Magnetic Properties of Scalar Particles — the Scalar Aharonov-Casher Effect and Supersymmetry

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Abstract

The original topological Aharonov-Casher (AC) effect is due to the interaction of the anomalous magnetic dipole moment (MDM) with certain configurations of electric field. Naively one would not expect an AC effect for a scalar particle for which no anomalous MDM can be defined in the usual sense. In this letter we study the AC effect in supersymmetric systems. In this framework there is the possibility of deducing the AC effect of a scalar particle from the corresponding effect for a spinor particle. In 3+1 dimensions such a connection is not possible because the anomalous MDM is zero if supersymmetry is an exact symmetry. However, in 2+1 dimensions it is possible to have an anomalous MDM even with exact supersymmetry.

Having demonstrated the relationship between the spinor and the scalar MDM, we proceed to show that the scalar AC effect is uniquely defined. We then compute the anomalous MDM at the one loop level, showing how the scalar form arises in 2+1 dimensions from the coupling of the scalar to spinors. This model shows how an AC effect for a scalar can be generated for
non-supersymmetric theories, and we construct such a model to illustrate the mechanism.

The study of topological phases has provided a deep understanding of quantum systems. A particularly interesting case of a topological phase is the Aharonov-Bohm (AB) effect, discovered in 1959 by Aharonov and Bohm [1]. The AB effect has been observed experimentally [2]. In 1984 Aharonov and Casher discovered [3] another configuration where a topological phase can develop, giving rise to what is now called the Aharonov-Casher (AC) effect. This effect has also been observed experimentally [4]. The original AC effect was for a particle with spin and a non-zero anomalous magnetic dipole moment (MDM) interacting with a two dimensional electric field perpendicular to the spin polarization direction. It was realized that spin 1/2 is a particularly simple and instructive case, but the AC effect and other related effects have also been studied for particles with different spins [5–11].

For a spin-1/2 particle the interaction responsible for the AC effect is given by the following anomalous MDM interaction,

\[ L_m = -\frac{1}{2} \mu \bar{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu}. \]  

The topological phase \( \theta_{AC} \) developed when the particle travels along a closed path that encircles a line charge of strength \( \Lambda \) per unit length is \( \theta_{AC} = \mu \Lambda \).

In general it is possible for a particle with a non-zero anomalous MDM to have an AC effect. One would naively think that there should be no such an effect for a spin-0 particle because there there is no MDM, anomalous or otherwise. This naive expectation may not hold in 2+1 dimensions, where anomalous MDM interaction can be interpreted as an interaction of a current with the dual electric field, as was first pointed out by Stern [12], and noted in the context of the AC effect for general spins by us [11]. With this interaction for a spin-0 particle, an AC like effect can be defined. This is a very suggestive way of identifying new topological effects. However one still can not be sure that the topological nature of the spin-0 case has the same origin as the spin-1/2 case. In this paper we address the question of whether a spin-0 particle can have an AC effect from the point of view of supersymmetry.
We find indeed that a spin-0 particle can have an AC effect in 2+1 dimensions. This will enable us to discuss the AC effect for a spin zero particle in more general situations.

We note that Carrington and Kunstatter [13] followed up Stern’s suggestion and showed that, in Maxwell-Chern-Simons scalar QED in 2+1 dimensions, a magnetic interaction added to the bare Lagrangian leaves the theory renormalisable at the one loop level. They also studied the AC effect of this interaction in the non-relativistic approximation. However, they also showed in a later paper [14], that at two loop level the scalar theory with a primitive magnetic interaction is not renormalisable at the two loop level. This non-renormalisability is not a difficulty for us, because we use the MDM interaction added to the Lagrangian as an effective Lagrangian to demonstrate the supersymmetric connection of the anomalous MDM of the scalar and the spinor, and never use it to generate higher order contributions. We will then discuss two renormalisable models in which the scalar magnetic moment is generated at one loop level, just as the Schwinger anomalous magnetic moment of the electron is generated in QED in 3+1 dimensions. These are

1. Supersymmetric Maxwell-Chern-Simons theory, and

2. QED of Yukawa coupled spin 1/2 and spin 0 particles.

In these models the gauge and the Yukawa couplings have dimensions of \(\text{mass}^{1/2}\), so both of our models are super-renormalisable, and have no ultra-violet divergences. The Chern-Simons masses of the photon (and photino when present), with the masses of the matter particles, ensure that the theory is not infra-red divergent either [15].

