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# SINGLE PHOTON DECAYS OF THE $Z^0$ AND SUSY WITH SPONTANEOUSLY BROKEN R-PARITY

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## Abstract

Spontaneous violation of R parity can induce rare single photon decays of the $Z^0$ involving the emission of (nearly) massless pseudoscalar Goldstone bosons, majorons, as well as massive CP even or CP odd spin zero bosons that arise in the electroweak breaking sector of these models. We show that the majoron emitting decays can have a sizeable branching ratio of $10^{-5}$ or so, without conflicting any experimental observation from neutrino physics or particle searches. These decays may lead to interesting structures for the single photon spectrum involving either mono chromatic photons as well as continuous spectra that grow with energy. They would easily account for an excess of single photon events at high energies recently hinted at by the OPAL collaboration.

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# 1 Introduction

One of the classic missing energy experiments in $e^+e^-$ annihilation is the neutrino counting with single photon events [1]. Of course, such events are expected to occur via initial state bremsstrahlung with the $Z$ decaying to a $\nu\bar{\nu}$ pair. While the accurate measurements of the $Z$ lineshape at LEP have now achieved a much better accuracy for counting the number of light neutrino species, the single photon energy spectrum still remains interesting. Recently the OPAL collaboration has published a high statistics single photon spectrum that shows some excess of high energy photons above the expectations from initial state radiation.

There has been a lot of interest on the phenomenology of supersymmetric models. The most well studied scheme has so far been the so-called minimal supersymmetric standard model [2], which assumes the conservation of a discrete R parity symetry [3]. In this model, in addition to the single photon events expected from initial state radiation (as in the standard model) one expects some excess of high energy photons from the production of two neutralinos, followed by the radiative decay of the heaviest to the lightest (LSP). In this case the missing momentum is carried by two LSPs and requires $m_Z \geq 2m_{LSP}$.

In this paper we note some interesting features related to single photon events which are expected in a class of SUSY models with spontaneous violation of R parity [4, 5]. These models are characterized by the existence of a massless (or nearly so) pseudoscalar Goldstone boson, called majoron [6], that follows from the spontaneous nature of the underlying lepton number violation.

These models predict the existence of new decay modes for this $Z$-boson involving single majoron emission

$$Z^0 \to J\gamma$$

where J denotes the majoron. Since the pseudoscalar boson is massless (or nearly so) this process should *always* be kinematically allowed. We demonstrate explicitly that in our considered model its expected branching ratio can reach $10^{-5}$ or so and lies therefore within the sensitivities of the LEP experiments. Its existence would give rise to a monoenergetic photon emitted with energy equal to half the $Z$ mass. In addition we expect also to have a process involving double majoron emission

$$Z^0 \to JJ\gamma$$

A simple estimate indicates that the rate for this process may be similar to that of the single emission process. This process would give rise to a continuous photon spectrum that could account for an excess of single-photon events at high energies.

Moreover, if kinematically allowed, there could be similar processes involving the emission of CP even scalar bosons, like the higgs bosons, or of massive pseudo-scalar bosons charactericitc of supersymmetric models, e.g. $Z^0 \to h\gamma$ , $\quad Z^0 \to hh\gamma$ , $\quad Z^0 \to A\gamma$ , etc. It is, indeed, quite conceivable that these rates can be quite high due to the fact that, in these models, low masses for the $h$-bosons are allowed, since their coupling to the $Z$ is suppressed relative to that of the standard model.

## 2 Model

Here we adopt as a model for the spontaneous violation of R parity the one proposed in ref [4]. The model is characterized by the basic superpotential terms

$$h_u u^c Q H_u + h_d d^c Q H_d + h_e e^c \ell H_d + (h_0 H_u H_d - \mu^2)\Phi + h.c. \tag{1}$$

