CAN WE IDENTIFY A LIGHT NEUTRALINO IN B-FACTORIES?

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**ABSTRACT**

If a light gaugino sector exists, then the lightest supersymmetric particle (LSP) has a chance of being pair-produced in rare B-decays. As a consequence of neutral flavour violation in most supersymmetric models, such decays can occur at the tree-level and reinforce the channels \(B \rightarrow K(K^*) + invisible\). We discuss how a study of such decay spectra in B-factories can help us either identify or exclude a light LSP.

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Since supersymmetry (SUSY) [1] is one of the most appealing prospects in our quest for physics beyond the standard model, all possible ways to uncover (or rule out) its existence are worthy of attention, even if it be in relatively improbable corners. Though the lower bounds on squark and gluino masses as announced by the CDF collaboration are 126 GeV and 141 GeV respectively [2], they are based on certain assumptions about superparticle decays and SUSY parameters. Relaxation of such limits cannot thus be altogether excluded [3]. In particular, there is a persistent, although controversial, claim that a window in the parameter space with a light gluino is still open [4, 5]. If that indeed be the case, then a gluino in the mass range of, say, 2.5 - 5 GeV will cause a squark to decay directly into it. The gluino will subsequently decay into the lightest supersymmetric particle (LSP), supposedly even lighter in an R-parity conserving SUSY. As a result the missing transverse momenta ($\not{P}_T$) associated with the LSP are considerably degraded and cannot survive the $\not{P}_T$-cuts employed in conventional SUSY searches. Therefore, this scenario also relaxes the squark mass limits [4]. Further motivations for a light gluino have come from the observation [6] that the values of the strong coupling $\alpha_s$ at low and high energies are in better agreement with theory if a low-mass, electrically neutral coloured fermion is present. Attempts have been made to demonstrate the plausibility of such a scenario by proposing SUSY models where the gauginos acquire their masses radiatively [7]. On the phenomenological side, recent studies include the implications of a light, long-lived gluino in strong processes [8], constraints on light gluinos from electroweak precision tests [9] and those coming from radiative b-decay [10].

Here we focus on such a scenario from another angle; namely, we try to extract signatures of the light LSP from the kinematics of rare B-meson decays [11]. We assume the LSP to be the lightest neutralino ($\chi_1^0$) in this case. Then the flavour-changing neutral current (FCNC) decays $B \rightarrow K(K^*)\chi_1^0\chi_1^0$ will give the same observable final states as $B \rightarrow K(K^*)\nu\overline{\nu}$. However, the decay spectra for the SUSY and standard model (SM) processes are going to
have different shapes. The net observed variation of $d\Gamma/dE_{K(K^*)}$ with the K(K*)-energy will be a result of superposition of the two types of final states, leading to a distribution with a kink. The position of the kink and the distortion to the spectrum relative to the purely SM case depends on the mass of the LSP. Some earlier studies had suggested the application of a similar effect in Kaon decay to unmask a massive tau-neutrino or a photino \[12\]. We have also recently discussed the implications of such spectral distortion in the context of decays of a heavy Higgs boson \[13\].

There are several advantages in looking for a light LSP in B-decays. First, as we shall see, an LSP in the mass range $0.5\text{MeV} - 1\text{GeV}$ produces a kink in a conspicuous part of the spectrum, thereby making the distortion rather obvious. If we explore the window in $m_\tilde{g} = 3 - 5\text{GeV}$, then the LSP is likely to lie in the above range. Secondly, B-decays are dominated by short-distance physics, so that quark-level estimates are reliable. And finally, with a number of B-factories being designed for the near future, the prospect of producing $10^7 - 8 \ B\bar{B}$-pairs are realistic \[14\]. Thus one may aspire to have a sufficient number of B’s at the threshold so that their rare decays can be under scrutiny in the rest frame.

