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# SENSITIVITY OF DARK MATTER DECTECTORS TO SUSY DARK MATTER

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**Abstract**

The sensitivity of dark matter detectors to the lightest neutralino ($\tilde{Z}_1$) is considered within the framework of supergravity grand unification with radiative breaking of SU(2)xU(1). The relic density of the $\tilde{Z}_1$ is constrained to obey $0.10 \leq \Omega_{\tilde{Z}_1} h^2 \leq 0.35$, consistent with COBE data and current measurements of the Hubble constant. Detectors can be divided into two classes: those most sensitive to spin dependent incoherent scattering of the $\tilde{Z}_1$ (e.g. $CaF_2$) and those most sensitive to spin independent coherent scattering (high A nuclei e.g. Pb). The parameter space is studied over the range of $100GeV \leq m_0, m_{\tilde{g}} \leq 1\, TeV; 2 \leq tan\beta \leq 20$; and $-2 \leq A_t/m_0 \leq 3$ and it is found that the latter type detector is generally more sensitive than the former type. Thus at a sensitivity level of $R \geq 0.1$ events/kg da, a lead detector could scan roughly 30% of the parameter space studied, and an increase of this sensitivity by a factor of 10 would lead to coverage of about 70% of the parameter space. Dark matter detectors are in general more sensitive to the high $tan\beta$, low $m_{\tilde{g}}$ and low $m_0$ parts of the parameter space. The conditions of radiative breaking of SU(2)xU(1) enter importantly in analysing the efficiency of dark matter detectors.

([1]Talk at Lake Louise Winter Institute - 1994.)



## 1. Introduction

There is strong astronomical evidence for the existance of dark matter both within our galaxy and in other galaxies and galactic clusters. A large number of candidates for dark matter have been proposed both in particle physics (neutralinos, neutrinos, sneutrinos, axions, etc.) and in astronomy (brown dwarfs, neutron stars, black holes, Jupiters, etc.). For supersymmetric theories with R parity invariance, the lightest supersymmetric particle (the LSP) is stable. For most SUSY models and for most of the parameter space

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of these models the LSP is the lightest neutralino, the $\tilde{Z}_1$. The dark matter (DM) for such SUSY models would then be the relic $\tilde{Z}_1$ of the big bang which now exist in the halo of the Galaxy (and explain the rotation curves of matter in the Galaxy). These particles would then impinge on DM detectors. What we will discuss here is the ability of such detectors to see these $\tilde{Z}_1$.

Models based purely on cold dark matter (CDM) appear to be inconsistent with the COBE and other data, and a mix with hot dark matter (HDM) in the ratio of $\simeq 2:1$ yields a satisfactory model. (A candidate for HDM might be massive neutrinos). In addition there can be baryonic dark matter (B) at the $\lesssim$ 10% level. Defining $\Omega_i = \rho_i/\rho_c$, where $\rho_i$ is the mass density of the $i^{th}$ constituent and $\rho_c$ is the critical mass density to close the universe, then a reasonable mix is

$$\Omega_{\tilde{Z}_1} \simeq 0.6; \quad \Omega_{HDM} \simeq 0.3; \quad \Omega_B \simeq 0.1 \tag{1}$$

What can be determined theoretically, however, is $\Omega_{\tilde{Z}_1} h^2$ where h = H/(100 km/s Mpc) and H is the Hubble constant. Measurements of h give the range $h \simeq 0.5 - 0.75$. Hence one has

$$\Omega_{\tilde{Z}_1} h^2 \cong 0.1 - 0.35 \tag{2}$$

In the following we will assume Eq. (2) is the allowed band of values for $\Omega_{\tilde{Z}_1} h^2$. These bounds strongly restrict the parameter space of SUSY models, and hence will constrain the predictions of the SUSY DM detector efficiencies. Eq. (2) represents estimated bounds on $\Omega_{\tilde{Z}_1} h^2$ and we will see that the results are a little sensitive to the lower bound. However, lowering this bound generally will raise the detection rates, and so Eq. (2) gives a conservative estimate of event rates.

