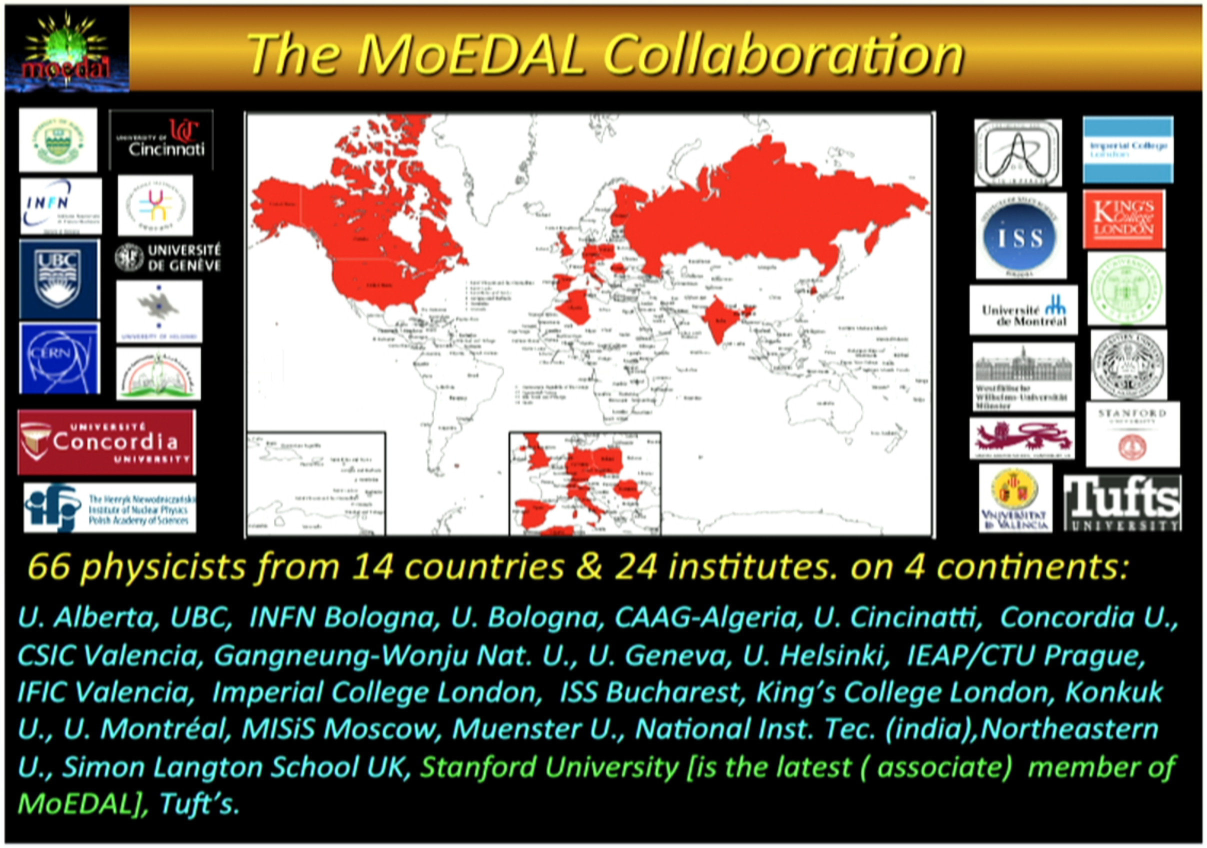

Figure : The MoEDAL Collaboration

Comparison with Other Monopoles

- There are other monopoles, but they are either unphysical or irrelevant.
- The Dirac monopole in electrodynamics has to be generalized to the electroweak monopole. Moreover, after the electroweak generalization it becomes the Cho-Maison monopole.
- The Wu-Yang monopole in QCD makes the monopole condensation to generate the confinement, so that it can not be observed.

- The 'tHooft-Polyakov monopole is based on the Georgi-Glashow model, a wrong theory.
- The grand unification monopole is too heavy that it could have been produced only in the early universe. Moreover, the inflation makes it completely irrelevant at the present universe.
- This makes the Cho-Maison monopole the only realistic monopole which we can actually produce and observe.

- But all monopoles are closely related. Basically they are either of the Dirac type or Wu-Yang type, naked or dressed. And the Wu-Yang monopole becomes Dirac type in the singular gauge.

- Notice, however, the electroweak monopole has the magnetic charge twice bigger than the Dirac monopole, and satisfies the Schwinger quantization rule

$$g_m = \frac{4\pi n}{e}.$$

This is because in the electroweak unification the $U(1)_{\rm (em)}$ comes from the $U(1)$ subgroup of $SU(2)$, which has the period of 4π.