Both the decays $B \rightarrow K\chi^0_1\chi^0_1$ and $B \rightarrow K^*\chi^0_1\chi^0_1$ are driven by the quark-level process $b \rightarrow s\chi^0_1\chi^0_1$. In the supersymmetric standard model, there is the interesting possibility of tree-level flavour violation in quark-squark-neutralino (or quark-squark-gluino) interactions \[15\]. This can occur because the quark and squark mass matrices are not simultaneously diagonal. In a basis where the $3 \times 3$ down-quark mass matrix is diagonal, the $6 \times 6$ down-squark mass matrix is given by

$$M_d^2 = \begin{pmatrix} m_L^2 1 + m_d^2 + c_0 K m_u^2 K^\dagger & 0 \\ 0 & m_R^2 1 + m_d^2 \end{pmatrix}$$

(1)

where $m_d, m_u$ are the diagonal down-and up-quark mass matrix respectively, and K is the
Kobayashi-Maskawa matrix. $m_L$ and $m_R$ are the flavour-blind SUSY breaking parameters that set the scale of squark masses. We can put $m_L = m_R$ without any loss of generality. The term proportional to $m_l^2$ occurs due to radiative corrections induced by Yukawa coupling with charged Higgsinos. Such a term is particularly important in a model based on N=1 supergravity (SUGRA), as the mass parameters evolve from the high SUGRA breaking scale to the scale of the residual global SUSY breaking at a lower energy. Because of this term, $m_d^2$ cannot be simultaneously diagonal with $m_i^2$. As a result, quark-squark-neutralino (or gluino) interactions can violate flavour. The flavour mixing in the down sector is controlled essentially by the top-quark mass, the Kobayashi-Maskawa matrix and the parameter $c_0$. The calculation of $c_0$ is model-dependent; we shall treat it here as a phenomenological input that needs to be restricted by SUSY contributions to various FCNC processes.

In the above framework (where we have also neglected the mixing between left- and right-squarks), the quark-squark-neutralino ($q - \tilde{q} - \chi^0_1, i = 1 - 4$) coupling in the down sector is

$$L_{q\tilde{q}\chi^0_1} = -\sqrt{2} g \sum_{ij} \bar{q}_j \tilde{\chi}^0_i \left[ \tan \theta_w e_j N^*_i \Gamma_{jk} \frac{1 - \gamma_5}{2} + \delta_{jk} (T_{3j} N_{i2} - \tan \theta_w (T_{3j} - e_j) N_{i1}) \frac{1 + \gamma_5}{2} \right] q_k + h.c. \quad (2)$$

where $\Gamma_{jk}$ is the (jk)-th element of the unitary matrix that diagonalises the upper 3 x 3 block of $m_d^2$ in equation(1). $N$ is the neutralino mixing matrix, and $T_{3j}$ the third component of the the isospin of the j-th flavour. In the absence of left-right mixing, only the first term in (2) is relevant for flavour-violating interactions.

For our calculations, the element $\Gamma_{23}$ will be important. We have used $m_t = 170 GeV$. For such a top-quark mass, the third term in the upper-left block of $m_d^2$ is important from the viewpoint of diagonalisation, so that for a not-too-small value of $c_0$, the elements of $\Gamma$ are
close to those of K in magnitude. We have parametrized $\Gamma_{23}$ by writing $\Gamma_{23} = cK_{23}$. Various values of $c_0$ and and the corresponding values of $c$ are given in table 1.

The two tree-level graphs (plus those with the momenta of the neutralinos interchanged) shown in figure 1 contribute to $b \rightarrow s\chi^0_1\chi^0_1$. For numerical calculations, we confine ourselves to a situation where the gluino mass is in the range 3-5 GeV. In such a case, the other parameters in the SUSY sector have to be compatible with the LEP-I results [16]. Under such circumstances, it is straightforward to verify that the LSP is dominated overwhelmingly by the photino. This is easily demonstrated if, for example, we adhere to a scenario inspired by Grand Unified Theories (GUT) [17]. In such cases the only independent inputs apart from the gluino mass are $\mu$, the Higgsino mass parameter, and $\tan\beta$, the ratio of the two scalar vacuum expectation values. In the above situation one gets confined to $50\,\text{GeV} \leq \mu \leq 100\,\text{GeV}$ and $1.0 \leq \tan\beta \leq 1.5$. Diagonalisation of the neutralino mass matrix with such inputs reveals the complete dominance of the photino state in the LSP. Therefore, the interaction (2) can be used in the $\chi^0_1 = \tilde{\chi}^0_1$ limit for our purpose [1(b)]. The amplitude for $b(p_0) \rightarrow s(p_3)\chi^0_1(p_2)\chi^0_1(p_1)$ can be expressed as