to which one adds the following terms

$$h_\nu \nu^c \ell H_u + h \Phi \nu^c S + h.c. \tag{2}$$

involving additional isosinglet superfields $({\nu^c}_i, S_i)$ carrying lepton numbers $(-1, 1)$ respectively. The couplings $h_u, h_d, h_e, h_\nu, h$ are arbitrary matrices in generation space, which explicitly break flavour conservation. However, the form of the superpotential is restricted by imposing the exact conservation of *total* lepton number and R parity. The addition of the new singlets to the minimal $SU(2) \otimes U(1)$ model [7] may lead to many novel weak interaction phenomena [8, 9, 10, 11]. Most relevant for us here is the fact that their presence allows both electroweak and R parity breaking to proceed at the tree level. The spontaneous breaking of R parity and lepton number is driven by nonzero VEVS for the additional singlets [4]

$$v_R = \langle \tilde{\nu}_{R\tau} \rangle \qquad\qquad v_S = \left\langle \tilde{S}_\tau \right\rangle \tag{3}$$

which are generated at the electroweak scale, whereas electroweak breaking and fermion masses arise from

$$\langle H_u \rangle = v_u \qquad \langle H_d \rangle = v_d \tag{4}$$

with $v^2 = v_u^2 + v_d^2$ fixed by the W mass.

The Majoron is given by the imaginary part of [4]

$$\frac{v_L^2}{Vv^2}(v_u H_u - v_d H_d) + \frac{v_L}{V}\tilde{\nu_\tau} - \frac{v_R}{V}\tilde{\nu^c}_\tau + \frac{v_S}{V}\tilde{S_\tau} \tag{5}$$

where $V = \sqrt{v_R^2 + v_S^2}$. Since the majoron is mainly an $SU(2) \otimes U(1)$ singlet it does not contribute to the invisible $Z^0$ decay width. Moreover, one may easily satisfy the astrophysical limit from stellar cooling [12] for $v_R = O(1\,TeV)$ and $v_L \lesssim O(100\,MeV)$. As shown in ref [4], this hierarchy between $v_L$ and $v_R$ may be achieved in a natural way.

In order to study the radiative $Z^0$ decays with majoron emission we need the structure of the *chargino* mass matrix, given by [4]

$$\begin{array}{c|ccc}
 & e_j^+ & \tilde{H_u^+} & -i\tilde{W}^+ \\
\hline
e_i & h_{eij} v_d & -h_{\nu ij} v_{Rj} & \sqrt{2} g_2 v_{Li} \\
\tilde{H_d^-} & -h_{eij} v_{Li} & \mu & \sqrt{2} g_2 v_d \\
-i\tilde{W}^- & 0 & \sqrt{2} g_2 v_u & M_2
\end{array} \tag{6}$$

where $g_{1,2}$ are the $SU(2) \otimes U(1)$ gauge couplings divided by $\sqrt{2}$ and $M_{1,2}$ denote the supersymmetry breaking gaugino mass parameters, related by $M_1/M_2 = \frac{5}{3} tan^2\theta_W$. In many models, such as the one in ref [4], the effective Higgsino mixing parameter $\mu$ may be given as $\mu = h_0 \langle \Phi \rangle$, where $\langle \Phi \rangle$ is the VEV of an appropriate singlet scalar.

The form of this matrix applies to a wide class of models and determines the masses of the physical charged leptons as well as those of the charginos. As a result of R parity breaking, the supersymmetric fermions will now mix with the weak-eigenstate leptons. Moreover eq. (6) also specifies the couplings of the majoron and of the $Z^0$ to the mass-eigenstate charged leptons and the charginos, which will be relevant for calculating the $Z^0 \to \gamma J$ decay width.

## 3 The process $e^+e^- \to Z^0 \to \gamma J$

Single photon events can be produced in our model via the radiative $Z^0$ decays into a photon plus the invisible majorons. At the one-loop level the single majoron monophoton events arise from the diagrams shown in Fig. 1. The general form of the amplitude for the process of Fig. 1 can be expressed as:

$$V^{\mu\nu} = i\left(V_1 g^{\mu\nu} + V_2 p^\mu p^\nu + V_3 q^\mu q^\nu + V_4 p^\mu q^\nu + V_5 p^\nu q^\mu\right) - V_6 \epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta \tag{7}$$

