Event Rates in Dark Matter Detectors for Neutralinos Including Constraints from $b \to s\gamma$ Decay

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Event rates for neutralino-nucleus scattering are studied including the constraint arising from the recent CLEO results on $b \to s\gamma$ using the cold hot dark matter (CHDM) model. It is found that the CLEO results strongly affect the supersymmetric spectrum and the event rates. The analysis given here uses the accurate method for the computation of the relic density and leads to a dip in the event rate when the neutralino mass is $\sim M_Z/2$ due to the Z pole and $\sim m_h/2$ due to the Higgs pole. The effect of the new Δq determinations on event rates is also discussed.

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The lightest neutralino, the $\tilde{Z}_1$, is a natural candidate for dark matter in supersymmetric theories with R parity invariance. The general method for calculating relic densities has been known for some time [1]. However, only recently have there been accurate calculations for supersymmetric models [2] that correctly take into account the important effects arising from narrow s-channel resonances [3]. For supersymmetry these are the h (light Higgs) and Z bosons, which if not correctly treated, can produce errors in the relic density of several orders of magnitude. The data from the Cosmic Background Explorer (COBE) satellite have put further constraints on the dark matter relic density. Assuming the inflationary scenario which requires $\sum \Omega_i = 1$, a reasonable mix is $\Omega_{\tilde{Z}_1} \simeq 0.6$, $\Omega_{\mathrm{HDM}} \simeq 0.3$ (consistent with the COBE data and the entire power spectrum of density fluctuations; HDM denotes hot dark matter), and $\Omega_B \simeq 0.1$. We find then the range $0.10 \leq \Omega_{\tilde{Z}_1} h^2 \leq 0.35$ for the theoretically relevant quantity $\Omega_{\tilde{Z}_1} h^2$, where $h = H/(100\ \mathrm{km/s\,Mpc})$ and H is the Hubble constant. (Astronomical observations give $h \cong 0.5-0.75$.) We shall label this solution the cold hot dark matter (CHDM) constraint. In this Letter we study the event rates for neutralino-nucleus scattering in supergravity unified models, using the accurate method for the computation of the relic density under the CHDM constraint given above and the experimental constraint from CLEO on the inclusive decay of $b \to s\gamma$ [4]:

$$B(b \to s\gamma) = (2.32 \pm 0.51 \pm 0.29 \pm 0.32) \times 10^{-14}. \tag{1}$$

(The first error is statistical; the second and the third errors are systematic due to uncertainty in yield and efficiency.) The analysis is carried out including a number of effects not generally taken into account, such as radiative breaking of the electroweak symmetry (which has been omitted in the analyses of Refs. [5,6]; only a brief mention of it appears in Ref. [7]) and the effect of heavy Higgs bosons, which, as pointed out by Kamionkowski in Ref. [5] and the authors of Ref. [7], can affect the event rates significantly. We also take into account one-loop effects on the Higgs boson mixing angle, as well as on the Higgs boson mass spectra. Another aspect of this analysis, which differentiates it from all the previous analyses of Refs. [5–7], is that we have used the accurate method for the computation of the relic density [2] and imposed the CHDM constraint and the constraint of Eq. (1), which can affect dark matter analyses significantly [8]. An analysis of the event rates without the constraint of Eq. (1) was given in Ref. [9], while an analysis including the constraint of Eq. (1) but in a different supersymmetry (SUSY) model and without the constraint of radiative electroweak symmetry breaking was given by Borzumati, Drees, and Nojiri in Ref. [8].

Dark matter detectors, which use elastic scattering of neutralinos off nuclei, involve the fundamental scattering process $\tilde{Z}_1 + q \to \tilde{Z}_1 + q$, which proceeds via a squark pole in the s channel and Z, h, H^0 poles in the t channel. The low-energy effective Lagrangian that governs this process is given by [10]

$$\mathcal{L}_{\mathrm{eff}} = \bar{\tilde{Z}}_1 \gamma_\mu \gamma_5 \tilde{Z}_1 \bar{q} \gamma^\mu (A_q P_L + B_q P_R) q + \bar{\tilde{Z}}_1 \tilde{Z}_1 m_q \bar{q} C_q q\,. \tag{2}$$

