Electric dipole moments and dark matter in a CP violating MSSM

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Abstract

We investigate electric dipole moments (EDMs) in a CP-violating minimal supersymmetric standard model with the Bino-like neutralino dark matter (DM) annihilating through the heavy Higgs funnel. Motivated by the current experimental results, in particular, the measured mass of the standard model-like Higgs boson, we consider a mass spectrum with stop masses of about 10 TeV. For the other sfermions, we consider masses of about 100 TeV. We show that CP-violating phases of the order of ten degrees in gaugino and Higgsino mass parameters are consistent with the current bound by EDMs of the electron, the neutron, and the mercury. They are within the reach of future experiments. We also show that effects of CP-violating phases induce a difference in DM-nucleon scattering cross section by a factor.
1. INTRODUCTION

Supersymmetry is an attractive candidate of physics beyond the Standard Model (SM), although current results from LHC experiments indicate that supersymmetric (SUSY) particles are heavier than have been expected. Attractive aspects come from the fact that, for instance, the gauge coupling unification is realized in the minimal SUSY SM (MSSM), the gauge hierarchy problem is improved, and elementary scalar fields such as Higgs fields are introduced in a theoretically natural way. Moreover, SUSY models may provide additional interesting consequences. SUSY interpretation of muon anomalous magnetic moment is one example \[1–3\]. SUSY models contain new sources of CP violation and/or flavor violation, which potentially induce new CP or flavor violating phenomena. The lightest SUSY particle (LSP) is stable and hence a good candidate for dark matter (DM) in our Universe, if the R-parity is unbroken \[4, 5\].

Electric dipole moments (EDMs) of the neutron and other heavy atoms are prime physical quantities for probing sources of CP violation. Parameters in the MSSM generally pose several CP violating phases. It used to be regarded that the null experimental EDM results confront the MSSM with \(O(1)\) CP violating phases and \(O(100)\) GeV masses of SUSY particles \[6–9\]. The LHC results indicate that masses of many SUSY particles are larger than \(O(10)\) TeV. Therefore CP violating phases of order unity in the SUSY sector \[10, 11\] seems still likely and worth investigating.

In the MSSM with R-parity, the lightest neutralino \(\tilde{\chi}\) is a candidate of the weakly interacting mass particle (WIMP) DM. While LHC experiments as well as direct detection experiments of DM, such as LUX \[12, 13\], XENON1T \[14\], and PandaX-II \[15, 16\] are constraining large parameter space of the MSSM, there are still viable scenarios reproducing thermal relic abundance of the DM consistently. Appropriate magnitude of annihilation cross section of neutralino in the early Universe is realized if (i) neutralinos annihilate significantly through SU(2) gauge interaction, or (ii) annihilation cross section of Bino-like neutralino is enhanced with a particular mass spectrum of other associated particles.

Higgsino-like neutralino DM with the mass of about 1 TeV is an example in the former class. Phenomenology in this scenario such as the direct detection of DM, contribution to the EDMs, and collider signals have been precisely studied in Ref. \[17\].

In this paper, we focus on another case in the later class; a Bino-like neutralino DM annihilates through heavy Higgs boson resonance \[18–22\].\(^1\) In this scenario where heavy Higgs boson resonance

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\(^1\) For a study of CP violation in stau coannihilation scenario, see e.g., Ref. \[23\]}
in the neutralino DM annihilation is utilized, masses of the heavy Higgs boson are about twice of
the mass of the neutralino DM. Since the Bino-like neutralino contains small Higgsino component,
the neutralino can be searched through Higgs bosons exchange by spin-independent scattering off
nucleus [24]. Masses of stops would be around 10 TeV in order to reproduce the measured SM-
like Higgs boson mass \( m_h = 125 \text{ GeV} \) [25, 26]. Then, all the other SUSY particle masses and
parameters except for the Bino mass, the Higgsino mass parameter \( \mu \), \( B\mu \), and stop masses can be
much larger than \( O(1) \) TeV. With such SUSY particle mass spectrum, most of SUSY contributions
to the low energy phenomena can be decoupled as the irrelevant SUSY particles are heavier, SUSY
contributions to the EDMs in CP violating models can still be significantly large nevertheless. The
main goal of this article is, by decoupling the other particles, to estimate the magnitude of EDMs
induced by CP violation in neutralino DM sector with taking account of CP-violating phase effects
into the thermal DM abundance [27–32].

We examine the electron EDM, the nucleon EDM, and the mercury EDM, as well as the
DM-nucleon scattering cross section on the parameter space, where appropriate thermal DM relic
abundance is reproduced, for order unity CP-violating phases of gaugino mass parameters and the
\( \mu \) parameter. For non-vanishing CP phase of \( \mu \) and \( A \) parameters, see, for example, Refs. [27, 30]
[33, 34]. The magnitude of scattering off cross section between DM and nucleon is affected by the
CP violating phases [30, 35–40]. We also study the dependence of spin-independent cross section of
the DM in our scenario and find that the effect changes by a factor. We show that wide parameter
regions in our scenario are now unconstrained yet, but will be explored by future experiments.