Imposing the on-shell conditions $p^2 = 0$, $q^2 = M_J^2 = 0$, $(p+q)^2 = M_Z^2$ and requiring the gauge-invariance conservation $V_{ON}^{\mu\nu} p_\nu = 0$, this reduces to:

$$V_{ON}^{\mu\nu} = i\left[V_1\left(g^{\mu\nu} - \frac{p^\mu q^\nu}{pq}\right) + V_2 p^\mu p^\nu + V_5 p^\nu q^\mu\right] - V_6 \epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta \tag{8}$$

In matrix element calculations form factors $V_2$ and $V_5$ do not contribute after contraction with the photon polarization vector, hence the effective form of the $Z^0\gamma J$ vertex can be expressed as:

$$V_{ON}^{\mu\nu} = iV_1\left(g^{\mu\nu} - \frac{p^\mu q^\nu}{pq}\right) - V_6 \epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta \tag{9}$$

Form factors $V_1$ and $V_6$ are obtained by the explicit calculation of the appropriate 3-point Green function. Let us denote the $Z^0\chi_i^-\chi_j^+$ and $J\chi_i^-\chi_j^+$ vertices as

$$ie\gamma^\mu(A_{ij}P_L + B_{ij}P_R) \qquad (Z^0\chi_i^-\chi_j^+) \tag{10}$$

$$e(C_{ij}P_L + D_{ij}P_R) \qquad (J\chi_i^-\chi_j^+) \tag{11}$$

respectively. These coupling matrices have been given explicitly in ref. [13, 14]. For definiteness and simplicity, we will assume CP conservation. It is important to notice that, in this case, these coupling matrices obey the following symmetry properties:

$$A_{ij} = A_{ji} \qquad B_{ij} = B_{ji} \qquad C_{ij} = -D_{ji} \tag{12}$$

Note that gauge invariance forces the $\gamma\chi_i^-\chi_i^+$ vertex to be diagonal in the $i, j$ indices and reads as (electric charge $q_i = 1$ in our case):

$$ieq_i\gamma^\mu \qquad (\gamma\chi_i^-\chi_i^+) \tag{13}$$

We work in the mass eigenstate basis, therefore the particles exchanged in the loop are the five physical singly charged fermions present in our model (the two charginos and the three charged leptons). The formulae for the form factors $V_1$ and $V_6$ (calculated on-shell) are the following:

$$\begin{aligned} V_1 &= -\frac{e^3}{8\pi^2}\sum_{i,j=1}^{5}\Big[m_i^2 m_j(A_{ji}D_{ij}+B_{ji}C_{ij}+A_{ij}C_{ji}+B_{ij}D_{ji})c_0 \\ &+ m_i(A_{ji}C_{ij}+B_{ji}D_{ij}+A_{ij}D_{ji}+B_{ij}C_{ji})(2c_{24}+pq(c_0+c_{12})) \\ &- m_j(A_{ji}D_{ij}+B_{ji}C_{ij}+A_{ij}C_{ji}+B_{ij}D_{ji})(2c_{24}+pq(c_{12}+2c_{23})+\frac{1}{2})\Big] \end{aligned} \tag{14}$$

$$\begin{aligned} V_6 &= -\frac{e^3}{8\pi^2}\sum_{i,j=1}^{5}[m_j(A_{ji}D_{ij}-B_{ji}C_{ij}-A_{ij}C_{ji}+B_{ij}D_{ji})c_{12} \\ &+ m_i(A_{ji}C_{ij}-B_{ji}D_{ij}-A_{ij}D_{ji}+B_{ij}C_{ji})(c_0+c_{12})] \end{aligned} \tag{15}$$

where $pq = M_Z^2/2$ and $c_0$, $c_{11}$ and $c_{12}$ are the usual three point functions of t'Hooft and Veltman [15], called with arguments $(p, q, m_i^2, m_i^2, m_j^2)$; for example, $c_0 \equiv c_0(p, q, m_i^2, m_i^2, m_j^2)$.

One should note that in order to obtain non-vanishing amplitude for the discussed process, R-parity must be broken in one of the $Z^0\chi_i^-\chi_j^+$ or $J\chi_i^-\chi_j^+$ vertices. This is clear, since the majoron arises from a $SU(2)\otimes U(1)$ singlet sneutrino and is therefore R-odd.