Mass of Cho-Maison Monopole

- The strong magnetic interaction ($1/\alpha$ stronger than the electron) of the monopole should make it easy to be detected. But we need to know the mass to find it.

- However, the Cho-Maison dyon has the infinite energy

$$E = E_0 + E_1,$$

$$E_0 = \frac{4\pi}{g^2}\int_0^\infty \frac{dr}{2r^2}\Big\{\frac{g^2}{g'^2} + (f^2-1)^2\Big\},$$

$$E_1 = \frac{4\pi}{g^2}\int_0^\infty dr\Big\{\frac{g^2}{2}(r\dot{\rho})^2 + \frac{\lambda g^2 r^2}{8}\big(\rho^2-\rho_0^2\big)^2 + \dot{f}^2 + \frac{1}{2}(r\dot{A})^2$$
$$+\frac{g^2}{2g'^2}(r\dot{B})^2 + \frac{g^2}{4}f^2\rho^2 + \frac{g^2r^2}{8}(B-A)^2\rho^2 + f^2A^2\Big\}.$$

- The boundary condition tells that E_1 is finite. But E_0 becomes infinite because of the point singularity at the origin.
- Most probably the quantum correction could regularize the point singularity to make the energy finite. But can we predict the mass?
- There are three 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. Dimensional Argument

- Physically the monopole mass originates from the Higgs mechanism. To see this consider the Georgi-Glashow model

$$\mathcal{L}_{GG} = -\frac{1}{4}\vec{F}_{\mu\nu}^2 - \frac{1}{2}(D_\mu\vec{\Phi})^2 - \frac{\lambda}{4}\big(\vec{\Phi}^2 - \frac{\mu^2}{\lambda}\big)^2,$$

where $\vec{\Phi}$ is the Higgs triplet. With the 'tHooft-Polyakov ansatz

$$\vec{A}_\mu = (1-f)\vec{C}_\mu, \quad \vec{C}_\mu = -\frac{1}{g}\hat{r} \times \partial_\mu \hat{r}, \quad \vec{\Phi} = \rho\, \hat{r},$$

we have

$$(D_\mu\vec{\Phi})^2 = (\partial_\mu\rho)^2 + g^2\rho^2 f^2(\vec{C}_\mu)^2.$$

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we have

$$(D_\mu\vec{\Phi})^2 = (\partial_\mu\rho)^2 + g^2\rho^2 f^2(\vec{C}_\mu)^2.$$

- This confirms that the same Higgs mechanism which generates the mass to the weak boson works for the monopole, except the coupling becomes magnetic. Exactly the same argument applies to the Weinberg-Salam model.

- From this we must have

$$M = C \times \frac{4\pi}{e^2} M_W, \quad C \simeq 1.$$

So the monopole mass is expected to be $1/\alpha$ times the W-boson mass, around 10 TeV.

B. Scaling Argument

- To estimate C notice that the monopole energy consists of 4 terms

$$K_A = \int d^3x \, \frac{1}{4} \vec{F}_{ij}^2, \quad K_B = \int d^3x \, \frac{1}{4} B_{ij}^2$$

$$K_\phi = \int d^3x \, |\mathcal{D}_i \phi|^2, \quad V_\phi = \int d^3x \, \frac{\lambda}{2} \big(|\phi|^2 - \frac{\mu^2}{\lambda}\big)^2,$$

but only K_B is divergent.

- If the regularized monopole exists, it should be stable under the scale transformation

$$\vec{x} \longrightarrow \lambda \vec{x},$$

- Under the scaling we have

$$K_A \to \lambda K_A, \quad K_B \to \lambda K_B, \quad K_\phi \to \lambda^{-1} K_\phi, \quad V_\phi \to \lambda^{-3} V_\phi.$$

So if the regularized monopole exists, we must have

$$K_A + K_B = K_\phi + 3V_\phi.$$

- From the Cho-Maison monopole (with $A = B = 0$) we have

$$K_A \simeq 0.1904 \times \frac{4\pi}{e^2} M_W, \quad K_\phi \simeq 0.1583 \times \frac{4\pi}{e^2} M_W,$$
$$V_\phi \simeq 0.0110 \times \frac{4\pi}{e^2} M_W.$$

- So we must have

$$K_B \simeq 0.0010 \times \frac{4\pi}{e^2} M_W,$$

and

$$E \simeq 0.3607 \times \frac{4\pi}{e^2} M_W \simeq 3.97 \text{ TeV}.$$

This strongly supports the dimensional argument ($C \simeq 0.3607$).