We display here the C_q, which exhibits explicitly the heavy Higgs boson contributions:

$$C_q^{\mathrm{Higgs}} = \frac{g_2^2}{4M_w} \left[\left\{ \begin{matrix} \frac{\cos\alpha}{\sin\beta} & \frac{F_h}{m_h^2} \\ -\frac{\sin\alpha}{\cos\beta} & \frac{F_h}{m_h^2} \end{matrix} \right\} + \left\{ \begin{matrix} \frac{\sin\alpha}{\sin\beta} & \frac{F_H}{m_H^2} \\ \frac{\cos\alpha}{\cos\beta} & \frac{F_H}{m_H^2} \end{matrix} \right\} \right]^{u\ \mathrm{quark}}_{d\ \mathrm{quark}} . \tag{3}$$

In Eq. (3), β is defined by $\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$, where H_2 gives mass to the up quark and H_1 gives mass to the down quark; α is the rotation angle that diagonalizes the CP-even Higgs boson (mass)^2 matrix. We have taken account of loop corrections to the Higgs boson mixing angle by

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including loop corrections to the Higgs boson $(\text{mass})^2$ matrix [11,12]. Further, in Eq. (3) the form factor F_H is given by $(n_1 - n_2 \tan\theta_W)(n_4 \sin\alpha - n_3 \cos\alpha)$ and F_h is given by $(n_1 - n_2 \tan\theta_W)(n_4 \cos\alpha + n_3 \cos\alpha)$, where θ_W is the weak angle and n_i $(i = 1,\dots,4)$ define the projection of the neutralino $\tilde{Z}_1$ into the four neutral states $\tilde{W}_3$, $\tilde{B}$, $\tilde{H}_1^0$ and $\tilde{H}_2^0$, i.e., $\tilde{Z}_1 = n_1 \tilde{W}_3 + n_2 \tilde{B} + n_3 \tilde{H}_1^0 + n_4 \tilde{H}_2^0$. The event rate in neutralino-nucleus scattering is then given by [5–7]

$$R = [R_{\text{coh}} + R_{\text{inc}}]\left[\frac{\rho_{\tilde{Z}_1}}{0.3\ \text{GeV}\,\text{cm}^{-3}}\right] \times \left[\frac{\langle v_{\tilde{Z}_1}\rangle}{320\ \text{km/s}}\right]\frac{\text{events}}{\text{kg day}}, \tag{4a}$$

where

$$R_{\text{coh}} = \frac{16 m_{\tilde{Z}_1} M_N^3 M_Z^4}{[M_N + m_{\tilde{Z}_1}]^2}\,|A_{\text{coh}}|^2, \tag{4b}$$

$$R_{\text{inc}} = \frac{16 m_{\tilde{Z}_1} M_N}{[M_N + m_{\tilde{Z}_1}]^2}\,\lambda^2 J(J+1)\,|A_{\text{inc}}|^2. \tag{4c}$$

Here $A_{\text{coh}} \sim C_q$, $A_{\text{inc}} \sim B_q - A_q$, J is the nucleus spin, and λ is determined via the magnetic moment of the nucleus. As discussed below, R_{inc} makes only a small contribution so our event rates do not depend sensitively on different determinations of λ (i.e., Ellis-Flores in Ref. [6] versus Ressel *et al.* in Ref. [5]). However, a significant source of uncertainty arises in A_{coh} which depends on the matrix element $\langle p|\bar{s}s|p\rangle$ which is uncertain by a factor of 2 leading to a similar uncertainty in the event rate.

In implementing the constraint of Eq. (1), we shall use the leading-order QCD calculation to compute the $b \rightarrow s\gamma$ branching ratio. To this order we have [13]

$$\frac{B(b \rightarrow s\gamma)}{B(b \rightarrow ce\bar{\nu})} = \frac{6\alpha}{\pi\rho\lambda}\frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2}\,|\bar{C}_7(m_b)|, \tag{5}$$

where ρ is the phase-space factor, λ is a QCD correction to the semileptonic decay, V_{ts} etc. are the Kobayashi-Maskawa matrix elements, and $\bar{C}_7(m_b)$ is the effective Wilson coefficient at scale m_b such that

$$\bar{C}_7(m_b) = \eta^{16/23} C_7(M_W) + \tfrac{8}{3}(\eta^{14/23} - \eta^{16/23}) C_8(M_W) + C_2, \tag{6}$$

