A New Technique for Detecting Supersymmetric Dark Matter

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We estimate the event rate for excitation of atomic transition by photino-like dark matter. For excitations of several eV, this event rate can exceed naive cross-section by many orders of magnitude. Although the event rate for these atomic excitation is smaller than that of nuclear recoil off of non-zero spin nuclei, the photons emitted by the deexcitation are easier to detect than low-energy nuclear recoils. For many elements, there are several low-lying states with comparable excitation rates, thus, spectral ratios could be used to distinguish signal from background.

The composition of most of the mass in our Galaxy is not known. Dynamical estimates of the mass of the Galaxy suggests that it exceeds the mass in luminous stars, gas and dust by an order of magnitude. This problem is not unique to our Galaxy, but appears ubiquitous: as dynamical estimates of the density of the universe suggest that it is also an order of magnitude larger than the baryon density inferred from light element abundances and big bang nucleosynthesis. Thus, most of our Galaxy may be composed not of ordinary baryonic matter but of some exotic non-baryonic component.

Supersymmetry, an elegant and well-studied extension of the standard model of particle physics, suggests a particle physics solution to this astronomical quandary. In the minimal supersymmetric model, the neutralino, the lightest mass eigenstate that carries a new conserved charge, R parity, may be stable. This particle, a linear combination of the photino, higgsino and zino interaction eigenstates, would have been created in the early universe and can be stable. For a wide range of parameters in the minimal supersymmetric model, its density would exceed the density in baryons.

In the past few years, a series of experiments at LEP and Fermilab appear to hint that supersymmetry may be real and that the supersymmetry scale may be just beyond that probed by the current generation of accelerators. In grand unified theories (GUTs) based solely on the standard model, \( \sin^2 \theta_W \), the electroweak mixing angle, is predicted to be \( 0.215 \pm 0.002 \), while in SUSY GUTs, it is predicted to be \( 0.233 \pm 0.002 \). These predictions were made at a time in which this angle was known to lie between 0.2 and 0.25. Experiments
at LEP find$^9 \sin^2 \theta_W = 0.233 \pm 0.001$, 10 $\sigma$ away from the standard model prediction. In SUSY GUTs, the top mass is predicted$^{10,11}$ to be between 170 and 190 GeV, while GUTs based on the standard model predict a top mass around 220 GeV. Recent experiments (CDF Collaboration, Fermilab-PUB-94/097-E) at the Fermilab Tevatron imply a top quark mass of $174 \pm 15$. These experimental hints strengthen the motivation to search for supersymmetric dark matter.

If the neutralino did indeed compose most of the mass of the Galaxy, then the flux of $(10^7 \text{GeV}/m_x)$particles/cm$^2$/s is potentially detectable. (Here, $m_x$ is the neutralino mass.) The electron interacts primarily with the photino component of the neutralino via the exchange of scalar selectrons, $\tilde{e}$. Neutralinos interact with quarks predominately through the exchange of scalar quarks, $\tilde{q}$ and scalar higgsinos, $\tilde{h}$. In the non-relativistic limit, appropriate for dark matter particles moving in our galaxy at $v \sim 300$ km/s, the scattering amplitude for the interaction with electrons, $\tilde{M} \simeq \frac{4e^2}{M_\tilde{e}} S_{\tilde{e}} \cdot S_e$, where $S_{\tilde{e}}$ is the photino spin, $S_e$ is the electron spin, $e$ is the electron charge and $M_\tilde{e}$ is the selectron mass. The scattering amplitude for quarks$^{12}$ is similar with the electron charge, spin and selectron mass replaced by the quark charge, spin and squark mass. Unlike squark exchange, the higgsino exchange is spin independent and thus is important scattering off of low spin nuclei.

Searches for neutralinos have attempted to detect their scattering elastically off of nuclei through squark exchange. This elastic scattering event deposits several keV of kinetic energy in the nucleus. In a solid state detector, this kinetic energy is converted into electron-hole pairs and phonons, which are potentially detectable in a sensitive low background detector. Because of the low event rate and the tiny energy deposition, this is a very challenging experiment. The difficulty of this experiment is further compounded by the limited range of materials that can be used: neutralino scattering cross-sections are suppressed in materials with an even number of protons. Despite heroic effort, the experimental limits on weakly interacting dark matter have not significantly improved in the decade since these experiments were proposed and are still several orders of magnitude away from the parameter range relevant for supersymmetric dark matter.