This article is organized as follows. In Sec. 2, we define a benchmark scenario for studying
phenomenology in our DM scenario. In Sec. 3, we show the results of our analysis on several EDM
measurements and the spin-independent cross section. Summary and conclusion are presented in
Sec. 4.

2. SETUP OF THE SCENARIO

In this section, we briefly review the MSSM Lagrangian, and we describe the parameter setup
for our analysis. The superpotential and the soft SUSY breaking terms in the MSSM are given
by [11]

\[
W = \epsilon_{ab} \left[ (y_e)_{ij} H_1^a L_i^b \bar{E}_j + (y_d)_{ij} H_1^a Q_i^b \bar{D}_j + (y_u)_{ij} H_2^a Q_i^b \bar{U}_j - \mu H_1^a H_2^b \right],
\]  

(2.1)
and

\[ \mathcal{L}_{\text{soft}} = - \frac{M_1}{2} \overline{B} B - \frac{M_2}{2} \overline{W} \alpha W^\alpha - \frac{M_3}{2} \overline{G} A G^A - m_{H_1}^2 H_1^a H_1^a + m_{H_2}^2 H_2^a H_2^a - \overline{q}_i L a (M_{\tilde{q}}^2)_{ij} \overline{q}^a_j L - \tilde{\ell}_i L a (M_{\tilde{\ell}}^2)_{ij} \tilde{\ell}^a_j L - \tilde{\nu}_i R (M_{\tilde{\nu}}^2)_{ij} \tilde{\nu}^a_j R - \tilde{\ell}_i R (M_{\tilde{\ell}}^2)_{ij} \tilde{\ell}^a_j R - \epsilon_{ij} [\langle T_e \rangle_{ij} H_1^a \tilde{\ell}_{iL} \tilde{\ell}_{jL} + (\langle T_d \rangle_{ij} H_1^a \tilde{\nu}_{iL} \tilde{\nu}_{jL} + (\langle T_u \rangle_{ij} H_2^a \tilde{d}_{iL} \tilde{d}_{jL} + m_3^2 H_1^a H_2^b + \text{h.c.} ] \right), \] (2.2)

respectively. The convention of the epsilon tensor is \( \epsilon_{12} = -\epsilon_{21} = 1 \). Here, we note that gaugino mass parameter for Bino \( M_1 \), Wino \( M_2 \), and gluino \( M_3 \) are in general complex. In the following, we focus on the Yukawa couplings of the third generation quarks and leptons, so that we use \( y_t \), \( y_b \), and \( y_\tau \) for the Yukawa couplings of top, bottom, and tau, respectively. Neglecting the flavor mixing in the soft SUSY breaking terms, we take flavor diagonal soft scalar masses as \( M_{\tilde{q}}^2 = (M_{\tilde{q}}^2)_{ii} \), \( M_{\tilde{\ell}}^2 = (M_{\tilde{\ell}}^2)_{ii} \), \( M_{\tilde{\nu}}^2 = (M_{\tilde{\nu}}^2)_{ii} \), \( M_{\tilde{d}}^2 = (M_{\tilde{d}}^2)_{ii} \), and \( M_{\tilde{\nu}}^2 = (M_{\tilde{\nu}}^2)_{ii} \). For the trilinear couplings, \( A \) parameters defined by \( \langle T_{\alpha} \rangle_{33} = A_\alpha y_\alpha \), \( \langle T_d \rangle_{33} = A_r y_b \), and \( \langle T_u \rangle_{33} = A_r y_\tau \) are used.

In the MSSM, the mass of the SM-like Higgs boson is expressed with some SUSY breaking parameters. In our analysis, we take \( \tan \beta := \langle H_2 \rangle / \langle H_1 \rangle = 30 \) and we fix the stop mass parameters as \( M_{\tilde{t}_1} = 7 \) TeV, \( M_{\tilde{t}_2} = 7 \) TeV and \( A_t = 10 \) TeV, then the measured SM-like Higgs boson mass \( m_h \simeq 125 \) GeV can easily reproduced \cite{25,26}. The other SUSY particles are relevant to neither the mass of the SM-like Higgs boson nor the DM relic density. We may assume that those are much heavier than stop so that those are decoupled from low energy observables. We here take masses of the other sfermions as 100 TeV and the Wino and gluino masses to be 10 TeV. In this article, we focus on the Bino-like DM with the Higgs funnel scenario, where heavy Higgs boson mass is close to twice the mass of the DM so that the Bino-like neutralino rapidly annihilate through the heavy Higgs bosons resonance and has left with the appropriate cosmic abundance for DM. Since masses of heavier neutral Higgs bosons, \( m_{H^\pm} \) and \( m_A \), are close to the charged Higgs boson mass \( m_{H^\pm} \) in the MSSM, we fix \( m_{H^\pm} \) to be twice of Bino mass parameter \( M_1 \) to realize resonant annihilation by the heavy Higgs bosons. In addition, the \( \tilde{\chi}_2 \)-Higgs boson coupling depends on non-vanishing Higgsino component in the neutralino. Thus, both the Bino mass \( |M_1| \) and the Higgsino mass \( |\mu| \) should be of the order of TeV. We leave \( M_1 \) as a free parameter and solve \( |\mu| \) from the measured dark matter energy density. We summarize the parameter set in our analysis...
as follows:

