Hidden Monopole Dark Matter via Axion Portal and its Implications for Direct Search and Beam-Dump experiments

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Hidden monopole dark matter

- Hidden monopole is a good dark matter (DM) candidate.
  - It is an inevitable topological object if the universe experiences a phase transition in the hidden sector.
  - Its stability is ensured by the topological nature.

Can we detect the hidden monopole DM?

A: No, at least in the minimum setup. One has to introduce certain couplings with the standard model (SM) sector.
Hidden monopole DM-SM interactions

- There are three possible portals connecting the hidden monopole DM and the SM sector.
  - Higgs portal (expected scattering cross-section is very small)
  - Vector portal (strictly constrained by many exps. and obs.)
  - Axion portal  Our main interest
    (c.f. W. Fischler & J. Preskill 83’)
    (c.f. Jaeckel & Ringwald, 2010)
It is well-known that a magnetic monopole can arise when a non-abelian gauge symmetry is spontaneously broken via the Higgs mechanism.

\[ \begin{align*}
\mathcal{L}_H &= -\frac{1}{4} F_{\mu\nu}^{H} \cdot F_{H\mu\nu} + \frac{1}{2} D^\mu \phi \cdot D_\mu \phi - \mathcal{V}(\phi) \\
&=
\partial^\mu A^\nu_H - \partial^\nu A^\mu_H + e_H A^\mu_H \times A^\nu_H \\
D^\mu \phi &= \partial^\mu \phi + e_H A^\mu_H \times \phi \\
\mathcal{V}(\phi) &= \frac{1}{4} \lambda_\phi \left( \phi^2 - v^2_H \right)^2
\end{align*} \]
Expand the Lagrangian density around the vacuum state

\[ \phi \rightarrow \phi + (0, 0, v_H) \quad \rightarrow \quad SU(2)_H \quad \frac{\langle \phi \rangle}{U(1)_H} \]

Particle spectrum in the hidden sector

- Monopole is a **static** solution with **finite energy** configuration.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass</th>
<th>Hidden electric charge</th>
<th>Hidden magnetic charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_H$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>$m_\varphi = \sqrt{2\lambda_\varphi} v_H$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W^\pm_H$</td>
<td>$m_{W^\pm} = \sqrt{4\pi\alpha_H} v_H$</td>
<td>$Q_E = \pm e_H$</td>
<td>0</td>
</tr>
<tr>
<td>$M(M)$</td>
<td>$m_M = \sqrt{4\pi/\alpha_H} v_H$</td>
<td>$Q_E = \pm e_H \theta_H/(2\pi)$</td>
<td>$Q_M = \pm 4\pi/e_H$</td>
</tr>
</tbody>
</table>
The Witten effect

The theta term of hidden U(1) gauge symmetry

\[ \mathcal{L}_\theta = \theta_H \frac{e_H^2}{32\pi^2} F^\mu_\nu \tilde{F}^\nu_\mu = -\theta_H \frac{e_H^2}{8\pi^2} E_H \cdot B_H \]

This term usually has no effect since it is a total derivative. However, it has physical effect in the monopole background.

\[ Q_M = \pm \frac{4\pi}{e_H} \]

\[ Q_E = \pm \frac{e_H \theta_H}{2\pi} \]
What we did

- Axion portal coupling + Yukawa interactions

S. Alekhin et al. 16'

Witten effect

Yukawa coupling

$\propto \frac{m_N}{f_a}$

Direct search experiments

Beam-dump experiments

$\frac{1}{f_a}$ (GeV$^{-1}$)

$B$ for $K^{\pm}$

$K^+\rightarrow \pi^+ + X$

$B\rightarrow K^{+} +$ inv

CHARM

SHIP

BBN constraints
Axion portal coupling

- **Lagrangian density**

\[ \mathcal{L} = -\frac{1}{4} F_{H}^{\mu\nu} F_{H\mu\nu} + \frac{1}{2} f_{a}^{2} \partial^{\mu} \theta \partial_{\mu} \theta - \frac{1}{2} m_{a}^{2} f_{a}^{2} (\theta - \theta_{0})^{2} + \theta \frac{e_{H}^{2}}{32\pi^{2}} F_{H}^{\mu\nu} \tilde{F}_{H\mu\nu} \]

(c.f. W. Fischler & J. Preskill 83')

\[ F_{H}^{\mu\nu} = \partial^{\mu} A_{H3}^{\nu} - \partial^{\nu} A_{H3}^{\mu} \quad \theta \equiv a / f_{a} + \theta_{H} \]

