A complete calculation for direct detection of wino dark matter

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Based on [J. Hisano, K. Ishiwata, N. N., 1004. 4090 and 1007. 2601]
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1. Introduction
Introduction

Observational evidence for dark matter (DM)

**Galactic scale**

![Graph showing velocity profile of NGC 8503](image)


**Cosmological scale**

![Graph showing CMB anisotropy](image)

Komatsu et. al. (2010).

**Scale of galaxy clusters**

![Image of galaxy cluster with Clowe et. al. (2006) reference](image)

About 80% of the matter in the Universe is nonbaryonic dark matter.
In this work, we assume the main ingredient of dark matter in the universe to be

**The neutral component of SU(2)\_L gauginos**

**(Pure) Wino dark matter**

**SM SU(2)\_L gauge bosons**

- $W^0$
- $W^\pm$

**SU(2)\_L Gauginos in MSSM**

- $\chi^0$: Neutral wino
- $\chi^\pm$: Charged wino
On the assumption of generic Kahler potential,

The neutral Wino can be the lightest SUSY particle in the anomaly mediation scenario.

**The anomaly mediated SUSY breaking scenario**

- **Gravitino**
- **Scalar Particles**
- **Higgsinos**
  - O(10) TeV
- **Gauginos**
- **Gluino**
- **Bino**
- **Wino**
  - O(1) TeV
  - Suppressed by one-loop factor

**the Split SUSY scenario**

Proportional to the gauge coupling beta functions
In the present situation, all of these tree diagrams are suppressed. The Wino-nucleon scattering process is dominated by loop diagrams.

**Previous works**


- In these works, they calculate the one-loop contribution, but their results are not consistent with each other.
- The two-loop gluon contribution is neglected in their works.
2. Direct Detection of Majorana DM
Effective Lagrangian for Majorana Dark Matter

\[ \mathcal{L}_q = d_q \tilde{\chi}^0 \gamma^\mu \gamma_5 \bar{q} \gamma_\mu q + f_q m_q \tilde{\chi}^0 \bar{q} q + \frac{g_1^{(1)}}{M} \tilde{\chi}^0 i \partial^\mu \gamma^\nu \tilde{\chi}^0 \mathcal{O}_{\mu \nu}^g + \frac{g_2^{(2)}}{M^2} \tilde{\chi}^0 i \partial^\mu i \partial^\nu \tilde{\chi}^0 \mathcal{O}_{\mu \nu}^g \]

\[ \mathcal{L}_g = f_G \tilde{\chi}^0 \chi^0 G_{\mu \nu}^a G^{a \mu \nu} + \frac{g_1^{(1)}}{M} \tilde{\chi}^0 i \partial^\mu \gamma^\nu \tilde{\chi}^0 \mathcal{O}_{\mu \nu}^g + \frac{g_2^{(2)}}{M^2} \tilde{\chi}^0 i \partial^\mu \gamma^\nu \tilde{\chi}^0 \mathcal{O}_{\mu \nu}^g \]

\[ \tilde{\chi}^0 : \text{DM} \]
\[ m_q : \text{quark mass} \]
\[ M : \text{DM mass} \]

- : Spin-dependent
- : Spin-independent
- : negligible

Twist-2 operators

\[ \mathcal{O}_{\mu \nu}^g \equiv \frac{1}{2} q i \left( D_\mu \gamma_\nu + D_\nu \gamma_\mu - \frac{1}{2} g_{\mu \nu} \slashed{\partial} \right) q, \]

\[ \mathcal{O}_{\mu \nu}^g \equiv \left( G^{a \rho}_{\mu} G^a_{\rho \nu} + \frac{1}{4} g_{\mu \nu} C^a_{\alpha \beta} G^{a \alpha \beta} \right). \]

Majorana condition

\[ \tilde{\chi}^0 \gamma^\mu \chi^0 = 0 \]
\[ \tilde{\chi}^0 \sigma^{\mu \nu} \chi^0 = 0 \]

\[ \sigma^{\mu \nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu] \]

We focus on the spin-independent (SI) interactions hereafter.
Nucleon matrix elements

- The mass fractions (for the scalar-type quark operators)

\[ \frac{\langle N|m_q\bar{q}q|N\rangle}{m_N} \equiv f_{Tq}, \quad 1 - \sum_{q=u,d,s} f_{Tq} \equiv f_{TG} \]

\[ m_N : \text{nucleon mass} \]

- For the twist-2 operators

\[ \langle N(p)|\mathcal{O}_{\mu\nu}^q|N(p)\rangle = \frac{1}{m_N} (p_\mu p_\nu - \frac{1}{4} m_N^2 g_{\mu\nu}) (q(2) + \bar{q}(2)), \]
\[ \langle N(p)|\mathcal{O}_{\mu\nu}^g|N(p)\rangle = \frac{1}{m_N} (p_\mu p_\nu - \frac{1}{4} m_N^2 g_{\mu\nu}) G(2). \]

- The second moments of the parton distribution functions (PDFs)

\[ q(2) + \bar{q}(2) = \int_0^1 dx \ x \ [q(x) + \bar{q}(x)], \]
\[ G(2) = \int_0^1 dx \ x \ g(x). \]
The matrix element of gluon field strength tensor can be evaluated by using the trace anomaly of the energy-momentum tensor in QCD.