## 2. Supergravity Gut Models

In order to calculate $\Omega_{\tilde{Z}_1} h^2$, one needs to specify the SUSY model. We will use here supergravity GUT models [1]. There are a number of advantages to this choice:

1. These models are consistent with the LEP results on unification of the gauge coupling constants at the GUT scale $M_G \approx 10^{16} GeV$.

2. They generate electroweak breaking naturally by radiative corrections i.e. using the renormalization group equations (RGE) starting at scale $Q = M_G$ one finds a Higgs $(mass)^2$ turning negative at $Q \approx M_Z$.

3. They depend on only four new parameters, in contrast to the low energy MSSM which usually is chosen to have 20 new parameters (and could have as many as 137!).

In SUSY models one needs two Higgs doublets ($H_1$ and $H_2$) to cancel anomalies and to give rise to masses for both u and d quarks. Running the RGE from $M_G$ down to the electroweak scale and minimizing the Higgs potential with respect to $\langle H_{1,2}\rangle$ one obtains two electroweak breaking equations,

$$\frac{1}{2}M_Z^2 = \mu^2 + \frac{\mu_1^2 - \mu_2^2 tan^2\beta}{tan^2\beta - 1}; \quad sin2\beta = \frac{2m_3^2}{2\mu^2 + \mu_1^2 + \mu_2^2} \tag{3}$$

where $tan\beta \equiv \langle H_2\rangle/\langle H_1\rangle, \mu_i^2 = m_{H_i}^2 + \Sigma_i, m_{H_i}$ are the running Higgs masses, $\Sigma_i$ are loop corrections and $\mu$ is the running Higgs mixing parameter (which enters in the superpotential as $-\mu H_1 H_2$). Then all SUSY masses, widths cross sections etc., can be determined from four parameters and the sign of $\mu$. These may be chosen as $m_0$ (universal soft breaking spin zero mass); $m_{\tilde{g}}$ (gluino mass); $A_t$ (t-quark cubic soft breaking parameter) and $tan\beta$. One limits the range of these parameters by imposing the experimental lower bounds of LEP and the Tevatron on the SUSY masses, and also we will require $m_0, m_{\tilde{g}} < 1\ TeV$ so that no extreme fine tuning of parameters will occur.

Since there are 32 new SUSY particles and only 4 parameters, there is considerable constraint in the system. Two predictions that result which are relevant to dark matter is an upper bound on the $\tilde{Z}_1$ mass and a lower bound on $tan\beta$:

$$m_{\tilde{Z}_1} \lesssim 150 GeV; \quad tan\beta > 1 \tag{4}$$

## 3. Calculation of $\tilde{Z}_1$ Relic Density

For models with R parity, the $\tilde{Z}_1$ is absolutely stable. However, the primordial $\tilde{Z}_1$ can annihilate in the early universe, the main diagrams being shown in Fig. 1. We consider the simplest approximation [2] where at high temperature the $\tilde{Z}_1$ is in equilibrium with the background. When the annihilation rate falls below the expansion rate of the universe, freezeout occurs at temperature $T_f$. The $\tilde{Z}_1$ are disconnected from the background and then continue to annihilate. Thus the larger the annihilation rate, the smaller the final relic density. The current relic density is [2]

Fig. 1 Annihilation diagrams of $\tilde{Z}_1$

$$\Omega_{\tilde{Z}_1} h^2 \cong 2.5 \times 10^{-11} (T_{\tilde{v}\rangle dx} \tag{5}$$

Here $\langle \quad \rangle$ means thermal average and $\sigma$ is the annihilation cross section at relative velocity $v$. Freezeout generally occurs when the $\tilde{Z}_1$ is non-relativistic i.e. $x_f \equiv kT_f/m_{\tilde{Z}_1} \simeq \frac{1}{20}$, and so the thermal average can be taken using the Boltzman distribution:

$$\langle \sigma v \rangle = \int_0^\alpha dvv^2 (\sigma v) exp[-v^2/4x] / \int_0^\alpha dvv^2 exp[-v^2/4x] \tag{6}$$

This has led in the past to using a non-relativistic expansion for $\sigma v$ i.e. $\sigma v \cong a + b(v^2/c^2) + ...$, with which it becomes trivial to take the thermal average. However, as has been pointed out [3], this expansion can be a bad approximation near a narrow s-channel pole, even though $v^2/c^2 << 1$. For the $\tilde{Z}_1$, the approximation turns out generally to be quite bad near the Higgs and $Z^0$ pole as indicated in Fig. 2 [4].

