Search for the Supersymmetric Partners of the Z^0 and $W^{\pm}$

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(Received 13 August 1984)

We report mass limits on the $\tilde{Z}^0$ and $\tilde{W}^{\pm}$, supersymmetric partners of the Z^0 and $W^{\pm}$, respectively, using the MARK-J detector at PETRA. The experimental signatures in both cases are acoplanar lepton pairs with missing energy. For the $\tilde{W}^{\pm}$, an additional signature is a single energetic lepton. No evidence is found for either the $\tilde{Z}^0$ ($M_{\tilde{Z}^0} < 35$ GeV) or the $\tilde{W}^{\pm}$ ($M_{\tilde{W}} < 25$ GeV).

PACS numbers: 14.80.Pb, 13.10.+q

The standard electroweak theory[1] predicts the existence of charged ($W^{\pm}$) and neutral (Z^0) vector gauge bosons. These particles were recently discovered at the CERN $p\bar{p}$ collider[2] and the measured masses ($M_W \simeq 82$ GeV, $M_{Z^0} \simeq 93$ GeV) agree with predictions. Earlier experiments at PETRA[3,4] and PEP[5] have measured the forward-backward charge asymmetry in the reaction $e^+e^- \rightarrow \mu^+\mu^-$ and found it to be consistent with the interference between the photon and the Z^0 as exchanged intermediate particles. They placed limits on the Z^0 mass. Final states with leptons can also be analyzed to search for effects not covered in the standard theory. The success of the electroweak theory leads naturally to the development of theories that offer explanations of the roles of the strong and gravitational interactions, the source of the masses of the gauge particles, and the existence of other bosons. Supersymmetric models[6] have been developed to resolve some of these problems. It has recently been suggested that supersymmetric grand-unified models based on supergravity predict the existence of a neutral spin-$\frac{1}{2}$ fermion, *the Z-ino* ($\tilde{Z}^0$), which is a partner to the Z^0, and a charged spin-$\frac{1}{2}$ fermion, *the W-ino* ($\tilde{W}^{\pm}$), which is a partner to the $W^{\pm}$. More specifically, the least massive Z-ino and W-ino are expected, in some models,[7-9] to have masses less than those of the Z^0 and the $W^{\pm}$, respectively, and in the model of Ref. 9 to have masses less than half of their partner bosons.

The Z-ino could be produced in e^+e^- annihilation via an exchange of a scalar electron, $\tilde{e}$:

$$e^+e^- \rightarrow \tilde{\gamma} + \tilde{Z}^0, \tag{1}$$

where the $\tilde{\gamma}$ is the spin-$\frac{1}{2}$ partner of the photon. If the $\tilde{\gamma}$ is lighter than the $\tilde{Z}^0$, a possible $\tilde{Z}^0$ decay is

$$\tilde{Z}^0 \rightarrow \bar{l} + \tilde{l} \quad \hookrightarrow l + \tilde{\gamma}, \tag{2}$$

where $\tilde{l}$ is the supersymmetric scalar partner of a charged lepton. The total cross section[9] for single Z-ino production depends on the masses of the scalar electron, the Z-ino, and the photino ($\tilde{\gamma}$). For $M_{\tilde{Z}} \simeq 35$ GeV, $M_{\tilde{e}} \approx 40$ GeV, and $M_{\tilde{\gamma}} \simeq 2$ GeV the total cross section is estimated to be about 3 pb at c.m. energy $\sqrt{s} \simeq 44$ GeV.[9] This is large enough for detection since the events are expected to have distinctive features. The lifetime of the $\tilde{Z}^0$ is estimated to be in the range 10^{-16} to 10^{-20} sec with the $e^+e^- + \tilde{\gamma}$ or $\mu^+\mu^- + \tilde{\gamma}$ branching ratios[10] each of the order of 10%. Our previous measurement[4] and our new data[11] on acoplanar photon pair production exclude the existence of unstable photinos with mass below 20 GeV, if the mass of $\tilde{e}$ is below 50 GeV. Therefore, we assume here that the photinos are long-lived neutrinolike particles. With two missing $\tilde{\gamma}$'s, the experimental signature of the $\tilde{Z}^0$ is the production of a pair of electrons or muons acoplanar with respect to the beam direction with large missing transverse momentum. The JADE collaboration[12] has ruled out $\tilde{Z}^0 \rightarrow \tilde{g} + q + \overline{q}$, in a mass range similar to that of the present paper.