where $\eta = \alpha_s(M_W)/\alpha_s(m_b)$, C_7 (C_8) are the Wilson coefficients for the photonic (gluonic) magnetic penguins, and C_2 is an operator mixing constant. This analysis is carried out in the framework of $N = 1$ supergravity grand unification [14]. We evolve the gauge, Yukawa, and soft SUSY-breaking terms using renormalization group equations from the grand unification scale M_G to the electroweak scale using supergravity boundary conditions and break the electroweak symmetry using radiative effects. Further, using data from the CERN e^+e^- collider (LEP) (on gauge coupling constants α_1, α_2, α_3 and on M_Z) we reduce the parameters of the theory to the following four: m_0, $m_{1/2}$, A_t, $\tan\beta$, and the sign of μ, where A_t is the value of A_0 at the electroweak scale. In the computation of the spin-dependent part of the event rate, i.e., R_{inc}, polarized quark densities Δu, Δd, and Δs enter. These have been determined using the experimental data from European Muon Collaboration [15], Spin Muon Collaboration [16], E142 [17], and E143 [18] experiments as well as the hyperon data [19]. Previous analyses using old data [15] give [6] $\Delta u = 0.77 \pm 0.08$, $\Delta d = -0.49 \pm 0.08$, and $\Delta s = -0.15 \pm 0.08$. The recent analysis of Ref. [20], which uses new data on polarized μ-p [16] and e-p [18] scattering, determines $\Delta u = 0.83 \pm 0.03$, $\Delta d = -0.43 \pm 0.03$, and $\Delta s = -0.10 \pm 0.03$ and is within 1 sigma of the previous determinations.

We have carried out the analysis of the event rates over the full parameter space of m_0, $m_{1/2}$, A_t, and $\tan\beta \leq 20$ for a number of target material over the domain where the maximum of the event rate is $\gtrsim 10^{-2}$ events/day. (This is the sensitivity one may hope for in current or planned dark matter detectors.) The targets examined include ^{3}He, ^{40}Ca^{19}F$_2$, ^{76}Ge + ^{73}Ge, ^{71}Ga^{75}As, ^{23}Na^{127}I, and ^{257}Pb. It is found that the effect of using the new [20] versus the old [6] values on the polarized quark densities Δu, Δd, and Δs can affect R_{inc} significantly, especially for the light target materials. However, the total change in the event rate is negligible ($\lesssim 1-2\%$) for heavy target material such as ^{76}Ge + ^{73}Ge and ^{257} Pb. The effect on the event rate for the light target material such as ^{40}Ca^{19}F$_2$ is $\lesssim 30\%$ over most of the parameter space. Thus estimates based on partial analyses which suggest large effects (as large as factors of 30) in Ref. [21] due to variations in quark polarizabilities do not actually materialize in the full analysis. One of the important results that emerges from the analysis is that the accurate method for the computation of relic density is very critical when the neutralino mass lies in the vicinity of $M_Z/2$ or lower. In this region the neutralino pairs annihilate rapidly via the Z pole and Higgs pole, often reducing the relic density below the CHDM limit and thus diminishing the region of the allowed parameter space consistent with the CHDM constraint. The eliminated part of the parameter space contains the region that yields large event rates. Consequently the use of the accurate method for relic density computations leads to a sharp dip in the event rate. In the gluino mass plot it implies a dip in the region of the $m_{\tilde{g}} = 250-400$ GeV. Results are exhibited in Figs. 1(a) and 1(b) where maxima and minima of event rates for CaF$_2$, Ge, and Pb over the allowed parameter space are plotted as a function of the gluino mass for $\mu > 0$ [Fig. 1(a)] and $\mu < 0$ [Fig. 1(b)]. Note that in Fig. 1 there is no clear dip due to the Higgs boson mass since all SUSY parameters except the gluino mass are allowed to vary over the permissible values. Once the Higgs boson mass is fixed there would also be a clear dip in the vicinity of $m_h/2$.

We discuss next the implications of the CLEO result for event rates. To see how significant the effect of Eq. (1) is, it is useful to define the ratio

$$r_{\text{SUSY}} = B(b \rightarrow s\gamma)_{\text{SUSY}}/B(b \rightarrow s\gamma)_{\text{SM}}. \tag{7}$$