The decay width for the process $Z^0 \to \gamma J$ can be written as:

$$\Gamma(Z^0\to\gamma J) = \frac{1}{96\pi M_Z}\left(4|V_1|^2 + M_Z^4|V_6|^2\right) \tag{16}$$

The differential and total cross sections for the process $e^+e^-\to\gamma J$ have the following forms (with the $Z^0e^+e^-$ vertex defined as $ie\gamma^\mu(v-a\gamma_5)$):

$$\begin{aligned} \frac{d\sigma}{d\Omega}(e^+e^-\to\gamma J) &= \frac{e^2}{512\pi^2 M_Z^2\Gamma_Z^2}\Big[(v^2+a^2)(4|V_1|^2+M_Z^4|V_6|^2)(1+\cos^2\theta) \\ &- 16avM_Z^2\mathrm{Re}(V_1V_6^\star)\cos\theta\Big] \end{aligned} \tag{17}$$

$$\sigma(e^+e^-\to\gamma J) = \frac{e^2(v^2+a^2)}{96\pi M_Z^2\Gamma_Z^2}\left(4|V_1|^2+M_Z^4|V_6|^2\right) \tag{18}$$

Note also that the $V_1$ form factor is non-vanishing only if the CP is broken, i.e. $V_1 \neq 0$ only if parameters in the lagrangian contain complex phases. This follows directly from the symmetry properties of the coupling matrices discussed above. We will proceed, in what follows, assuming CP conservation, so that $V_1 = 0$.

In order to calculate the attainable values of the the branching ratio for the 2-body $Z$ decay to a single photon plus missing momentum in the spontaneously broken

R parity model we have varied the unknown model parameters, which include the standard supersymmetric parameters $\mu$, $M_2$, $\tan\beta$, as well as the effective R parity violating parameter $h_\nu v_R$ over a reasonable range specified as

$$\begin{aligned} -500\ GeV \le \mu \le 500\ GeV \\ 30\ GeV \le M_2 \le 500\ GeV \\ 10\ \le tan\beta \le 40 \\ 1 \le h_\nu \le \sqrt{4\pi} \\ 10GeV \le v_R \le 100\ GeV \end{aligned} \tag{19}$$

We should stress that, in order to perform a systematic analysis of the attainable values of this branching ratio one needs to reject all points that violate the constraints that follow from all existing observations, including those from laboratory, cosmology and astrophysics. They follow mostly from neutrino physics and from SUSY particle searches, and have been described in earlier papers [13, 14].

We have found that the branching ratio for the 2-body $Z$ decay to a single photon plus missing momentum in the spontaneously broken R parity model can reach $10^{-5}$ or so and is, therefore, within the sensitivities of the high luminosities possible at LEP. This is illustrated in Fig. 2.

## 4 Non-monochromatic single photon production at LEP

In the spontaneously broken R parity model, in addition to the standard model diagrams, there are new sources contributing to non-monochromatic single photon production coming from the decay $Z^0 \to JJ\gamma$ in which two majorons are emitted.

The leading diagram [§] for this process is the same that gives the single emission process, but removing the $R$ parity violating insertion $V_R$ by the second propagating majoron and is illustrated in Fig. 3. This amplitude can lead to a sizeable $Z^0 \to JJ\gamma$

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[§] Other mechanisms of generating non- monochromatic single photon events exist in the spontaneously broken R parity model. For example, LSP pair production followed by the radiative decay of one of them and the invisible decay of the other $\chi^0 \to J\nu$. Here we are not considering this possibility.

decay branching ratio for sufficiently large values of $h_\nu$ and correspondingly low $V_R$ values, in order to keep the $\nu_\tau$ mass within the experimentally allowed range. A simple estimate suggests that $BR(Z^0 \to \gamma JJ) \sim 10^{-5}$ is allowed.

There is another class of diagrams contributing to the $JJ\gamma$ process. They are similar to a corresponding class of standard model radiative diagrams leading to $Z^0 \to \nu\bar{\nu}\gamma$. However, now the $Z^0\nu\bar{\nu}$ vertex is replaced by the $hJJ$ vertex. These amplitudes may be assumed to be negligible in the region of parameters where the $hJJ$ coupling is small.