In this paper we show that the scalar magnetic dipole moment interaction leads exactly to the AC effect in 2+1 dimensions — the non-relativistic approximation is not required. Carrington and Kunstatter also observed, in the non-relativistic limit, that the charged scalar particle with a magnetic interaction can exhibit anomalous statistics, the scalar equivalent of the result obtained by us [6] for Dirac particles in 2+1 dimensions without the non-relativistic approximation. Our result on spin-1/2 particles, can be adapted \textit{mutatis mutandis} to apply to the spin-0 interactions considered here, and shows that the possibility of anomalous
statistics is also an exact result for charged scalar particles with magnetic interactions in 2+1 dimensions.

In supersymmetry, the spinor (spin-1/2) and the scalar (spin-0) particles are partners. If certain effects exist for a spinor, there should be corresponding effects for the scalar superpartner. Therefore one would expect that there must be an AC effect for a spin-0 particle. This turns out to be not automatically true. In fact it was shown some time ago that in 3+1 dimensions, if supersymmetry is exact, no anomalous MDM can exist for a spinor [16]. Of course, in nature supersymmetry is broken, so there can be a non-zero anomalous MDM for a spinor and therefore an AC effect. The corresponding effect for the scalar superpartner need not exist because supersymmetry is broken. However this result holds only in 3+1 dimensions. In 2+1 dimensions with exact supersymmetry, a spinor can have an anomalous MDM and therefore the associated AC effect. Because supersymmetry is exact, one can uniquely identify the corresponding AC effect for the scalar superpartner.

In 3+1 dimensions with supersymmetry, a matter field is assigned to a chiral superfield \( \Phi \) which contains the spinor \( \psi \) and scalar \( \phi \) as component fields [17]

\[
\Phi = \phi(z) + \sqrt{2}\theta\psi(z) + \theta\theta F(z),
\]

where \( z_\mu = x_\mu + i\theta\sigma_\mu\theta \). \( \theta \) is the anti-symmetric spinor coordinates of the superfield. \( F \) is an auxiliary field which can be eliminated by the use of the equations of motion.

The gauge superfield \( V \) in the Wess-Zumino gauge is given by [17]

\[
V = -\theta\sigma_\mu\bar{\theta}A^\mu(x) + i\theta\theta\bar{\lambda}(x) - i\bar{\theta}\theta\lambda(x) + \frac{1}{2}\theta\theta\bar{\theta}\theta D(x),
\]

where \( A^\mu \) is the usual gauge field, \( \lambda \) is the gaugino field and \( D \) is an auxiliary field.

The usual anomalous MDM interaction of 3 + 1 dimensions is contained in the superfield effective Lagrangian [16]

\[
\bar{L}_m = ig\Phi^* D_\alpha \Phi W^{\alpha},
\]

where \( D_\alpha = \partial/\partial\theta^\alpha + i\sigma^\mu_{\alpha\beta}\bar{\theta}^\beta \partial_\mu \), \( W^{\alpha} = (-1/4)\bar{D}\bar{D}D^{\alpha}V \) with \( \bar{D}_\alpha = -\partial/\partial\bar{\theta}^\alpha - i\theta^\alpha \sigma^{\mu}_{\alpha\beta} \partial_\mu \).
Expanding $\tilde{L}_m$ in terms of $\theta$, one would obtain [16]

$$\tilde{L}_m = E + \chi \theta + \bar{\psi} \tilde{\theta} + M \theta \theta + J_{\mu} \theta \sigma^\mu \theta + \bar{\xi} \tilde{\theta} \theta \theta. \quad (5)$$

The anomalous MDM interaction can be contained only in the $M$ term. This can be seen easily from a dimensional analysis argument. The anomalous MDM interaction is a dimension 5 operator composed of fields and derivatives. Inspection of $\tilde{L}_m$, shows that only the $M$ term is of dimension 5. However the superfield Lagrangian $\tilde{L}_m$ is not a chiral field, so the $M$ term, even being a F-term type, can not appear in the supersymmetric Lagrangian density. There is no way one can obtain a supersymmetric anomalous MDM in $3+1$ dimensions.

In $2+1$ dimensions the situation changes dramatically. It is possible to have a supersymmetric anomalous MDM. In this case the matter field $\Phi$, the gauge field, and the corresponding $W^\alpha$ are given by

$$\begin{align*}
\Phi(x_\mu, \theta) &= \phi(x) + \theta^\lambda \psi_\lambda(x) - \frac{1}{2} \epsilon_{\lambda\tau} \theta^\lambda \theta^\tau F(x), \\
V^\alpha(x_\mu, \theta) &= i\theta^\beta (\gamma^\mu A_\mu(x))_\beta^\alpha - \epsilon_{\lambda\tau} \theta^\lambda \theta^\tau \lambda^\alpha(x), \\
W^\alpha &= \frac{1}{2} D^\beta D^\alpha V_\beta, \quad D_\alpha = \frac{\partial}{\partial \theta^\alpha} + i\theta^\beta \epsilon_{\alpha\delta} (\gamma^\mu \partial_\mu)^\delta.
\end{align*} \quad (6)$$

Here $\epsilon_{\alpha\beta}$ is the totally anti-symmetric tensor with $\epsilon_{12} = 1$.