Note that the non-relativistic expansion for $\sigma v$ can fail over a wide range of $m_{\tilde{g}}$ (due to the smearing of the thermal averaging and often closeness of the h and Z poles.).

Fig. 2 $\Omega$approx/$\Omega$ vs $m_{\tilde{g}}$ for $m_0 = 700$ GeV, $tan\beta = 2.25, A_t = 0$, $\mu > 0$ and $m_t = 140$ GeV. $\Omega$approx is calculated using $\sigma v = a + bv^2$ while $\Omega$ is calculated by accurate evaluation of the integrals of Eqs. (6,7) numerically. The h and Z poles are where the curves go from positive to negative values.

In general, the allowed values of $\Omega_{\tilde{Z}_1}h^2$ of Eq.(2) are quite small, implying the need for a large amount of annihilation to occur. This happens in the regions of parameter space where $2m_{\tilde{Z}_1}$ is close to $m_h$ or $M_Z$ or when the slepton/squark masses are small (enhancing the t-channel poles). The former occurs commonly in many models, while the latter can occur when $m_0$ is small, as is the case in the no-scale models [4] (where $m_0$ is zero).

### 5. Expected Detector Event Rates

In the supergravity Gut models, the value of R depends on the point in this

$$100GeV \leq m_0, m_{\tilde{g}} \leq 1TeV; \quad -2m_0 \leq A_t \leq 3.5m_0; \quad 2 \leq tan\beta \leq 20 \qquad (7)$$

The parameter space is further restricted by the requirements that $(i) 0.10 \leq \Omega_{\tilde{Z}_1}h^2 \leq 0.35$, (ii) experimental bounds on SUSY masses from LEP and the Tevatron are not violated, and (iii) radiative breaking [Eq. (3)] of SU(2)xU(1) occurs. Event rates for the following detectors have been analyzed:

$$^3He; \quad ^{40}Ca^{19}F_2; \quad ^{76}Ge +^{73} Ge; \quad ^{71}Ga^{75}As; \quad ^{23}Na^{127}I; \quad ^{207}Pb \qquad (8)$$

The first two detectors have large spin dependent $\tilde{Z}_1$ scattering ($CaF_2$ being the largest) while the last four have increasingly large spin independent coherent $\tilde{Z}_1$ scattering. We will see that throughout most of the parameter space the heavy nuclei with large coherent scattering are more efficient detectors than those with the large spin dependent scattering.

While the different parameters of Eq. (17) which define the theory enter in many different places in the calculation (e.g. in calculating the relic density in Sec. 2, the $\tilde{Z}_1$ coefficients of Eq. (11), $A_q$, $B_q$ and $C_q$ of Eqs. (10), (13) etc.) it is possible to exhibit the general dependence of the event rate on them.

$m_{\tilde{g}}$ [GeV]

Fig. 4 R[Pb] (solid) and R [$CaF_2$] (dashed) vs $m_{\tilde{g}}$ for $tan\beta$=6 (lower curves) and $tan\beta$=20 (upper curves). $A_t$=1.5 $m_0$, $m_0$=100GeV, and $\mu > 0$.

Fig. 4 shows that the event rate decreases with the gluino mass, and that the Pb detector (largest coherent scattering) has considerably higher event rates than $CaF_2$ (largest spin dependent scattering). The decrease of R with $m_{\tilde{g}}$ arises from the fact that as $m_{\tilde{g}}$ increases, the $\tilde{Z}_1$ becomes more and more Bino, and one needs an interference between the Bino and Higgsino parts of $\tilde{Z}_1$ to generate sizable scattering in Eq. (13). Note also that the $tan\beta$=20 curve lies higher then the $tan\beta$=6 curve. This is in part due to the $1/cos\beta$ factor in the $C_d$ contribution of Eq. (13) yielding a $tan^2\beta$ dependence for the $C_d$ part of the coherent scattering. This behavior can be seen more explicitly in Fig. 5. At fixed $tan\beta, m_0$ has been chosen in Fig. 5 so that $\Omega_{\tilde{Z}_1}h^2$ is approximately equal for each curve. Thus Fig. 5 also shows that the event rate increases with $A_t$ for a fixed value of $\Omega_{\tilde{Z}_1}h^2$. The NaI curves lie higher than the Ge curves since $^{127}I$ has higher nuclear mass than $^{76}Ge +^{73} Ge$.