The $\tilde{W}^{\pm}$ can be produced either in pairs,[13] or singly,[14]

$$e^+ + e^- \rightarrow \tilde{W}^+ + \tilde{W}^-, \tag{3}$$

or

$$e^+ + e^- \rightarrow e^{\pm} + \tilde{\nu} + \tilde{W}^{\mp}, \tag{4}$$

where $\tilde{\nu}$ is the supersymmetric partner of the neutrino. The W-ino can decay into two-body[14] and three-body[15] final states such as $\tilde{\nu} + \mu$ and $\mu + \overline{\nu} + \tilde{\gamma}$. In either case with $\tilde{W}$ decay leads to a single charged lepton with large missing energy due to the missing $\tilde{\nu}$ or $\overline{\nu} + \tilde{\gamma}$. For $M_{\tilde{\nu}} < M_{\tilde{W}}$, the dominant decay modes of $\tilde{W}$ are the two-body decay channels $\tilde{W} \rightarrow l + \tilde{\nu}$, where $l = e, \mu$, and τ.[10,14] For $M_{\tilde{\nu}} > M_{\tilde{W}}$, we assume the $\tilde{W} \rightarrow \mu(e,\tau) + \overline{\nu} + \tilde{\gamma}$ branching ratios to be 10% each. The experimental signature for (3) is the production of two energetic and acoplanar leptons (ee, $\mu\mu$, $\mu\tau$, or μe) with large missing transverse momentum. The signature for (4) is the production of a single energetic lepton, since the primary electron usually remains near or inside of the beam pipe.[14]

The main backgrounds for Reactions (2)–(4) are as follows:

(1) Electron or muon pairs produced by electroweak processes[4]: These backgrounds are predominantly collinear, with the energy of each lepton $\simeq E_{\text{beam}}$. A small fraction of the background dileptons with a photon emitted at a polar angle $\theta > 10°$ are identified by the presence of an electromagnetic shower in the detector.

(2) Two pairs of leptons produced by higher-order QED processes[4]: Here the final states can be two electrons produced close to the beam pipe, escaping detection, together with another electron or muon pair produced at larger angles. The latter pair of leptons, on the average, are produced with low invariant pair mass, low transverse momentum, and are coplanar with respect to the beam direction.

The MARK-J detector is a calorimetric detector covering nearly 4π sr in solid angle, which measures the energy vectors of electrons, photons, charged and neutral hadrons, and jets. The momenta of muons are measured with three sets of drift chambers interleaved with magnetized iron plates and scintillation counters. Details are given in Ref. 4.

The relevant detector elements for the present experiment are the following: (1) Electrons and photons are detected by three layers of lead-scintillator counters; each layer is segmented in the azimuthal direction. The energy resolution is 17% (full width at half maximum) for electrons with $|\cos\theta| < 0.9$. The position resolution along the beam direction has a Gaussian distribution with $\sigma = 1.64$ cm. (2) Photons are distinguished from electrons by the absence of tracks in the four layers of drift tubes. For this analysis we use the entire 2π range of the azimuthal angle ϕ and the polar angle accepted is $10° < \theta < 170°$. (3) Hadrons are distinguished from electrons by an additional four layers of scintillation counters sandwiched with magnetized iron. Each layer is also segmented in the ϕ angle. Since the MARK-J calorimeter covers most of the solid angle, any large missing P_T is due to the escape of neutrinolike particles. (4) Muons are identified and momentum analyzed in ~ 1 m of magnetized iron.

The data analysis is based on an integrated luminosity of 93 pb^{-1} in the energy range $29.97 \leq \sqrt{s} \leq 37$ GeV, and 18 pb^{-1} in the energy range $37 \leq \sqrt{s} \leq 46.78$ GeV.

To detect acoplanar dimuons, events with two muons and no other particles in the detector are selected. The acoplanarity angle Φ is defined as 180° minus the difference in the azimuthal angles of the two muons. We required that $\Phi > 30°$, and $P_T > 0.1\sqrt{s}$; P_T is the total momentum transverse to the beam. *No* events were observed.

To detect acoplanar dielectron events, we required that each electron (positron) have an energy $> 0.1\sqrt{s}$, a production angle $|\cos\theta| < 0.85$, and that the dielectrons have $P_T > 0.1\sqrt{s}$ and $\Phi > 30°$. No events were observed.

For both cases, the detection efficiencies ϵ were then determined by a Monte Carlo calculation as a function of the masses of $\tilde{\gamma}$, $\tilde{e}$, and $\tilde{Z}$. For example, with $M_{\tilde{e}} = 50$ GeV and $M_{\tilde{\gamma}} \leq 5$ GeV, $\epsilon \simeq 0.1$ at $M_{\tilde{Z}} = 5$ GeV, and $\epsilon \simeq 0.2$ at $M_{\tilde{Z}} \gtrsim 25$ GeV.