- More importantly this mass is within the reach of the present LHC, so that the MoEDAL should be able to detect it. But how can we regularize the Cho-Maison monopole?

Ultraviolet Regularization of Cho-Maison Monopole

- Obviously the standard model has no finite energy monopole. But the Weinberg-Salam theory is the "bare" theory which must change to the "effective" theory after the quantum corrections.

- Physically the effective theory should describe the real world, so that the real monopole must be the solution of the effective theory. This is evident in QCD.

- How can we find the effective theory of the Weinberg-Salam model which can make the monopole mass finite?

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

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

where $\epsilon(\phi)$ is a positive dimensionless function of the Higgs doublet.

- Notice that $\mathcal{L}_{eff}$ describes the standard model with $\epsilon \to 1$ asymptotically. Moreover, with the rescaling of B_μ to B_μ/g', the $U(1)_Y$ gauge coupling g' changes to the running coupling $\bar{g}' = g'/\sqrt{\epsilon}$.

- From the Lagrangian we have

$$\dot{\rho} + \frac{2}{r}\dot{\rho} - \frac{f^2}{2r^2}\rho = -\frac{1}{4}(A-B)^2\rho + \frac{\lambda}{2}(\rho^2-\rho_0^2)\rho + \frac{\epsilon}{g'^2}\Big(\frac{1}{r^4} - \dot{B}^2\Big)\rho,$$

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

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

$$\ddot{B} + (\frac{2}{r} + \frac{1}{\epsilon}\frac{d\epsilon}{d\rho}\frac{\dot{\rho}}{\rho})\dot{B} = -\frac{g'^2}{4\epsilon}\rho^2(A-B).$$

This confirms that $\epsilon(\phi)$ effectively changes g' to the running coupling $\bar{g}' = g'/\sqrt{\epsilon}$.

- So, by choosing a proper $\epsilon(\phi)$ which can generate the physical (real) running coupling $\bar{g}'$ of the standard model, we can implement the quantum correction with $\epsilon(\phi)$. This assures that we can indeed treat $\mathcal{L}_{eff}$ as an effective action of the standard model.

- Moreover, we can make the monopole energy finite making $\epsilon(\phi)$ vanishing at the origin.

- To see how it works, let $\epsilon = (\dfrac{\rho}{\rho_0})^8$ and find the following running coupling.

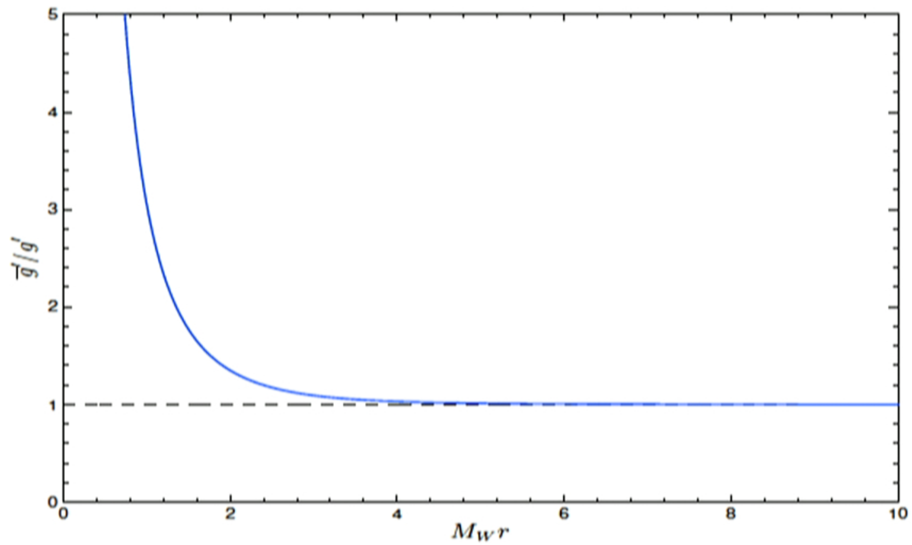

Figure : The effective coupling $\bar{g}'$ induced by $\epsilon(\phi)$. The permittivity $\epsilon(\phi)$ can accommodate the quantum correction, modifying the $U(1)_Y$ gauge coupling g' to $\bar{g}'$.

- Moreover, notice that

$$K_B \to \int d^3x \, \frac{\epsilon}{4} \, G_{ij}^2 = 2\pi \int_0^\infty dr \frac{\epsilon}{g'^2 r^2} < \infty.$$

This assures that the effective action can make the energy of Cho-Maison dyon finite.