$tan\beta$

Fig. 5 R vs $tan\beta$ for NaI and Ge detectors for $m_{\tilde{g}} = 275GeV, \mu > 0$. The solid curve is for $A_t/m_0 = 0.0$, $m_0 = 200GeV$, dashed curve for $A_t/m_0 = 0.5$, $m_0 = 300GeV$, and dash-dot curve for $A_t/m_0 = 1.0$, $m_0 = 200GeV$. For each pair the upper curve is for NaI and the lower for Ge.

$m_0$[GeV]

Fig. 6 R vs $m_0$ for $m_{\tilde{g}} = 300GeV, A_t/m_0 = 0.5, tan\beta = 8, \mu > 0$. The dashed curve is for $CaF_2$, the solid curves (from bottom to top) are for Ge, NaI and Pb.

Fig. 6 shows that R decreases with $m_0$, as one might expect since the slepton pole contribution decreases. (Actually, the situation is more complicated as $m_0$ enters in the radiative breaking equations, Eq. (3), which determine $\mu$, and $\mu$ enters in the nuetralino mass matrix which determines $\alpha, \beta, \gamma, \delta$ of Eq. (11)). For the particular parameters chosen in Fig. 6, the incoherent spin-dependent scattering for the $CaF_2$ detector exceeds the coherent s cattering seen by the other detectors. (This type situation rarely occurs). Note also that the Ge, NaI and Pb curves sequence themselves in the order of their atomic numbers.

Fig. 7 shows the maximum and minimum event rates for the $CaF_2$ and Pb detectors as a function of $A_t$ as one varies all other parameters over the entire parameter

Fig. 7 Maximum and minimum event rates of $CaF_2$ (dashed curve) and Pb (solid curve) detectors for $\mu > 0$ as one varies all parameters.

space: $2 \leq tan\beta \leq 20; 100GeV \leq m_0, m_{\tilde{g}} \leq 1TeV; -2 \leq A_t/m_0 \leq 3.5$. One sees that the Pb detector exceeds the $CaF_2$ detector in sensitivity by a factor of 5-10. The very large event rates all come from the largest $tan\beta$, while the minimum rates come from different smaller values of $tan\beta$ for different $A_t$. The expected rates for the other detectos (e.g. Ge, NaI etc.) scale approximately with the Pb detector by their atomic numbers.

## 6. Conclusions

We have examined here the expected sensitivity of dark matter detectors to udes the constraint of radiative breaking of SU(2)×U(1) as well as the requirement that $0.10 \leq \Omega_{\tilde{Z}_1} h^2 \leq 0.35$ consistent with the COBE data. Detectors fall into two catagories: those that are sensitive to the spin dependent incoherent $\tilde{Z}_1$ scattering (e.g. $CaF_2$) and those most senstive to the coherent scattering (e.g. Pb). The latter have event rates that increase with the nuclear mass, and hence favor heavy nuclei. We find in general that throughout almost all the parameter space, the latter type detectors are significantly more efficient than the former.

In general the dark matter detectors are more sensitive to the high $tan\beta$ and small $m_{\tilde{g}}$ part of the parameter space (and generally the small $m_0$ part). At the current expected sensitivity of $R > 0.1$ events/kg da, one can expect to examine about 20-30% of the parameter space (using high A nuclei) for $\mu > 0$. (The $\mu < 0$ event rates are generally smaller.) An increase in the sensitivity by a factor of 10 would enable these detectors to examine 60-70% of the parameter space. One would need a sensitivity of $R > 0.001$ events/kg da to cover the entire parameter space.

Since the assumption that the $\tilde{Z}_1$ is the cold dark matter is high r dark matter in part of the parameter space will be a significant aid in reducing the ambiguities that exist in supergravity Gut models.

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