\begin{align}
|M_2| = |M_3| &= 10 \text{ TeV}, \\
M_{\tilde{q}_{1,2}} &= M_{\tilde{u}_{1,2}} = M_{\tilde{d}_{1,2,3}} = M_{\tilde{e}_{1,2,3}} = 100 \text{ TeV}, \\
M_{\tilde{q}_3} &= M_{\tilde{t}} = 7 \text{ TeV}, \\
A_t &= 10 \text{ TeV}, \\
m_{H^\pm} &= 2M_1, \\
\tan \beta &= 30.
\end{align}

The other A-terms are zero. With the above parameter set, besides the CKM phase and the CP phases in the sfermion mass matrices, five parameters, \( \mu \), gaugino masses \( M_i \) and \( A_t \), may have CP phases \( (\phi_{\mu}, \phi_{M_1}, \phi_{M_2}, \phi_{M_3}, \phi_{A_t}) \), respectively. Here, each phases of a quantity \( X \) are defined by \( X = |X|e^{i\phi_X} \).

There is a rephasing degree of freedom in the MSSM. Thus, all the physical quantities are described by the following combinations,

\begin{align}
\arg(M_i M_j^*) , \quad \arg(M_i A_t^*) , \quad \arg(\mu M_i) , \quad \arg(\mu A_t) , \quad (i,j = 1,2,3).
\end{align}

Without loss of generality, we can take the basis of CP phases as \( \phi_{M_3} = 0 \). In addition, we take \( \phi_{A_t} = 0 \) to concentrate on the CP violation in the neutralino sector as well as, technically speaking, to keep \( m_h \approx 125 \text{ GeV} \) avoiding complicated parameter dependence of the SM-like Higgs boson mass. Hence, in the rest of this paper, we scan the following four parameters,

\begin{align}
( |M_1|, \phi_{\mu}, \phi_{M_1}, \phi_{M_2} )
\end{align}

3. OBSERVABLES

As we mentioned in the previous section, we choose \( |\mu| \) to achieve the correct DM relic density. We use micrOMEGAs 4.3.5 \cite{micromegas} with CPsuperH2.3 \cite{cph} in calculations of dark matter thermal relic density. With the correct DM relic abundance, we calculate the electron EDM, the neutron EDM, and the mercury EDM. The electron and mercury EDMs give strong constraints on the parameter space as we will see later. We also discuss the scattering cross section for the direct detection experiments.
3.1. EDM

The EDMs of fermions \( d_f \), the EDM of electron \( d_e \), the chromo EDM (cEDM) of quarks \( d_C^q \), and the Wilson coefficient of the Weinberg operator \( \omega \) are defined by

\[
L \supset - d_f \bar{f} i \sigma^{\mu \nu} \gamma_5 F_{\mu \nu} - d_e \bar{e} i \gamma_5 F_{\mu \nu} - \frac{1}{6} f^{abc} G_{\mu \nu}^a G_{\rho \alpha}^b g^{\rho \mu \alpha \beta} e^{\mu \alpha \beta},
\]

where the convention of the epsilon tensor is \( \epsilon^{0123} = +1 \). We calculate \( d_u \), \( d_d \), \( d_e \), \( d_C^u \), and \( d_C^d \) by using CPsuperH2.3 [43] implemented in micrOMEGAs 4.3.5 [42]. We use the formulae given in Ref. [44] and couplings calculated by CPsuperH2.3 to evaluate \( \omega \).² These EDMs and the Wilson coefficient are evaluated at the electroweak scale \( \mu_W = m_t \). The neutron EDM and the mercury EDM have to be evaluated at the hadronic scale \( (\mu_H \approx 1 \text{ GeV}) \). The renormalization group evolution from the electroweak scale to the hadronic scale is taken into account [45]. At the leading order of QCD, we find³

\[
d_u (\mu_H) = 0.35 d_u (\mu_W) - 0.17 g_s (\mu_W) d_C^u (\mu_W) - (9.24874 \times 10^{-5} \text{GeV}) \omega (\mu_W),
\]

\[
d_C^u (\mu_H) = 0.34 g_s (\mu_W) d_C^u (\mu_W) + (0.00031 \text{GeV}) \omega (\mu_W),
\]

\[
d_C^d (\mu_H) = 0.40 d_u (\mu_W) + 0.098 g_s (\mu_W) d_C^d (\mu_W) + (0.00010 \text{GeV}) \omega (\mu_W),
\]

\[
d_e (\mu_H) = 0.38 g_s (\mu_W) d_C^u (\mu_W) + (0.00070 \text{GeV}) \omega (\mu_W),
\]

\[
\omega (\mu_H) = 0.39 \omega (\mu_W).
\]