- With $A = B = 0$ we have the regularized monopole with energy

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

which supports the scaling argument.

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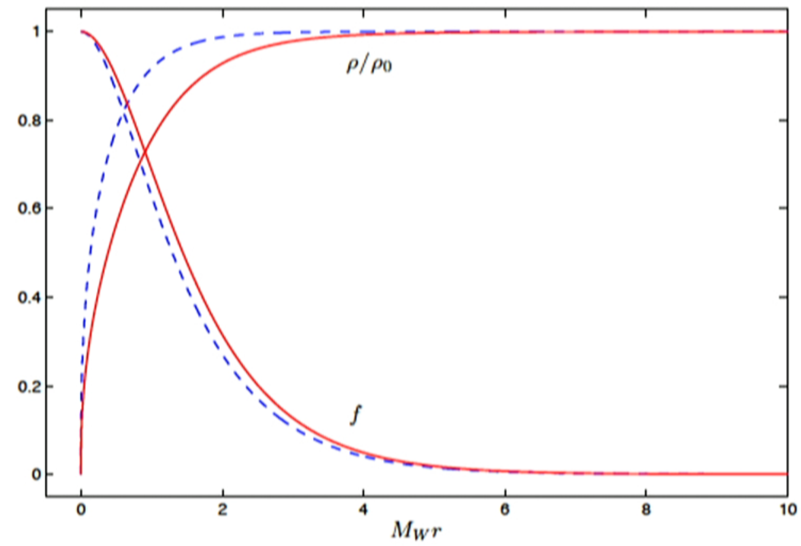
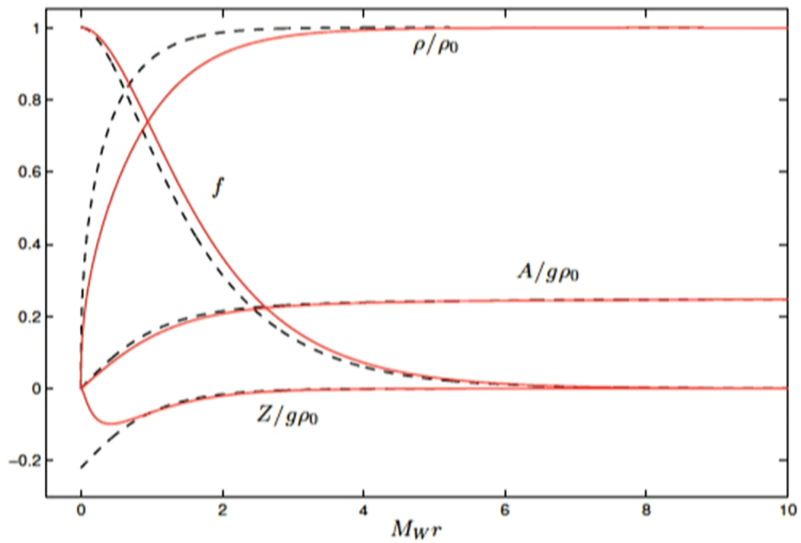


Figure : The finite energy electroweak monopole solution. The solid line (red) represents the regularized monopole and the dotted (blue) line represents the Cho-Maison monopole.



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- 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 $H \to \gamma + \gamma$, 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 in pairs, and the MoEDAL might actually detect it.

J. Ellis, N. Mavromatos, and T. You, arXiv 1602.01745

- There is another way to obtain a finite energy monopole solution. Suppose the quantum correction at short distance modifies the standard model by $\delta\mathcal{L}$, and consider the modified Lagrangian

$$\mathcal{L}' = \mathcal{L} + \delta\mathcal{L},$$
$$\delta\mathcal{L} = ie\alpha F_{\mu\nu}^{(\mathrm{em})} W_\mu^* W_\nu + \beta \frac{g^2}{4}(W_\mu^* W_\nu - W_\nu^* W_\mu)^2 - \gamma \frac{g^2}{4}\rho^2 |W_\mu|^2,$$

Notice that, when $Z_\mu = 0$, $\mathcal{L}'$ describes Georgi-Glashow model when $\alpha = 0$, $(1+\beta) = e^2/g^2$, and $(1+\gamma) = 4e^2/g^2$, if we identify e as the coupling constant of the Georgi-Glashow model.