In $2+1$ dimensions, the anomalous MDM interaction has dimension 7/2. The superfield effective Lagrangian which contains the anomalous MDM in $2+1$ dimensions, given by

$$\tilde{L}_m = \Phi^* W_\alpha \Delta^\alpha \Phi, \quad (7)$$

(with $\Delta^\alpha = D^\alpha - ieV^\alpha$), has dimension 5/2. Expanding in terms of the $\theta$, we have

$$\tilde{L}_m = A + B\theta + C\theta\theta. \quad (8)$$

The $C$ term has dimension 7/2 which has the right dimension for the anomalous MDM interaction and is also supersymmetric. Therefore in $2+1$ dimensions it is possible to have an anomalous MDM interaction and also the associated AC effect in a supersymmetric
theory. Since the interaction is supersymmetric, it is possible to identify uniquely the scalar AC effect. In the following we provide the detailed calculation to obtain the form of scalar AC effect interaction.

The supersymmetric Maxwell Lagrangian for the gauge and matter kinetic energies, and gauge and matter interactions is given by

$$L = \int d^2 \theta \left[ \frac{1}{4} W^\alpha W_\alpha + \frac{1}{2} (\Delta^\alpha \Phi)^* (\Delta_\alpha \Phi) - m \Phi^* \Phi \right], \quad (9)$$

which gives

$$L = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} + \frac{1}{2} i \bar{\lambda} \gamma^\mu \partial_\mu \lambda + \bar{\psi} i \gamma^\mu D_\mu \psi - m \bar{\psi} \psi + (D^\mu \phi)^* (D_\mu \phi) + L_F$$

$$+ i e \bar{\lambda} \phi - i e \bar{\lambda} \psi^* \phi^*. \quad (10)$$

Here $D^\mu = \partial^\mu - ie A^\mu$ is the gauge covariant derivative. $L_F$ contains the $F$ term and is given by

$$L_F = F^* F - (m F^* \phi + m \phi^* F). \quad (11)$$

Using the equation of motion for $F$, $F^* = m \phi^*$ and $F = m \phi$ to eliminate the auxiliary field $F$, one obtains the scalar mass term

$$L_F = -m^2 \phi^* \phi. \quad (12)$$

A straightforward calculation demonstrates that gauge invariant Chern-Simons mass terms, which have the superfield form

$$L_{cs} = \frac{M_{cs}}{8} \int d^2 \theta V^\alpha W_\alpha \quad (13)$$

are generated at one loop level. Integrating out the Grassman variables,

$$L_{cs} = + \frac{M_{cs}}{2} \epsilon^{\mu \nu \lambda} A_\mu \partial_\nu A_\lambda - \frac{M_{cs}}{2} \bar{\lambda} \lambda. \quad (14)$$

There is no symmetry principle to forbid the introduction of this $P$ and $T$ violating term, given that we have already introduced a violation of Parity and Time reversal invariance.
in the mass term for the spin-1/2 particles. We therefore allow it to appear in the bare Lagrangian, which is now referred to as a super-Maxwell-Chern-Simons theory.

A non-zero anomalous MDM interaction is represented by the introduction of a new superfield term, of the form $\Phi^* W^{\alpha} \Delta_\alpha \Phi$, to the effective Lagrangian. We will return to discuss how this term is generated in the perturbation expansion of the vertex function in the theory, but for the moment we introduce it into the effective Lagrangian and show how it leads to an AC effect for the scalar.

\[ L_m = ig \int d^2 \theta \Phi^* W^{\alpha} \Delta_\alpha \Phi = -\frac{1}{2} g \bar{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu} - is \epsilon^{\mu\nu\lambda} F_{\mu\nu} \phi^* D\lambda \phi \\
+ 2eg \bar{\lambda} \lambda \phi^* \phi - g \bar{\lambda} \gamma^\mu \psi (D^\mu \phi)^* - g \bar{\psi} \gamma^\mu \lambda (D^\mu \phi) - ig \bar{\psi} \lambda F + ig \bar{\lambda} \psi F^*. \quad (15) \]

Here $s = \pm$ is defined as $\gamma^\mu \gamma^\nu = g^{\mu\nu} + is \epsilon^{\mu\nu\lambda} \gamma^\lambda$.