The trace anomaly of the energy-momentum tensor in QCD

\[
\Theta^\mu_\mu = \frac{\beta(\alpha_s)}{4\alpha_s} G^a_{\mu\nu} G^{a\mu\nu} + \sum_{q=u,d,s} m_q \bar{q}q + \sum_{Q=c,b,t} m_Q \bar{Q}Q
\]

\[
m_N \quad \beta(\alpha_s) = -\frac{7\alpha_s^2}{2\pi} \quad \text{for} \quad N_F = 6
\]

\[
m_N f_{TG} = -\frac{9\alpha_s}{8\pi} \langle N | G^a_{\mu\nu} G^{a\mu\nu} | N \rangle
\]

The effective coupling of DM with nucleon is given as follows:

\[ \mathcal{L}_{\text{eff}} = f_N \tilde{\chi}\tilde{\chi}\bar{N}N \]

\[
\frac{f_N}{m_N} = \sum_{q=u,d,s} f_q f_{Tq} + \sum_{q=u,d,s,c,b} \frac{3}{4} \left( q(2) + \bar{q}(2) \right) (g_q^{(1)} + g_q^{(2)}) \\
- \frac{8\pi}{9\alpha_s} f_{TG} f_G + \frac{3}{4} G(2) \left( g_G^{(1)} + g_G^{(2)} \right).
\]

The gluon contribution can be comparable to the quark contribution even if the DM-gluon interaction is induced by higher loop diagrams.
Elastic scattering cross section

One can derive the SI cross section by using the SI effective couplings as follows:

$$\sigma_{SI}^T = \frac{4}{\pi} \left( \frac{M m_T}{M + m_T} \right)^2 |n_p f_p + n_n f_n|^2$$

$m_T$ : the mass of the target nucleus
$n_p$ : the number of proton
$n_n$ : the number of neutron

From now on, we just show the results for the SI cross section of DM with a proton as a reference value.
3. Results
The interaction Lagrangian:

$$\mathcal{L}_{\text{int}} = -g_2(\bar{\chi}^0 \gamma^\mu \chi^- W^\dagger_\mu + h.c.)$$

1-loop diagrams:

- **(a)**: $q \longrightarrow h^0 \longrightarrow q$
- **(b)**: $q \longrightarrow W^- \longrightarrow W^- \longrightarrow q$

Effective couplings:

$$f_q = \frac{\alpha_2^2}{4m_W m_{h_0}^2} g_H(x),$$
$$d_q = \frac{\alpha_2^2}{m_W^2} g_{WL}(x),$$
$$g_q^{(1)} = \frac{\alpha_2^2}{m_W^3} g_{T1}(x), \quad \alpha_2 \equiv \frac{g_2}{4\pi},$$
$$g_q^{(2)} = \frac{\alpha_2^2}{m_W^3} g_{T2}(x), \quad x \equiv \frac{m_W^2}{M^2}$$

Remark:

The SI effective interaction is not suppressed even if the Wino mass is much larger than the W boson mass.

$$g_H(x) \simeq -2\pi, \quad g_{T1}(x) \simeq \pi/3, \quad (\text{for} \quad x \to 0)$$

2-loop diagrams:

The effective scalar coupling of gluon:

\[
f_G = -3 \times \frac{\alpha_s}{12\pi} \frac{\alpha_s^2}{4m_W^2 m_h^2} g_{B1}(x) + \frac{\alpha_s}{4\pi} \frac{\alpha_s^2}{m_W^3} g_{B3}(x, y) + 2 \times \frac{\alpha_s}{4\pi} \frac{\alpha_s^2}{m_W^3} g_{B1}(x),
\]

\[
x = \frac{m_W^2}{M^2}, \quad y = \frac{m_W^2}{M^2}, \quad g_{B3}(x, y) \simeq \frac{(3\sqrt{y} + 2\sqrt{x})x}{24(\sqrt{x} + \sqrt{y})^3\pi}, \quad g_{B1}(x) \simeq \frac{\pi}{12}. \quad (\text{for } x, y \to 0)
\]

Each contribution in the spin-independent effective coupling, $f_p$

- The contribution of twist-2 operator is dominant.
- The other contributions yield substantial contribution by the opposite sign.
- There is a cancellation among these contributions.

Spin-Independent scattering cross section (Wino DM)

While the SI cross section is almost independent of the Wino mass, it is quite sensitive to the Higgs mass due to the cancellation.

- This cross section is smaller than those in the previous works by more than an order of magnitude.
4. Summary
Summary

• We evaluate the wino-nucleon elastic scattering cross sections based on the method of effective theory.

• The interaction of DM with gluon as well as quarks yields sizable contribution to the cross section, though the gluon contribution is induced at higher loop level.

• In the wino dark matter scenario we find the cross section is smaller than the previous results by more than an order of magnitude.