Here the unit of the EDMs and of the cEDMs are GeV\(^{-1} \), and the unit of \( \omega \) is GeV\(^{-2} \). In the evaluation, we used the following values,

\[
g_s (\mu_W) = 1.1666, \quad g_s (\mu_H) = 2.13309,
\]

\[
m_u (\mu_W) = 0.003 \text{ GeV}, \quad m_u (\mu_H) = 0.0024 \text{ GeV},
\]

\[
m_d (\mu_W) = 0.006 \text{ GeV}, \quad m_d (\mu_H) = 0.0054 \text{GeV}.
\]

We estimate the neutron EDM and the Mercury EDM as

\[
d_n = 0.79 d_d - 0.20 d_u + e(0.30 d_C^u + 0.59 d_C^d) \pm (10 - 30) \text{MeV} \omega,
\]

\[
\frac{d_{Hg}}{e} = 7 \times 10^{-3} \times (d_C^u - d_C^d) - 10^{-2} \frac{d_e}{e},
\]

² CPsuperH2.3 also calculate the Wilson coefficient of the Weinberg operator, but it returns very unstable numbers during the scanning the parameter because of the loss of significant digits.

³ The definition of the cEDM in the CPsuperH2.3 is different from ours, \( d_C^q \_{\text{CPsuperH2.3}} = g_s d_C^q \).
Here, we used the results given in Refs. [46, 47] for \( d_n \) and the results given in Refs. [33, 34, 48] for \( d_{Hg} \). We found the contribution from the Weinberg operator is much smaller than the contributions from cEDMs. Thus, we ignore the contribution from the Weinberg operator in the following analysis.

Upper bounds on the electron EDM [49], the mercury EDM [50], and the neutron EDM [51] are

\[
|d_e| < 8.7 \times 10^{-29} \text{ e } \cdot \text{cm } (90\% \text{ C.L.}), \\
|d_{Hg}| < 7.4 \times 10^{-30} \text{ e } \cdot \text{cm } (95\% \text{ C.L.}), \\
|d_n| < 2.9 \times 10^{-26} \text{ e } \cdot \text{cm } (90\% \text{ C.L.}).
\]

We note that the constraint from the thallium EDM [52] is in practice equivalent with that to the electron EDM [53–56]. Prospects for the electron and neutron EDMs are

\[
|d_e| = 1 \times 10^{-30} \text{ e } \cdot \text{cm } \text{[57, 58]}, \\
|d_n| = 2.5 \times 10^{-29} \text{ e } \cdot \text{cm } \text{[59]}.
\]

Let us consider the parameter dependence of the electron EDM in the MSSM. The quark EDM has the similar dependence to the electron EDM. In our setup, the EDMs are generated by the diagrams shown in Figs. 1 and 2. First, we see the one-loop contributions, where SUSY contributions are given by slepton-electroweakino loop diagrams. The relevant diagrams which give leading order contributions are shown in Fig. 1. The contribution from each diagram depends on the SUSY parameter as follows:

\[
\begin{align*}
&d_e^{(N1)} \propto \text{Im}(M^2_{eLR} M_1), \\
&d_e^{(N2)} \propto \text{Im}(\mu M_1), \\
&d_e^{(N3)} \propto \text{Im}(\mu M_1), \\
&d_e^{(N4)} \propto \text{Im}(\mu M_2), \\
&d_e^{(C)} \propto \text{Im}(\mu M_2),
\end{align*}
\]

with

\[
M^2_{eLR} = A^*_e m_e - \mu m_e \tan \beta .
\]

At the two-loop level, Barr-Zee diagrams shown in Fig. 2 give significant contributions. We can see that (WW) diagram is strongly suppressed compared to the other diagrams because it has not only a chirality suppression by the electron mass but also a suppression by double mass insertion in the loop. Contribution from each diagram depends on the SUSY parameter as follows:

\[
\begin{align*}
&d_e^{(H1)} \propto \text{Im}(\mu M_2), \\
&d_e^{(H2)} \propto \text{Im}(M^2_{fLR\mu}), \\
&d_e^{(H3)} \propto \text{Im}(M^2_{fLR\mu}), \\
&d_e^{(ZH)} \propto \text{Im}(\mu M_2), \\
&d_e^{(WH1)} \propto \text{Im}(\mu M_2), \\
&d_e^{(WH2)} \propto \text{Im}(\mu M_2), \\
&d_e^{(WW)} \propto \text{Im}(\mu M_2),
\end{align*}
\]
with