$$\mathcal{M} = \frac{e^2 c V_{23}}{9} \left[ \frac{1}{[(p_0 - p_1)^2 - m_{\tilde{q}}^2]} \bar{u}(p_1) \left( 1 - \gamma_5 \right) b(p_0) \bar{s}(p_3) \left( 1 + \gamma_5 \right) v(p_2) - \frac{1}{[(p_0 - p_2)^2 - m_{\tilde{q}}^2]} \bar{u}(p_2) \left( 1 - \gamma_5 \right) b(p_0) \bar{s}(p_3) \left( 1 + \gamma_5 \right) v(p_1) \right]$$

where $m_{\tilde{q}}$ is the assumed common mass of the $\tilde{s}$ and $\tilde{b}$ squarks. In order to factor out the hadronic part of the amplitude, one needs to do a Fierz transformation on (3), which gives

$$\mathcal{M} = \frac{e^2 c V_{23}}{18} \left[ \frac{1}{[(p_0 - p_1)^2 - m_{\tilde{q}}^2]} \bar{s}(p_3) \gamma^\mu \left( 1 - \gamma_5 \right) b(p_0) \bar{u}(p_1) \gamma_\mu \left( 1 + \gamma_5 \right) v(p_2) - \frac{1}{[(p_0 - p_2)^2 - m_{\tilde{q}}^2]} \bar{s}(p_3) \gamma^\mu \left( 1 - \gamma_5 \right) b(p_0) \bar{u}(p_2) \gamma_\mu \left( 1 + \gamma_5 \right) v(p_1) \right]$$

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To proceed further, one has to obtain the hadronic matrix elements for the above quark current. Using a common parametrization for the matrix elements for rare B-decays \[18\], one can write

\begin{align*}
\langle K(p_3)| \bar{s}\gamma_\mu b| B(p_0) \rangle &= f_+(q^2)(p_3 + p_0)_\mu + f_-(q^2)q_\mu , \\
\langle K(p_3)| \bar{s}\gamma_\mu\gamma_5 b| B(p_0) \rangle &= 0 \tag{5} \\
\langle K^*(p_3)| \bar{s}\gamma_\mu (1 - \gamma_5 ) b| B(p_0) \rangle &= i \epsilon_{\mu\nu\alpha\beta} \epsilon'(p_3) (p_0 + p_3)^\alpha q^\beta V(q^2) - \\
& \quad \epsilon_\mu(p_3) \left[ m_B^2 - m_{K^*}^2 \right] A_0(q^2) - (\epsilon \cdot q) (p_0 + p_3)_\mu A_+(q^2) - (\epsilon \cdot q) q_\mu A_-(q^2) \tag{7}
\end{align*}

where \( q_\mu = (p_0 - p_3)_\mu \) and \( \epsilon_\mu(p_3) \) is the polarization vector for the \( K^* \). Our results are based upon numerical values of the various form-factors (and pole fits for their momentum-transfer dependence) obtained from the relativistic quark model of reference \[19\]. These form-factors have been computed in the literature using other models, too \[20\]; the question of matching such calculations with the general relationship predicted by heavy quark effective theories have also been discussed \[21\]. However, the uncertainties due to model-dependence do not affect the general features of our results. It should also be noted that we have not taken QCD corrections into account here. Though such corrections moderately alter the decay rates \[22\], the key feature of the spectral distortions should not be affected, since at the lowest order electroweak level, the SUSY and standard model effective interactions have the same operator structure.

The differential decay rates of our interest are given by

\begin{equation}
\frac{d\Gamma}{dE_{K(K^*)}} = \frac{1}{64\pi^3 m_B} \int_{E_1(min)}^{E_1(max)} |\mathcal{M}|^2 dE_1 \tag{8}
\end{equation}

where \(|\mathcal{M}|^2\) is the squared matrix element and

\begin{equation}
E_1(max) = \frac{1}{2} \left[ (m_B - E_{K(K^*)} + p_3 \sqrt{1 - 4m_{\chi_0}^2/q^2} \right] \tag{9}
\end{equation}
\[ E_1(\text{min}) = \frac{1}{2} \left[ (m_B - E_{K(K^*)} - p_3 \sqrt{1 - \frac{4m_{\chi_1^0}^2}{q^2}} \right] \]  

(10)

\[ q^2 = m_{K(K^*)}^2 + m_B^2 - 2m_B E_{K(K^*)} \]  