- **Equation of motion of the axion field**

\[ \frac{d^{2} \theta}{d r^{2}} + \frac{2}{r} \frac{d \theta}{d r} - \left( m_{a}^{2} + \frac{r_{0}^{2}}{r^{4}} \right) \theta + m_{a}^{2} \theta_{0} = 0 \]

\[ r_{0} = \frac{e_{H}}{8\pi^{2} f_{a}} \]

- **Boundary conditions**

\[ \theta(r \to 0) = 0 \ , \ \theta(r \to \infty) = \theta_{0} \]

The total energy density of the axion-monopole system must be finite.
Axion profile around the monopole

\[ \theta(r) \]

\[ \theta_0 = 1 \]
\[ \sqrt{m_a r_0} = 10^{-2} \]

Analytical

Numerical
Hidden monopole-nucleon scattering

- Axion-nucleon interaction (Yukawa coupling)

\[ H_{a-N} = i \frac{m_N}{f_a} \int d^3x \left[ a(x) \bar{\psi}_N(x) \gamma^5 \psi_N(x) \right] \]

- Amplitude of the hidden monopole-nucleon scattering

\[ i \mathcal{M}_{M+N \rightarrow M+N} = m_N \bar{u}_N(p_{out}) \gamma^5 u_N(p_{in}) \int d^3x \theta(x) e^{-i q \cdot x} \]

- Spin-dependent cross-section

\[ \frac{d\sigma_{M+N \rightarrow M+N}}{d\Omega} \approx \frac{\alpha_H \theta_0^2}{16\pi^3} \frac{m_N^2}{m_a f_a^2} |q|^2 \]

\[ q = p_{out} - p_{in} \]
Direct search exps. : $m_a$ vs $f_a^{-1}$

Preliminary

$\alpha_H \simeq 0.73$

$m_M \simeq 216$ TeV

$\Omega_M/\Omega_{DM} \simeq 0.35$

$\alpha_H \simeq 0.01$

$m_M \simeq 102$ TeV

$\Omega_M/\Omega_{DM} \simeq 0.01$
Beam-dump experiments

Experimental setup (CHARM)

Target \rightarrow a \rightarrow Detector

Proton beam \rightarrow beam-dump \rightarrow \gamma, e^\pm, \mu^\pm, \gamma_H, ...

\[ N_{\text{det}} \approx N_a \exp\left(-\frac{480 \text{ m}}{\gamma_a \beta_a c \tau_a}\right) \left[1 - \exp\left(-\frac{35 \text{ m}}{\gamma_a \beta_a c \tau_a}\right)\right] \sum_{X=e, \mu, \gamma} B(a \rightarrow X \bar{X}) < 2.3 \]

\[ \gamma_a = (1 - \beta_a^2)^{-1/2} \approx 10 \text{ GeV} / m_a \quad \tau_a = \frac{1}{\Gamma_a} = \frac{1}{\Gamma(a \rightarrow \gamma_H \gamma_H) + \Gamma(a \rightarrow \text{vis})} \]

J.D. Clarke et al. 2014

11/13
Beam-dump exps. : $m_a$ vs $f_a^{-1}$
Combined result: $m_a$ vs $f_a^{-1}$

We find two parameter regions where both the hidden monopole DM and the axion are within the reach of the direct search and beam-dump experiments.

$\alpha_H \approx 0.73$

$m_M \approx 216 \text{ TeV}$

$|r_{aK}\mid > 10^{-11}$

$B_{s}\rightarrow \mu^+\mu^-$

$B\rightarrow K+\text{inv}$

$B\rightarrow K\mu^+\mu^-$

$\text{CHARM}$

$\text{SHiP}$

$\text{BBN}$

$\text{COUPP-4}$

$\text{COUPP-60}$

$\text{PICO-250L}$

$m_a = \mathcal{O}(10) \text{ MeV}$

$f_a = \mathcal{O}(10^5) \text{ GeV}$

$m_a = \mathcal{O}(100) \text{ MeV}$

$f_a = \mathcal{O}(10^4) \text{ GeV}$

Preliminary
Back up
Kibble-Zurek mechanism

Second-order phase transition

\[ \zeta = \zeta_0 |\epsilon|^{-\nu}, \quad \tau = \tau_0 |\epsilon|^{-\mu}, \quad \epsilon \equiv \frac{T - T_c}{T_c} \]

Correlation length  Relaxation time

Frozen :

\[ t_f - t_c = \tau_f \]

\[ |\epsilon_f| = \left[ \tau_0 H(t_c) \right]^{1/(1+\mu)} \]

\[ \zeta_f = \zeta_0 \left[ \tau_0 H(t_c) \right]^{-\nu/(1+\mu)} \]

\[ n_M \approx \zeta_f^{-3} \]