Lower limits[11,12] for $M_{\tilde{Z}}$ and $M_{\tilde{e}}$ can now be obtained by comparison of the observed number of events with the expected number, computed from the measured luminosity, the theoretical cross section, the detection efficiency, and the $\tilde{Z} \rightarrow e\overline{e}\tilde{\gamma}$ or $\mu\overline{\mu}\tilde{\gamma}$ decay branching ratio.

In Fig. 1 we plot contours in the $M_{\tilde{Z}}$-$M_{\tilde{e}}$ plane for

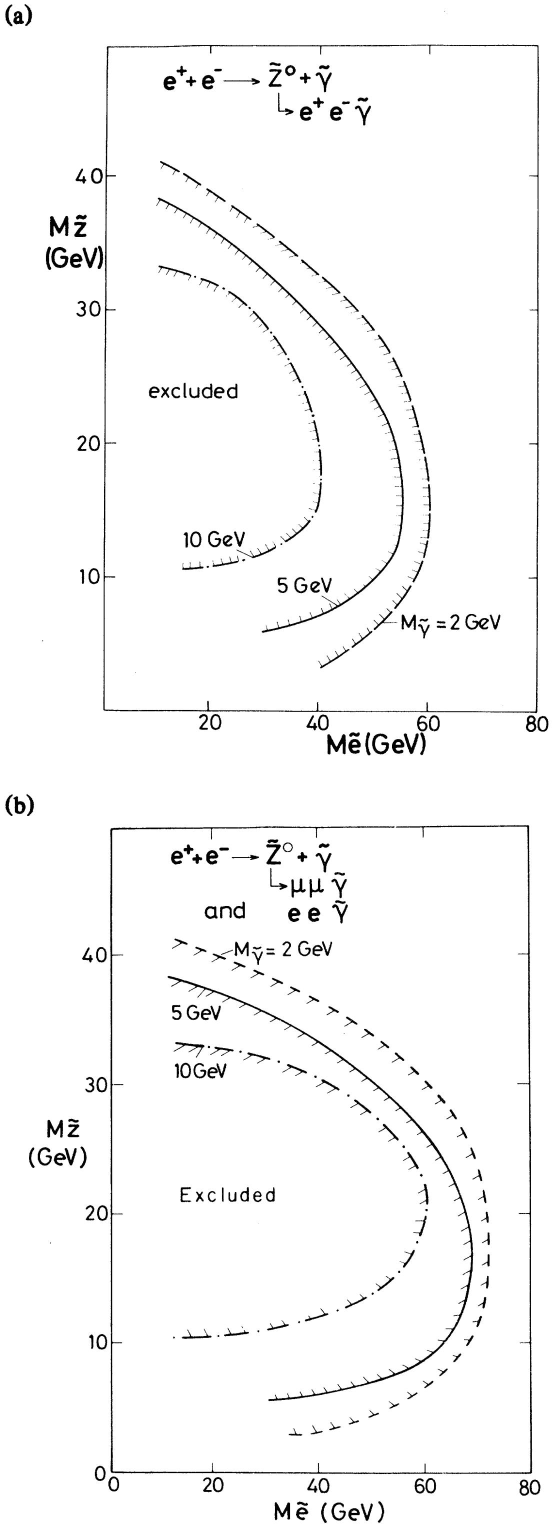

FIG. 1. The 95%-confidence-level limits in the plane $M_{\tilde{Z}}$-$M_{\tilde{e}}$ for the reaction $e^+e^- \rightarrow \tilde{Z}^0 + \tilde{\gamma}$ for $M_{\tilde{\gamma}} = 2$, 5, and 10 GeV: (a) $\tilde{Z}^0 \rightarrow e\bar{e}\tilde{\gamma}$; (b) $\tilde{Z}^0 \rightarrow e\bar{e}\tilde{\gamma}$ and $\mu\bar{\mu}\tilde{\gamma}$ combined.