(11a)

\[ p_3^2 = E_{K(K^*)}^2 - m_{K(K^*)}^2 \]  

(11b)

\[ E_{K(K^*)} \] is the \( K(K^*) \) energy in the rest frame of decaying B and its kinematically allowed range is

\[ m_{K(K^*)} \leq E_{K(K^*)} \leq \left( m_B^2 + m_{K(K^*)}^2 - 4m_{\chi_1^0}^2 \right)/2m_B \]  

(11c)

Further, one has to add the rates for the SUSY process with that for \( \Sigma B \to K(K^*)\nu_i\bar{\nu}_i \) which occurs via triangle as well as box diagrams.

The numerical results are shown in figures 2-5. For the \( K^* \) final states, the polarizations have been summed over. The fact that the standard model final states consist of \( \nu\bar{\nu} \) pairs explains why the distributions are not vitiated by peaks due to the \( J/\psi \) and \( \psi' \) resonances.

We have drawn the graphs for \( m_\tilde{q} = 100GeV \) which is easily allowed in this scenario. Two sets of graphs each for the \( K \) and \( K^* \) final states are presented in order to demonstrate the dependence of the rates on the parameter \( c_0 \). Evidently, with even quite conservative choices for \( c_0 \) one can notice distortions to the spectrum over a considerable region of the parameter space. The effect becomes less and less obvious with increasing squark mass, and is barely perceptible for \( B \to K\chi_1^0\chi_1^0 \) with \( c_0 \approx .01, m_\tilde{q} = 500GeV \). Also, the response to a variation in the mass of the LSP in the region 0.4 – 1GeV is manifest. A few hundred events in a B-factory should suffice to explore this kind of a distortion.

It is to be noted that while the differential decay rate for \( \Sigma(B \to K\nu_i\bar{\nu}_i) \) increases monotonically with \( E_K \), it dips after an initial rise in the case of \( \Sigma(B \to K^*\nu_i\bar{\nu}_i) \). This is
because the transverse component of $K^*$ has an important role in the rate. For it, the upper end of the phase space (corresponding to the maximum allowed value of $E_{K^*}$) corresponds to a configuration that is disfavoured by helicity conservation. The corresponding distortions to the spectrum caused by the LSP are less conspicuous than in the case of decays into a K, although the overall rate for the former is higher by about an order of magnitude.

The graphs also clearly portray the fact that with light LSP’s the total rates for both the decays can be jacked up by as much as an order of magnitude due to presence of a light LSP. At least over a certain amount of parameter space such an overall rate enhancement can be taken as a positive signal of such an LSP.

To conclude, if $10^{7-8}$ $B \bar{B}$-pairs are produced in a B-factory per year, then the tree-level flavour violating interaction in SUSY models strongly affect the decay patterns in $B \rightarrow K + nothing$ and $B \rightarrow K^* + nothing$, provided that a light LSP is present. This can be, in a somewhat model-dependent way, a pointer to the light gluino as well. Therefore, a detailed investigation of the above types of decays in B-factory experiments are going to help one in constraining the light sparticle scenario to a large extent.
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Table caption

Table 1: Different values of the parameter $c_0$ and the corresponding values of $c$, for $m_{\tilde{q}} = 100 \, GeV$. 

Figure Captions

Figure 1:
The tree-level contributions to $b \rightarrow s \chi^0_1 \chi^0_1$. In addition there will be crossed diagrams where the four-momenta of the LSP’s are interchanged.

Figure 2:
The differential decay rates for $B \rightarrow K + nothing$ for $m_{\tilde{q}} = 100 GeV$, $c = 0.1$. The solid, dotted and short-dashed curves correspond to three LSP masses expressed in GeV. The long-dashed curve below is for the purely standard model case with three massless neutrinos.

Figure 3:
Same as figure 2, but with $c = 0.5$.

Figure 4:
The differential decay rates for $B \rightarrow K^* + nothing$, with the same choice of parameters as in figure 2.

Figure 5:
Same as in figure 4, but with $c=0.5$. 
| $c_0$ | 0.01 | 0.001 | 0.0001 |
|------|------|-------|--------|
| $c$  | 0.9  | 0.5   | 0.1    |

Table 1
\( \chi_0^0 (p_2) \) + Crossed

FIG. 1