In this letter, we explore an alternative approach to detecting neutralinos: detecting their inelastically exciting atomic states. This possibility has not been carefully explored in the past as a naive estimate of the cross-section would suggest that it is suppressed relative to nuclear scattering by the square of the ratio of $m_e$, the mass of the electron, to $m_n$, the mass of the nucleus. As we will show in this letter, there are several mitigating factors that balance this $4 \times 10^6 A^2$ suppression factor: (1) there is a kinematic enhancement of $\mathcal{O}((\Delta E/v_\tilde{e})/(m_\tilde{e} v_\tilde{e}))^2$ $\simeq \mathcal{O}(10^{-2} (\alpha f_s c/v)^3) \simeq 10^2$ (the $10^{-2}$ being an approximate numerical factor due to the higher overlap integrals for smaller $\Delta E$’s): (2) the electron charge is either $(3/2)$ or 3 times larger
than the quark charge, leading to an enhancement of up to 3^4; (3) the selectron mass is expected to be significantly smaller that the squark mass, this enhances the atomic scattering processes by another factor of perhaps 2^4; (4) the possibility of exciting in a given atom any of the outer shell electrons to one of several possible states can lead to an enhancement in the overall event rate by another factor of a few. These four factors, when combined, enhance the cross-section by a factor of few \times 10^5 and makes this process worthy of more detailed study.

Atomic excitation may also have several experimental advantages over nuclear scattering. As several different energy levels are excited at predictable rates, neutralino should have a clean experimental signature. In nuclear recoil interactions, neutralinos couple only to nuclei with non-zero spin, a relatively limited set of materials can be used in these experiments. A much broader class of materials can be used in an atomic excitation experiment and a broader class of detection techniques are available for detecting several eV photons.

As the electron-photino interaction can be approximated as point-like, the cross-section for exciting an atom from from an initial state with wave function \( \psi_1 \) and energy \( E_1 \) to a final state with wave function \( \psi_2 \) and energy \( E_2 \), the cross section is easily calculated:

\[
\sigma = \frac{4e^4}{m_e^4} | < f | \hat{S}_e | i > |^2 \int d^3q \int d^3q' N | \int d^3r \int d^3r' \psi_1(\vec{r})\psi_2^*(\vec{r}') e^{i(\vec{q}_N - \vec{q}')} \cdot \vec{r} e^{-i\vec{q}N(1+m_e/m_N) \cdot \vec{r}_N} \times \delta(3)(\vec{r}_N - \vec{r}_e))^2 2\pi \delta(E_N - E_1 - (E_2 - E_1)) .
\]

Here \( \vec{r} = \vec{r} - \vec{r}_N \), (un)primed quantities refer to the (initial) final state, and we have neglected the motion of the nucleus relative to the atomic center of mass. We have also approximated the electron-photino interaction as pointlike, which is valid for \( m_e >> E \).

Using \( \delta(3)(\vec{r}_N - \vec{r}_e) \), we eliminate the integral over \( d^3r_N \). The integral \( d^3r_N \) gives a delta function of 3-momentum; which is used to eliminate the \( d^3q' \) integral. The remaining energy delta function is used to do the integral \( d\cos\theta_N \) over the angle between the outgoing nuclear recoil momentum and the incoming photino momentum. We are left finally with

\[
\sigma \simeq \frac{4e^4}{2\pi m_e^4} | < f | \hat{S}_e | i > |^2 \int_{q_{min}}^{q_{max}} q_N dq_N \left| \int d^3r \psi_1(\vec{r})\psi_2^*(\vec{r'}) e^{i\vec{q}_N \cdot \vec{r}} \right|^2 .
\]

Here \( q_{min} \simeq (E_2 - E_1)/v_\gamma \) and \( q_{max} \simeq 2m_N\beta_\gamma \) are the maximum and minimum nuclear recoil momenta allowed by kinematics, obtained by enforcing \( |\cos\theta_N| \leq 1 \).