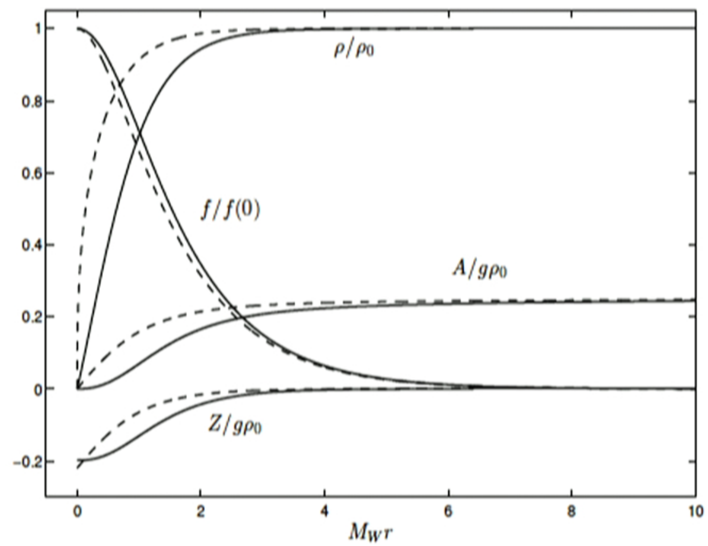

Figure : The finite energy electroweak dyon solution. The solid line represents the finite energy dyon and dotted line represents the Cho-Maison dyon.

- Moreover, when $\alpha = 0, \quad 1 + \beta = e^2/g^2, \quad 1 + \gamma = 4e^2/g^2,$ we have

$$\dot{\rho} \pm \frac{1}{er^2}(\frac{e^2}{g^2}f^2 - 1) = 0, \quad \dot{f} \pm e\rho f = 0,$$

in the BPS limit $\lambda = 0$, and have an analytic solution whose energy is given by the Bogomol'nyi bound

$$\rho = \rho_0 \coth(e\rho_0 r) - \frac{1}{er}, \quad f = \frac{g\rho_0 r}{\sinh(e\rho_0 r)},$$

$$E \simeq 0.4624 \times \frac{4\pi}{e^2}\, M_W \simeq 5.08\ \text{TeV}.$$

- From this we can confidently say that the mass of the electroweak monopole could be around 4 to 10 TeV.

- The above exercise strongly implies that the quantum correction can make the energy of the Cho-Maison monopole finite. In particular, it endorses the dimensional estimate $E = C \times (4\pi/e^2)M_W$.

- Another way to regularize the Cho-Maison monopole is to embed the electroweak $SU(2) \times U(1)_Y$ to a simply connected unified group G. But this will inevitably introduce a new scale M_X which could make the monopole mass much heavier.

- This type of embedding can naturally arise in the left-right symmetric grand unification, for example in $SO(10)$ grand unification.

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Physical Implications

- The existence of the electroweak monopole of mass around 4 to 10 TeV has deep physical implications.

- It explains why the Dirac's monopole has not been discovered. This is not supposed to exist. More importantly, it explains why the search for the monopole has failed so far. We have not reached the monopole production threshold energy.

- Fortunately, the recent LHC upgrade may have finally reached the monopole production threshold energy, so that the MoEDAL has the possibility to detect it.

- If the monopole mass becomes above 7 TeV, however, LHC will not be able produce them. In this case we have to wait for the next upgrade of LHC, or look for the cosmic remnants of the monopole.
- If detected it will become the first topological elementary particle, the true God's particle, in nature.
- Since the monopole must be stable, it could have unlimited important applications from the practical point of view. For example it can generate the magnetic current.

Important Issues

- To detect the monopole we need to study

1. The monopole-antimonopole production rate at LHC. Roughly speaking (above the threshold) the rate is expected to be $1/\alpha$ times bigger than W^+W^- production rate. But we need a more accurate production rate.

2. To do that we must first identify the monopole-antimonopole production mechanism (the Drell-Yan process, the photon fusion process, etc.).

3. The cosmic monopole density in the early and present universe. This is very important to detect the remnant cosmic monopoles. For this we need to calculate the monopole production rate in the early universe first.

4. The electroweak decay process of the monopole-antimonopole resonance ($p\bar{p} \to M\bar{M} \to e\bar{e}, \mu\bar{\mu}, E\bar{E}, W^+W^-$). This becomes important when the monopole-antimonopole production threshold is near LHC energy 14 TeV.

5. The monopole bound states with e, μ, E etc...

Challenges

- How can we justify the perturbative expansion in the presence of the monopole?
- How can we construct the quantum field theory of monopole, Quantum Electro-Magneto-Dynamics (QEMD), from QED?
- What are the new physical processes which can be induced by the monopole?

- What are the cosmological implications of the monopole?
- Can the gravity regularize the monopole? Or does it make the monopole a blackhole?
- The quest must go on...

New Physics

- References

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