Eliminating the auxiliary field we obtain the full Lagrangian

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} i \bar{\lambda} \gamma^\mu \partial_\mu \lambda \\
+ \bar{\psi} i \gamma^\mu D^\mu \psi - m \bar{\psi} \psi + (D^\mu \phi)^* (D^\mu \phi) - m^2 \phi^* \phi + i e \bar{\psi} \lambda \phi - ie \bar{\lambda} \psi \phi^* \\
- \frac{1}{2} g \bar{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu} - is \epsilon^{\mu\nu\lambda} F_{\mu\nu} \phi^* D\lambda \phi \\
+ 2eg \bar{\lambda} \lambda \phi^* \phi - g \bar{\lambda} \gamma^\mu \psi (D^\mu \phi)^* - g \bar{\psi} \gamma^\mu \lambda (D^\mu \phi) \\
- ig^2 \bar{\psi} \lambda \bar{\lambda} \bar{\psi} -igm \bar{\psi} \lambda \phi +igm \bar{\lambda} \psi \phi^* + \frac{M_{cs}}{2} \epsilon^{\mu\nu\lambda} A_{\mu} \partial_\nu A_\lambda - \frac{M_{cs}}{2} \bar{\lambda} \lambda. \quad (16) \]

The first term proportional to $g$ in the above equation contains the usual anomalous MDM term $\bar{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu}$ for a spinor with $g = \mu$ compared with Eq.(1). This term is responsible for the AC effect of a spin-1/2 particle. We identify the second term proportional to $g$ in the above equation to be the corresponding AC effect term for a scalar particle.

To see the topological nature of these terms we note that they can be written as

\[ L_{AC} = \frac{g}{2} s F^{\mu\nu} \epsilon_{\mu\nu\lambda} \bar{J}_F^\lambda - \frac{g}{2} s F^{\mu\nu} \epsilon_{\mu\nu\lambda} \bar{J}_S^\lambda, \quad (17) \]
where \( j_F^\lambda = \bar{\psi} \gamma^\lambda \psi \), and \( j_S^\lambda = i(\phi^* D^\lambda \phi - (D^\lambda \phi^*) \phi) \) are the current of the spinor and the scalar, respectively.

In general the interaction \( F^{\mu \nu} \epsilon_{\mu \nu \lambda} j^\lambda \) generates a topological phase regardless of the specific value of the spin of the particle if the AC conditions required for the electric field is satisfied. This can be seen by studying the change of the action \( \Delta S \) of the system due to \( L_{AC} \), for a closed trajectory from time 0 to time T for a point particle with velocity \( \vec{v} \propto \vec{j} \).

The topological phase generated for the spinor is given by [11]

\[
\theta_{AC}^F = -\frac{1}{2} g \int_0^T F^{\mu \nu} \epsilon_{\mu \nu \lambda} j_F^\lambda = -g \int_0^T (\vec{S} \cdot \vec{v}) dt = -g \oint \vec{S} \cdot d\vec{r} = g \Lambda. \tag{18}
\]

In the above \( S_\mu = (1/2) \epsilon_{\mu \alpha \beta} F^{\alpha \beta} \). In the AC electric field configuration, \( S_\mu = (0, E_2, -E_1) \).

Similarly one obtains a topological phase \( \theta_{AC}^S \) for the scalar when the AC conditions are satisfied with \( \theta_{AC}^S = -g \Lambda \). We note that the topological phases developed for the spinor and scalar are the same in size and opposite in sign.

Having shown that the term of eq. (15), which contains a supersymmetric anomalous MDM interaction, give an AC effect for the scalar, we now turn to discuss how such an interaction can be naturally generated from the well known interactions of eq. (9) itself.

To this end we study the radiative correction of spinor-photon, and scalar-photon interactions at the one loop level starting with the Lagrangian in eq. (10). This theory the anomalous MDM, absent at tree level, can be generated at one loop level, in just the same way that the Pauli magnetic moment interaction is generated at one loop level in QED in 3+1 dimensions. The relevant diagrams are shown in Figure 1. Figure 1.a is the usual QED diagram generating an anomalous MDM for a spinor. Due to supersymmetric interactions, there is an additional diagram, Figure 1.b, contributing to the anomalous MDM for a spinor. Evaluating these two diagrams, we obtain an effective \( g \) in eq. (16) with

\[
g = \frac{e^3}{16 \pi m^2} \int_0^1 dx \int_x^1 \frac{y dy}{(y^2 - x(y - x)q^2/m^2)^{3/2}}, \tag{19}
\]