\[
M_f^{2}_{LR} = \begin{cases} 
A_t^* m_t - m_t \mu \cot \beta & f = t, \\
A_f^* m_f - m_f \mu \tan \beta & f = b, \tau.
\end{cases}
\] (3.20)

\[
\begin{array}{cc}
\gamma & \tilde{e}_L \\
\tilde{e}_L & \bar{B} \\
\bar{B} & \tilde{e}_R \\
\tilde{e}_R & \gamma
\end{array}
\] (N1)

\[
\begin{array}{cc}
\gamma & \tilde{e}_L \\
\tilde{e}_L & \bar{H}^0 \\
\bar{H}^0 & \tilde{e}_R \\
\tilde{e}_R & \gamma
\end{array}
\] (N2)

\[
\begin{array}{cc}
\gamma & \tilde{e}_L \\
\tilde{e}_L & \bar{W}^0 \\
\bar{W}^0 & \tilde{e}_R \\
\tilde{e}_R & \gamma
\end{array}
\] (N3)

\[
\begin{array}{cc}
\gamma & \tilde{\nu}_L \\
\tilde{\nu}_L & \bar{W}^\pm \\
\bar{W}^\pm & \tilde{e}_R \\
\tilde{e}_R & \gamma
\end{array}
\] (N4)

\[
\begin{array}{cc}
\gamma & \tilde{e}_L \\
\tilde{e}_L & \bar{B} \\
\bar{B} & \tilde{e}_R \\
\tilde{e}_R & \gamma
\end{array}
\] (C)

Figure 1: Diagrams for leading-order contributions to the electron EDM at the one-loop level.

In our benchmark case, the one-loop contributions are strongly suppressed by large selectron and sneutrino masses, and the two-loop Barr-Zee diagrams provide dominant contributions unless Wino, stop, and sbottom masses are heavy enough to be decoupled. In the diagrams (H2) and (H3), the stop and sbottom loops dominate the contribution, because the color factor enhances it and the Yukawa couplings are larger than the other sfermions. In the diagrams (H1), (ZH), (WH1) and (WH2), the leading order contributions are given by the Wino and the Higgsino loops so that these diagrams are decoupled when the Wino mass \( M_2 \) becomes larger.

We discuss the \( \phi_\mu \) and \( \phi_{M_2} \) dependence of the EDMs. The left panels in Fig. 3 shows the electron EDM, the mercury EDM, and the neutron EDM with \( \phi_{M_1} = 0 \). The shaded regions are already excluded by the current upper bound on the EDMs. We find the combination of the
electron EDM and the mercury EDM exclude the large region of the parameter space. Both $\phi_\mu$ and $\phi_{M_1}$ cannot be large. We also find that the electron EDM strongly depends on $\phi_{M_2}$. On the other hand, $\phi_{M_2}$ dependence of the mercury EDM and the neutron EDM are milder. We focus on $M_1$ dependence by comparing the left panels and the right panels in Fig. 3 where $M_1 = 1$ TeV and 2 TeV, respectively. We find that larger $M_1$ weaken the constraint from EDM experiments because $M_1$ is approximately the mass of the dark matter candidate here and heavy Higgs bosons and Higgsinos become heavier if we take larger $M_1$.

The $\phi_{M_1}$ dependence can be seen in Fig. 4. After taking into account the constraint from the mercury EDM, we find that the mercury EDM and the neutron EDM are almost independent of
electron EDM is important for determining $\phi$ and blue shaded regions are excluded by the electron EDM and the mercury EDM, respectively. The dashed lines show the negative values. The red and blue shaded regions are excluded by the electron EDM and the mercury EDM, respectively. The electron EDM has mild but visible dependence on $\phi_M$. Thus the electron EDM is important for determining $\phi_M$.

Most of the parameter space in Figs. 3 and 4 are within the future prospects of the electron
Figure 4: The EDMs for $M_1 = 1$ TeV and $\tan \beta = 30$. In the left (right) panels, $\phi_{M_2} = 0^\circ$ ($30^\circ$). The shadings and contours are the same as in Fig. 3.

EDM and the neutron EDM shown in Eqs. (3.15) and (3.16). The neutron and the mercury EDMs are sensitive to $\phi_\mu$, and also weakly depend on $\phi_{M_2}$. On the other hand, the electron EDM is sensitive to $\phi_{M_2} + \phi_\mu$, and weakly depend on $\phi_{M_1}$. Therefore, we can determine the three CP phases by using the correlation among the EDMs measured in future experiments.