Assuming that a Gaussian distribution for the dark matter particles impinging on the Earth, \( f(v) = \)
\[
\exp\left(\frac{(\vec{v} - \vec{v}_e)^2}{2\Sigma^2}\right) \text{ yields an average interaction rate:}
\]
\[
<\sigma v> \approx \frac{2}{\pi} |<f|\vec{S}|i>|^2 \frac{16\pi^2\alpha^2}{m_e^2\alpha^0} \frac{c}{\Sigma} g_{ij} \mathcal{J}
\]
\[
\approx 2.75 \times 10^{-33} \text{ events atom}^{-1} \text{ day}^{-1} \mathcal{J} g_{ij} \left(\frac{m_e}{100\text{GeV}}\right)^2 \left(\frac{\rho_{\text{DM}}}{1\text{GeV cm}^{-3}}\right) \left(\frac{250\text{km/s}}{\Sigma \sqrt{2}}\right)
\]
\[
\approx 1.7 \text{ events kT}^{-1} \text{ day}^{-1} \mathcal{J} g_{ij} \left(\frac{m_e}{100\text{GeV}}\right)^2 \left(\frac{\rho_{\text{DM}}}{1\text{GeV cm}^{-3}}\right) \left(\frac{\rho_{\text{detector}}}{1\text{g cm}^{-3}}\right) \left(\frac{250\text{km/s}}{\Sigma \sqrt{2}}\right)
\]

\(g_{ij}\) is the product of the (average) occupation number of the initial state, \(o_i (0 \leq o_i \leq 1)\) and \(1 - o_f\). All of
the atomic structure is contained in the factor, \(\mathcal{J} \leq O(1)\), and can be can be calculated numerically from
\[
\mathcal{J} = \frac{\sigma}{\sqrt{2}v_e} \int_0^\infty a^2 dq q \int d^3r \psi_1(\vec{r}) \psi_2^*(\vec{r}) e^{i\vec{q} \cdot \vec{r}}^2 \times
\]
\[
x \left\{ \text{erfc} \left[ \max \left( \frac{\Delta E}{q\sigma\sqrt{2}}, \frac{q}{\sigma\sqrt{2}m_N}\sigma \right) - \frac{v_e}{\sigma\sqrt{2}} \right] - \text{erfc} \left[ \max \left( \frac{\Delta E}{q\sigma\sqrt{2}}, \frac{q}{\sigma\sqrt{2}m_N}\sigma \right) + \frac{v_e}{\sigma\sqrt{2}} \right] \right\}
\]

using numerical wave functions for any atom (or molecule) of interest. We have calculated \(\mathcal{J}\) for a variety
of transitions in selected atoms. For energy levels separated by a few eV, \(\mathcal{J}\) is between 0.1 and 1 for most
atomic states. When these excited states decay emitting few eV photons, these photons may be more easily
detectable than the phonons and electron-hole pairs produced through nuclear scattering.

Any experiment that seeks to detect the rare photons produced by neutralino excitation of atoms faces
several challenges. The detector will have to be very massive, very quiet, and placed in a low-background
environment such as the Gran Sasso tunnel. It will have to be cooled to a temperature less than \(135(E/\text{eV})^{-1}\)
to avoid thermal photon background. The atom will have to deexcite predominantly by spontaneous decay
(with the emission of a photon) and not by collisional de-excitation. The material will have to be transparent
enough so that the photon is not degraded through reabsorption followed by collisional deexcitation. This
concern may be addressed by focusing on those transitions which frequently decay to the ground state by
a cascade of two or more photons, rather than directly. In this case only the last of these photons would
resonantly re-excite the ground state; while the others would scatter mostly elastically.

There are, on the other hand, several sources of encouragement for the experiment. In many materials,
the event rates are interesting for excitation to excited states. Thus, there are potentially several different
lines that may be detectable. The event rate in each of the lines will be annually modulated by the motion
of the Earth around the Sun with an amplitude that varies in a predictable way from line-to-line. In many
atoms and molecules, there are a variety of fine structure splitting states and isoelectronic states separated
from the ground state by a few eV. Thus, there is a wide variety of materials that can be used in the detector.
The authors will provide to interested experimentalists (or collaborate with them in the calculation of) event rates in various materials.

While the current generation of scintillator detectors designed for solar neutrino work do not appear to be sensitive to the eV photons discussed here, there are a wide variety of detectors that can be used. In some materials, in which the electron orbitals are aligned along a particular direction, such as liquid crystals, there is the possibility of a directional dependence in the signal.

The challenge to experimental physicists, material scientists and chemists is to identify low noise eV detectors for large volume targets. The potential reward is the ability to detect the material that composes most of the mass of the Galaxy and find the first Supersymmetric particle.

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