where \( q \) is the photon momentum. Ferrara and Remiddi [16] showed that in 3+1 dimensions these two contributions canceled, but we find that in 2+1 dimensions this cancellation does not happen.
The above result is logarithmically infrared divergent when $q^2$ approaches zero because of the absence of a Chern-Simons mass. In the presence of the Chern-Simons mass, the theory is free from infrared divergence. In this theory a Chern-Simons term will be generated at one loop level from eq. (10). The inclusion of these contributions leads to two modifications to eq. (19). The first is that the Chern-Simons term, representing a non-zero mass $M_{cs}$ for the photon and photino, modifies the denominator of eq. (19) to $(y^2+(1-x)M_{cs}^2/M^2-x(y-x)q^2/m^2)^{3/2}$ and $g$ is infrared divergent free. Another modification is that the diagram of Figure 1.a (or of Figure 1.c) also contributes to the magnetic moment, because of the term in the propagator proportional to $M_{cs}\epsilon_{\mu\nu\lambda}q^\lambda/q^2$ whose contributions have been calculated by Kogan [19]. We do not include the Chern-Simons contribution to $g$ in our calculation, as (unless the bare Chern-Simons mass is non-vanishing) it is generated at the one loop level in perturbation theory from the Lagrangian of eq. (9) and $M_{CS}$ is of order $e^2m$. Thus its contribution to $g$ is of order $e^5m$, whereas the magnetic moment of eq. (19) is of order $e^3m$.

There are similar radiative corrections to scalar-photon couplings. These are shown in

FIG. 1. Feynman diagrams for the anomalous MDM.
Figures 1.c and 1.d. Evaluating these diagrams, we indeed find the second term proportional to \( g \) in eq. (16) with the same \( g \) as in eq. (19) generated, as expected. The source for a non-zero contribution to \( g \) of order \( e^3m \) in this case is purely Figure 1.d. This is quite different from the spinor case where Figures 1.a and 1.b both contribute to the anomalous MDM at this order. As remarked in the previous paragraph, and reference [19], a Chern-Simons mass term gives rise to a scalar anomalous MDM from Figure 1.c, but this contribution is of order \( e^5m \).

It is clear that the scalar AC effect in the above example is generated by the Yukawa coupling of a scalar with two spinors, Figure 1.d. In 3+1 dimensions, such an interaction can not generate an AC effect for a scalar. This shows that the AC effect is intrinsically a 2+1 dimensional effect. Supersymmetry then provides the link between the spinor and scalar AC effects. With this understanding one can easily construct a model which generates a topological AC effect for a scalar in a non-supersymmetric theory by introducing Yukawa couplings with at least one of the spinor having non-zero electric charge. For example, a Yukawa interaction of the type

\[
L_Y = a \bar{\psi}_1 \psi_2 \phi + H.C.
\]  

will generate a non-zero \( g \) through a diagram of the type of Figure 1.d.

\[
g = \frac{|a|^2 e_1}{16\pi^2 m^2} \int_0^1 dx \int_x^1 \frac{[(m_1/m_\phi + m_2/m_\phi) y - m_2/m_\phi] dy}{[y^2 - x(y - x)q^2/m^2 + m^2 + m^2/(m_\phi - y(1 - (m_1^2 - m_2^2)/m^2))]^{3/2}}
\]

\[
+ (m_1 \rightarrow m_2, m_2 \rightarrow m_1, e_1 \rightarrow e_2),
\]

where \( m_{1,2,\phi} \) are the masses of \( \psi_{1,2} \) and \( \phi \), \( e_{1,2} \) are the electric charges of \( \psi_{1,2} \), respectively. The above equation reduces to Eq. (19) when \( m_1 = m_\phi = m, e_1 = e, \) and \( m_2 \) and \( e_2 \) are both set to zero, as expected.

We emphasize that, in our models the scalar magnetic moment interaction is generated by one loop corrections, and does not appear in the primary Lagrangian, as assumed in the work of Carrington and Kunstatter [13]. We therefore escape the problem that a scalar magnetic moment in the primary Lagrangian gives non-renormalisable contributions at two loop level.
To summarize we have studied the supersymmetric AC effect. In 3+1 dimensions, if supersymmetry is exact, no anomalous MDM interaction can exist. But in 2+1 dimensions, we find that a non-zero anomalous MDM interaction is possible. The related topological effect for a scalar is identified which is due to scalar current interaction with the dual of electric field. Since the Aharonov-Casher effect is essentially a phenomenon of two spatial dimensions, we conclude that there is an Aharonov-Casher effect for a spin-0 particle. This effect can be easily generated at one loop level through Yukawa couplings.

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