We next discuss the decoupling property for larger $M_2$. Figure 5 shows the EDMs for $M_2 =$
100 TeV and 200 TeV. Comparing with the right panels in Fig. 3, we find that larger $M_2$ drastically reduce the values of the EDMs. In particular, the electron EDM is sensitive to the $M_2$ choice but the mercury EDM is not. This property can be understood as follows. The dominant contribution to the electron EDM is the $H^0_i-\gamma-\gamma$ Barr-Zee diagram, where Wino loop gives the main contribution. On the other hand, the dominant contribution to the mercury EDM which originates from the quark EDMs is $H^0_i-g-g$ Barr-Zee diagram, and the diagram is independent of Wino contribution. In Figs. 6 and 7 we show how each contribution to the electron EDM and to the down quark cEDM is decoupled for a larger value of $M_2$.

3.2. DM-nucleon scattering cross section

Since we are working in the Higgs funnel scenario, the DM candidate couples to neutral scalar bosons. The DM candidate and nucleon interact with each other through these couplings. The couplings are rather small because of the funnel scenario. However, the couplings lead to a significant size of the spin-independent cross section which is within future prospects of the DM direct detection experiments.

There is also a Z-exchange diagram that generates spin-dependent cross section. This coupling depends on the mixing between Bino-Higgsino and Bino-Wino in the Bino-like DM scenario. The mixings are suppressed by the soft breaking neutralino mass parameters. We find that this coupling is so small that the resultant spin-dependent cross section $\sigma_{SD} = \mathcal{O}(10^{-8})$ pb is smaller than the prospect [60]. In the following, we focus on the spin-independent cross section. Figure 8 shows the $\phi_{M_2}$ and $\phi_\mu$ dependence of $\sigma_{SI}$ where its parameter choice is the same as in Fig. 3. Figure 9 shows the $\phi_{M_1}$ and $\phi_\mu$ dependence of $\sigma_{SI}$ with the same parameter choice as in Fig. 4. We find that the spin-independent cross section is smaller than the current upper bound [13, 14, 16] in all the region of the parameter space but within the prospects of the DARWIN [60], the DarkSide-20k [61], and the LZ [62]. We also find that the scattering cross section depends on $\phi_{M_1} + \phi_\mu$, and the $\phi_{M_2}$ dependence is not important. Since $|M_2|$ is much larger than $|M_1|$ and $|\mu|$ in our analysis, the sector related to dark matter physics is approximately the Bino-Higgsino system, and thus the scattering cross section weakly depends on $\phi_{M_2}$. In the Bino-Higgsino system, there is only one physical CP phase. This is the reason why the scattering cross section depends on one combination of the CP phases, $\phi_{M_1} + \phi_\mu$. 

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4. SUMMARY

In this paper, we have estimated EDMs of the electron, the neutron, and the mercury as well as the DM-nucleon scattering cross section and shown the present constraints and prospects in the
Bino-like neutralino DM with the heavy Higgs funnel scenario in the CP-violating MSSM. In our analysis, we have fixed soft SUSY breaking parameters of stops to be $O(10)$ TeV and $\tan \beta = 30$ to reproduce the measured SM-like Higgs boson mass and other sfermion masses to be 100 TeV in order to be decoupled from low energy observables.

With such SUSY particle mass spectrum, we have shown that CP violating phases of $O(10)^{\circ}$ in the gaugino and Higgsino mass parameters are currently allowed. Future experiments will be able to constrain those phases at $O(1)^{\circ}$ level if the results are null. We also pointed out that those EDMs have different phase dependence. For instance, the electron EDM mostly depends on one combination $\phi_{M_2} + \phi_\mu$, while the neutron and mercury EDMs do on mostly $\phi_\mu$ and weakly $\phi_{M_2}$. Once a few non-vanishing EDMs will be measured, it is possible to estimate individual CP phases.

We also have calculated the dependence of spin-independent cross section of the DM in our scenario. In fact, the non-vanishing CP violation effects change the cross section just by a factor. The predicted scattering cross section with a nucleon is within the sensitivity of future experiments.

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[1] J. L. Lopez, D. V. Nanopoulos and X. Wang, Phys. Rev. D 49, 366 (1994) [hep-ph/9308336].
[2] U. Chattopadhyay and P. Nath, Phys. Rev. D 53, 1648 (1996) [hep-ph/9507386].
[3] T. Moroi, Phys. Rev. D 53, 6565 (1996) Erratum: [Phys. Rev. D 56, 4424 (1997)] [hep-ph/9512396].
[4] H. Goldberg, Phys. Rev. Lett. 50, 1419 (1983) Erratum: [Phys. Rev. Lett. 103, 099905 (2009)].
[5] J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive and M. Srednicki, Nucl. Phys. B 238, 453 (1984).
[6] J. R. Ellis, S. Ferrara and D. V. Nanopoulos, Phys. Lett. 114B, 231 (1982).
[7] W. Buchmuller and D. Wyler, Phys. Lett. 121B, 321 (1983).
[8] J. Polchinski and M. B. Wise, Phys. Lett. 125B, 393 (1983).
[9] M. Dugan, B. Grinstein and L. J. Hall, Nucl. Phys. B 255, 413 (1985).
[10] P. Nath, Phys. Rev. Lett. 66, 2565 (1991).
[11] Y. Kizukuri and N. Oshimo, Phys. Rev. D 45, 1806 (1992).
[12] D. S. Akerib et al. [LUX Collaboration], Phys. Rev. Lett. 112, 091303 (2014) [arXiv:1310.8214 [astro-ph.CO]].