Note that the photons produced in the $Z^0 \to JJ\gamma$ decay have a different energy distribution from the corresponding bremsstrahlung $Z^0 \to \nu\bar{\nu}\gamma$ decays of the standard model. Indeed, under quite general arguments one can write the relevant amplitude as being proportional to a factor

$$V_{\mu\nu} = i(V_1 g_{\mu\nu} + V_2 p_\mu p_\nu + V_3 p_\mu q_{1\nu} + V_4 p_\mu q_{2\nu}$$

$$+V_5 q_{1\mu} p_\nu + V_6 q_{2\mu} p_\nu + V_z q_{1\mu} q_{2\nu} + V_8 q_{1\mu} q_{2\nu}$$

$$+\epsilon^{\mu\nu\alpha\beta}(V_9 p_\alpha q_{1\beta} + V_{10} p_\alpha q_{2\beta} + V_{11} q_{1\alpha} q_{2\beta})$$

Now imposing electromagnetic gauge invariance, $CP$ invariance and bose symmetry for the two emitted majorons, one can express the on-shell amplitude in terms of a single form factor $V_0$ as

$$A(Z^0 \to JJ\gamma) = \epsilon_\mu(Q)\epsilon_\nu(p)V_0[p^\mu(q_1+q_2)^\nu - p(q_1+q_2)g^{\mu\nu}] \qquad (20)$$

The $V_0$ form-factor is, in general, a function of the kinematical variables which has to be determined by the calculation of the loop diagram in Fig. 3.

As the simplest illustration we neglect this dependence and derive the $\gamma$-spectrum following from eq. 20 in the approximation of constant $V_0$. We obtain

$$\frac{d\Gamma}{dE_\gamma} = \frac{|V_0|^2 m_Z}{96\pi^3} E_\gamma^3$$

with $0 \leq E_\gamma \leq \frac{m_Z}{2}$ .

Note that in this idealized limit we obtain a spectrum characterized by a single free parameter $|V_0|$. In general, however, we expect that the shape of the $\gamma$ spectrum in this case will depend upon the unknown supersymmetric parameters that characterize the couplings in the loop diagram in Fig. 3 in a rather complicated way.

Superimposed upon the continuous spectrum we have, in addition, a spike at its endpoint, corresponding to the emission of the monochromatic $\gamma$ from the $Z^0 \to \gamma J$ decay.

# 5 Discussion

Unlike the standard model, where missing energy is always carried by a neutrino-antineutrino pair, in the spontaneously broken R parity models, due to the existence of the light pseudoscalar majoron, one can generate *mono-energetic* photons plus missing momentum in $Z^0$ decays. This feature is also characteristic of other singlet majoron models with the spontaneous violation of lepton number ocurring at a scale similar to the weak interaction scale. The single production rates at LEP will, of course, be model dependent. The existence of the majoron in these models is also very interesting from the point of view of opening new decay channels for the higgs boson which may even be dominant with respect to the standard $b\bar{b}$ decay mode [16]. The role of these invisible higgs decays in the strategies to search for the higgs bosons has been considered both for $e^+e^-$ [17] as well as hadron colliders [18]. Many other phenomenological features of these models have been considered [19].

As we have seen, these models also provide new mechanisms for generating non-monochromatic single photons at LEP, coming from the decay $Z^0 \to JJ\gamma$ in which two majorons are emitted. These decays will lead to a continuous photon spectrum that might account for a possible excess of high energy photons over the expectations from initial state radiation.

In short, we find our results encouraging from the point of view of the recent hints from the OPAL experiment. They suggest that a more thorough experimental investigation of single-photon events would be welcome since it might lead, with good luck, to a way to sort out the novel decays considered here from those with similar characteristics, that happen within the standard model. A more detailed theoretical study of the shape of the continuous single photon spectrum would also be desirable.

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# Figure Captions

Fig. 1:

Feynman diagrams contributing to the monochromatic photon emission process $Z^0 \to \gamma J$.

Fig. 2:

Allowed values for the branching ratios for the process $Z^0 \to \gamma J$, as a function of $m_{\nu_\tau}$, for various values of $tan\beta$ and $v_R$. Other supersymmetric parameters were randomly chosen as described in text.

Fig. 3:

Higher order diagram contributing to the non-monochromatic single photon production.

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