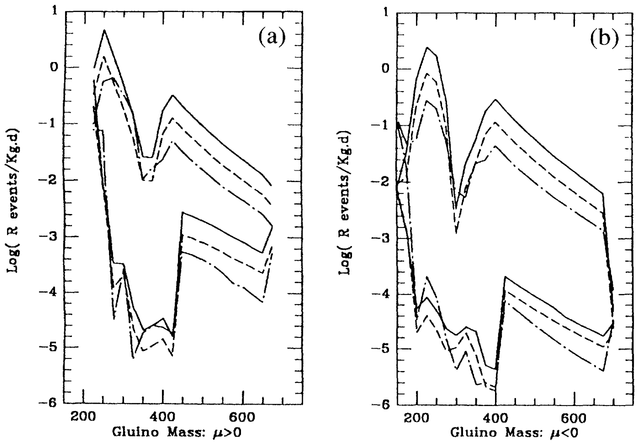

FIG. 1. (a) Maximum and minimum curves of event rates for CaF_2 (dash-dotted), Ge (dashed), and Pb (solid) as a function of gluino mass when $\mu > 0$ and all other parameters ($m_0, A_t, \tan\beta \le 20$) run over the allowed ranges; $m_t = 168$ GeV where m_t is the physical mass. The $b \rightarrow s\gamma$ constraint is not imposed. (b) Same as (a) for $\mu < 0$.

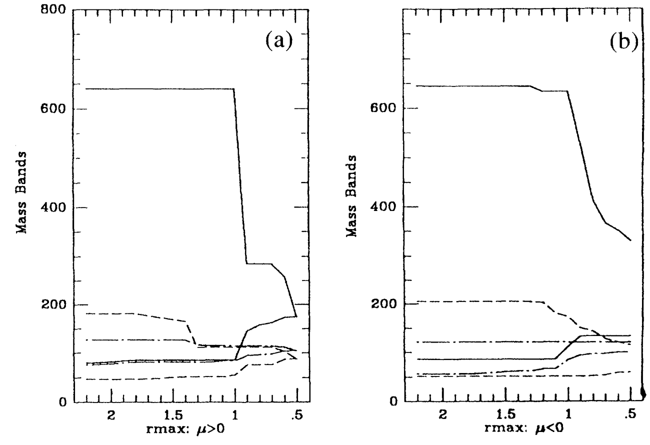

FIG. 2. (a) Mass bounds for the light Higgs boson (dash-dotted), chargino (dashed), and the lighter top squark (solid) as a function of $r_{\max}$ for $\mu > 0$ when all other parameters ($m_0, m_{\tilde{g}}, A_t, \tan\beta \le 20$) run over their allowed ranges; $m_t = 168$ GeV. (b) Same as (a) for $\mu < 0$.

One can also define $r_{\rm expt} = B(b \rightarrow s\gamma)_{\rm expt}/B(b \rightarrow s\gamma)_{\rm SM}$, where we use the experimental value of Eq. (1) in the numerator. Regarding the branching ratio for the standard model (SM) that enters in $r_{\rm expt}$, Ciuchini [22] has recently given an updated value of this quantity, partially taking into account the next-to-leading order (NLO) QCD corrections. They find for $B(b \rightarrow s\gamma)_{\rm SM}$ the branching ratio $(1.9 \pm 0.2 \pm 0.5) \times 10^{-4}$. However, this result is an average of two significantly different evaluations, one using the 't Hooft–Veltman (HV) regularization and the other using the naive dimensional reduction regularization (NDR). The significant difference between the HV and the NDR results seems to underline the importance of including the full set of next-to-leading order QCD corrections [23]. For this reason several workers prefer to use the $b \rightarrow s\gamma$ branching ratio in the SM based on consistent leading-order (LO) QCD correction only, pending the full analysis of NLO. A typical value that the SM gives in the LO approximation (as quoted in Ref. [4]) is $B(b \rightarrow s\gamma)_{\rm SM} = (2.75 \pm 0.8) \times 10^{-4}$. The range of $r_{\rm expt}$ obtained from the above determination of SM values is

$$r_{\rm expt} = 0.46-2.2\,. \qquad (8)$$

The value of $r_{\rm expt}$ is important in constraining the SUSY theory. We study the SUSY case under the assumption that $r_{\rm SUSY} = r_{\rm expt}$ and allow $r_{\rm SUSY}$ to vary in the interval $(0.46 - r_{\max})$, where $r_{\max}$ lies in the interval (0.46–2.2). An interesting phenomenon that appears is that the masses of the light spectra (the light neutral Higgs bosons, the charginos, and the top squarks) show a strong dependence on $r_{\max}$ for values of $r_{\max} \lesssim 1.5$. Specifically, one finds that the allowed mass bands for the light Higgs boson, the light chargino, and the light top squark become narrow. Results are shown in Fig. 2(a) ($\mu > 0$) and Fig. 2(b) ($\mu < 0$). The narrowing of the mass bands occurs because one needs light particles to move $r_{\max}$ below 1. Equation (8) gives a midvalue of $r_{\rm expt} = 1.33$. Figure 3 is a plot of the maximum and minimum values of event rates for CaF_2, Ge, and Pb as a function of the gluino mass when $r_{\rm SUSY} \le 1.33$. Comparison with Fig. 1 shows that there is a very significant effect of the $b \rightarrow s\gamma$ constraint on the event rate. For $\mu > 0$ the effect is more drastic than for $\mu < 0$ in that the maximum rates are significantly reduced. In Fig. 4, the maximum and the minimum event rate curves are plotted as a function of $r_{\max}$ in the range (0.46–2.2), where, for any given $r_{\max}$,