[13] D. S. Akerib et al. [LUX Collaboration], Phys. Rev. Lett. 118, no. 2, 021303 (2017) [arXiv:1608.07648 [astro-ph.CO]].

[14] E. Aprile et al. [XENON Collaboration], Phys. Rev. Lett. 119, no. 18, 181301 (2017) [arXiv:1705.06655 [astro-ph.CO]].

[15] A. Tan et al. [PandaX-II Collaboration], Phys. Rev. Lett. 117, no. 12, 121303 (2016) [arXiv:1607.07400 [hep-ex]].

[16] X. Cui et al. [PandaX-II Collaboration], Phys. Rev. Lett. 119, no. 18, 181302 (2017) [arXiv:1708.06917 [astro-ph.CO]].

[17] N. Nagata and S. Shirai, JHEP 1501, 029 (2015) [arXiv:1410.4549 [hep-ph]].

[18] M. Drees and M. M. Nojiri, Phys. Rev. D 47, 376 (1993) [hep-ph/9207234].

[19] H. Baer and M. Brhlik, Phys. Rev. D 53, 597 (1996) [hep-ph/9508321].

[20] H. Baer and M. Brhlik, Phys. Rev. D 57, 567 (1998) [hep-ph/9706509].

[21] V. D. Barger and C. Kao, Phys. Rev. D 57, 3131 (1998) [hep-ph/9704403].

[22] J. R. Ellis, T. Falk, G. Ganis, K. A. Olive and M. Srednicki, Phys. Lett. B 510, 236 (2001) [hep-ph/0102098].

[23] G. Belanger, O. Kittel, S. Kraml, H.-U. Martyn and A. Pukhov, Phys. Rev. D 78, 015011 (2008) [arXiv:0803.2584 [hep-ph]].

[24] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267, 195 (1996) [hep-ph/9506380].

[25] P. Draper and H. Rzehak, Phys. Rept. 619, 1 (2016) [arXiv:1601.01890 [hep-ph]].

[26] B. C. Allanach and A. Voigt, arXiv:1804.09410 [hep-ph].

[27] T. Falk, K. A. Olive and M. Srednicki, Phys. Lett. B 354, 99 (1995) [hep-ph/9502401].

[28] P. Gondolo and K. Freese, JHEP 0207, 052 (2002) [hep-ph/9908390].

[29] M. E. Gomez, T. Ibrahim, P. Nath and S. Skadhaue, Phys. Rev. D 70, 035014 (2004) [hep-ph/0404025].

[30] T. Nihei and M. Sasagawa, Phys. Rev. D 70, 055011 (2004) Erratum: [Phys. Rev. D 70, 079901 (2004)] [hep-ph/0404100].

[31] S. Y. Choi and Y. G. Kim, Phys. Lett. B 637, 27 (2006) [hep-ph/0602109].

[32] G. Belanger, F. Boudjema, S. Kraml, A. Pukhov and A. Semenov, Phys. Rev. D 73, 115007 (2006) [hep-ph/0604150].

[33] D. A. Demir, O. Lebedev, K. A. Olive, M. Pospelov and A. Ritz, Nucl. Phys. B 680, 339 (2004) [hep-ph/0311314].

[34] K. A. Olive, M. Pospelov, A. Ritz and Y. Santosos, Phys. Rev. D 72, 075001 (2005) [hep-ph/0506106].

[35] U. Chattopadhyay, T. Ibrahim and P. Nath, Phys. Rev. D 60, 063505 (1999) [hep-ph/9811362].

[36] T. Falk, A. Ferstl and K. A. Olive, Phys. Rev. D 59, 055009 (1999) Erratum: [Phys. Rev. D 60, 119904 (1999)] [hep-ph/9806413].

[37] T. Falk, A. Ferstl and K. A. Olive, Astropart. Phys. 13, 301 (2000) [hep-ph/9908311].
[38] S. Y. Choi, S. C. Park, J. H. Jang and H. S. Song, Phys. Rev. D 64, 015006 (2001) [hep-ph/0012370].
[39] T. Abe, R. Kitano and R. Sato, Phys. Rev. D 91, no. 9, 095004 (2015) Erratum: [Phys. Rev. D 96, no. 1, 019902 (2017)] arXiv:1411.1335 [hep-ph].
[40] T. Abe, Phys. Lett. B 771, 125 (2017) arXiv:1702.07236 [hep-ph].
[41] B. C. Allanach et al., Comput. Phys. Commun. 180, 8 (2009) arXiv:0801.0045 [hep-ph].
[42] D. Barducci, G. Belanger, J. Bernon, F. Boudjema, J. Da Silva, S. Kraml, U. Laa and A. Pukhov, Comput. Phys. Commun. 222, 327 (2018) [arXiv:1606.03834 [hep-ph]].
[43] J. S. Lee, M. Carena, J. Ellis, A. Pilaftsis and C. E. M. Wagner, Comput. Phys. Commun. 184, 1220 (2013) [arXiv:1208.2212 [hep-ph]].
[44] T. Abe, J. Hisano and R. Nagai, JHEP 1803, 175 (2018) arXiv:1712.09503 [hep-ph].
[45] G. Degrassi, E. Franco, S. Marchetti and L. Silvestrini, JHEP 0511, 044 (2005) [hep-ph/0510137].
[46] D. A. Demir, M. Pospelov and A. Ritz, Phys. Rev. D 67, 015007 (2003) [hep-ph/0208257].
[47] K. Fuyuto, J. Hisano, N. Nagata and K. Tsumura, JHEP 1312, 010 (2013) arXiv:1308.6493 [hep-ph].
[48] J. R. Ellis, J. S. Lee and A. Pilaftsis, JHEP 0810, 049 (2008) arXiv:0808.1819 [hep-ph].
[49] J. Baron et al. [ACME Collaboration], Science 343, 269 (2014) arXiv:1310.7534 [physics.atom-ph].
[50] B. Graner, Y. Chen, E. G. Lindahl and B. R. Heckel, Phys. Rev. Lett. 116, no. 16, 161601 (2016) Erratum: [Phys. Rev. Lett. 119, no. 11, 119901 (2017)] arXiv:1601.04339 [physics.atom-ph].
[51] C. A. Baker et al., Phys. Rev. Lett. 97, 131801 (2006) [hep-ex/0602020].
[52] B. C. Regan, E. D. Commins, C. J. Schmidt and D. DeMille, Phys. Rev. Lett. 88, 071805 (2002).
[53] Z. W. Liu and H. P. Kelly, Phys. Rev. A 45, R4210 (1992).
[54] A.-M. Martensson-Pendrill, Methods in Computational Chemistry, Volume 5: Atomic, Molecular Properties, ed. S. Wilson (Plenum Press, New York 1992).
[55] E. Lindroth, A.-M. Martensson-Pendrill, Europhys. Lett. 15, 155 (1991).
[56] M. Pospelov and A. Ritz, Annals Phys. 318, 119 (2005) [hep-ph/0504231].
[57] D. M. Kara, I. J. Smallman, J. J. Hudson, B. E. Sauer, M. R. Tarbutt and E. A. Hinds, New J. Phys. 14, 103051 (2012) arXiv:1208.4507 [physics.atom-ph].
[58] D. Kawall, J. Phys. Conf. Ser. 295, 012031 (2011).
[59] A. Lehrach, B. Lorentz, W. Morse, N. Nikolaev and F. Rathmann, arXiv:1201.5773 [hep-ex].
[60] J. Aalbers et al. [DARWIN Collaboration], JCAP 1611, 017 (2016) arXiv:1606.07001 [astro-ph.IM].
[61] C. E. Aalseth et al., Eur. Phys. J. Plus 133, no. 3, 131 (2018) doi:10.1140/epjp/i2018-11973-4 arXiv:1707.08145 [physics.ins-det].
[62] D. S. Akerib et al. [LUX-ZEPLIN Collaboration], arXiv:1802.06039 [astro-ph.IM].
Figure 6: Contributions to the electron EDM from each diagram. The solid green and blue curved lines are the contributions from the one-loop diagrams with chargino and neutralino, respectively. The dashed orange, dashed black, and dashed blue curved lines are the contributions from the Barr-Zee diagrams with $H^-\gamma\gamma$, $W^\pm H^{\mp}\gamma$, and $W^+W^-\gamma$ effective vertices, respectively, where $H$ denotes three neutral Higgs bosons.
Figure 7: Contributions to the down quark chromo-EDM from each diagram. The solid green, blue, and orange curved lines are the contributions from the one-loop diagrams with chargino, neutralino, and gluino, respectively. The dashed yellow curved lines are the contributions from the Barr-Zee diagrams with $H-g-g$. 
Figure 8: The DM-nucleon scattering cross sections for $\tan \beta = 30$ and $\phi_{M_1} = 0^\circ$. The left (right) panel is for $|M_1| = 1$ TeV (2 TeV). The shadings are the same as in Fig. 3.

Figure 9: The DM-nucleon scattering cross sections for $M_1 = 1$ TeV and $\tan \beta = 30$. The left (right) panel is for $|\phi_{M_2}| = 0^\circ$ (30°). The shadings are the same as in Fig. 3.