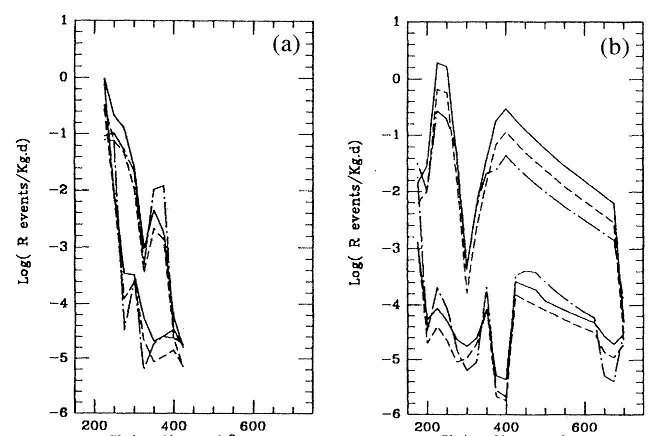

FIG. 3. (a) Same as Fig. 1(a) except that $r_{\max} \le 1.33$. Dependence of maximum and minimum event rates as a function of $r_{\max}$ is given in Fig. 4. (b) Same as (a) except that it is for $\mu < 0$.

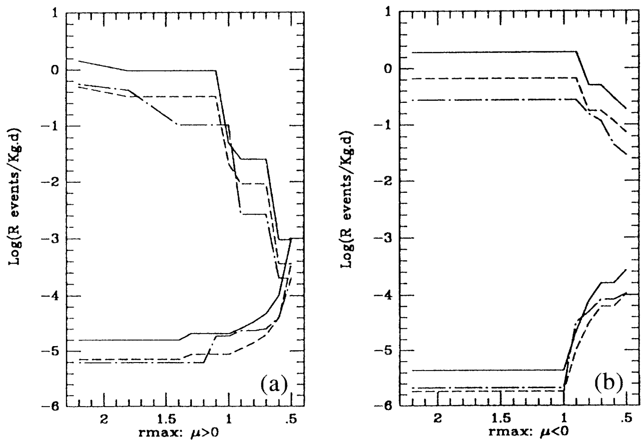

FIG. 4. (a) Same as Fig. 1(a) except that the plot is a function of $r_{\max}$ and $m_{\tilde{g}}$ runs over its allowed range. (b) Same as (a) except that $\mu < 0$.

$r_{\rm SUSY} \leq r_{\max}$. One finds that the maximum event rate shows a drastic reduction as $r_{\max}$ falls below 1.

In conclusion, we have exhibited in this paper the new phenomenon of a dip in the event rate when the neutralino mass lies in vicinity of $M_Z/2$ or in the vicinity of $m_h/2$. We also find that the CLEO result on the first measurement of the inclusive $b \rightarrow s\gamma$ decay branching ratio has the possibility of generating very significant effects on the SUSY spectrum and on the event rates if $r_{\rm expt}$ lies below the midpoint given by Eq. (8). These effects manifest in the narrowing of the allowed mass bands of SUSY particles and also narrowing of the allowed ranges of the event rates. A significant reduction of the maximum event rates for $\mu > 0$ was also observed. Further progress requires a reduction of errors in the theoretical evaluation of the $b \rightarrow s\gamma$ in the SUSY theory (including additional corrections due to SUSY thresholds [24]), as well as of the experimental ones. An encouraging result for dark matter experiments is that there is a reasonable part of the parameter space where $R > 0.1$, which is the lower limit for detecting event rates with the current technology. For $\mu > 0$ this region of the parameter space exists if $r_{\rm expt} > 1.3$, while for $\mu < 0$, this region exists for the entire range of Eq. (8). Thus the sign of μ plays an important role and possibility of the observation of neutralino dark matter is significantly enhanced if μ is negative.

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