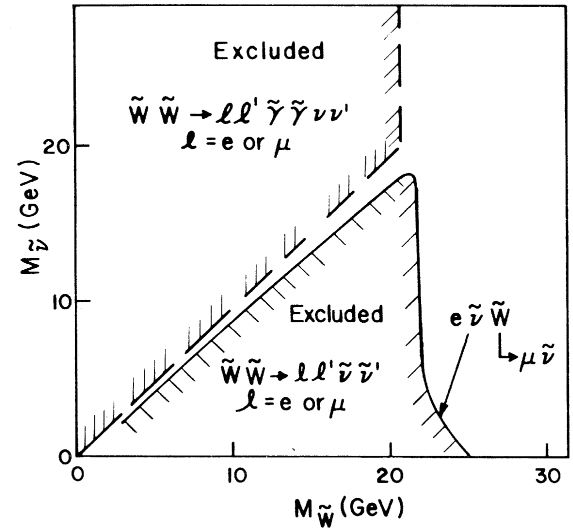

FIG. 2. The 95%-confidence-level limits in the plane $M_{\tilde{W}}$ vs $M_{\tilde{\nu}}$ for Reactions (3) and (4). The dashed curve is the limit obtained from the three-body decay of the W-ino as in Reaction (3). The solid curve is the limit obtained from the two-body decays in Reactions (3) and (4).

three values of $M_{\tilde{\gamma}}$ assuming a 10% branching ratio of the Z-ino into $\mu\bar{\mu}\tilde{\gamma}$ or $e\bar{e}\tilde{\gamma}$. We show the 95%-confidence-level limits for (a) $\tilde{Z}^0 \rightarrow e\bar{e}\tilde{\gamma}$, and (b) $\tilde{Z}^0 \rightarrow e\bar{e}\tilde{\gamma}$ and $\mu\bar{\mu}\tilde{\gamma}$ combined. As seen from Fig. 1(b), if $M_{\tilde{\gamma}} < 2$ GeV and $M_{\tilde{e}} < 40$ GeV, we find $M_{\tilde{Z}} \geqslant 35$ GeV. If we assume a 5% branching ratio for each decay mode ($\mu\bar{\mu}\tilde{\gamma}, e\bar{e}\tilde{\gamma}$), then we find $M_{\tilde{Z}} \geqslant 33.5$ GeV.

For W-inos produced by Reaction (3) we select acoplanar dimuon or dielectron events with the same criteria as those described for the Z-ino. The selection of μe events is made by requiring $|\cos\theta_e| < 0.75$, $E_e > 0.05\sqrt{s}$, and $P_T > 0.1\sqrt{s}$.

To select single-muon events originating from Reaction (4) we require only one high-energy muon with $P_{\parallel} > 0.2\sqrt{s}$ and no other photons or charged tracks originating from the vertex in the region $10° < \theta < 170°$. *No* candidates for Reactions (3) or (4) were observed. The acceptance for different values of $\tilde{\nu}$ and $\tilde{W}$ masses is calculated with a Monte Carlo method similar to the $\tilde{Z}^0$ case and the corresponding 95%-confidence-level limits for $M_{\tilde{W}}$ and $M_{\tilde{\nu}}$ are shown in Fig. 2.

We observe the following from Fig. 2: In the kinematic region $M_{\tilde{\nu}} > M_{\tilde{W}}$, Reaction (3) dominates and the limits are determined by the three-body decay channel $\tilde{W} \rightarrow \mu(e) + \bar{\nu} + \tilde{\gamma}$. The limits are not sensitive to the exact values of the branching ratio assumed. For example, if the branching ratios increase by a factor of 3, the limit in $M_{\tilde{W}}$ increases by 2 GeV. In the kinematic region $M_{\tilde{\nu}} < M_{\tilde{W}} < \sqrt{s}/2$, the limits are determined by the decay channel $\tilde{W} \to e + \tilde{\nu}$, where the W-inos are also pair produced. In the region $M_{\tilde{W}} \geqslant \sqrt{s}/2$, the limit is set by the $\tilde{W} \to \mu + \tilde{\nu}$ decay channel from W-inos produced via Reaction (4). For $M_{\tilde{\nu}} << M_{\tilde{W}}$, we find that $M_{\tilde{W}} > 25$ GeV. If the branching ratio $\tilde{W} \to \mu + \tilde{\nu}$ increases by a factor of 2, the limit on $\tilde{W}$ mass increases by 2 GeV.

In summary, no evidence has been found for production of the supersymmetric partners of the Z^0 and of the $W^{\pm}$. Depending on the masses of their decay products we exclude a large mass range of $\tilde{Z}^0$ and $\tilde{W}^{\pm}$: For example, for $M_{\tilde{\gamma}} < 2$ GeV and $M_{\tilde{e}} = 40$ GeV, we exclude $M_{\tilde{Z}} < 35$ GeV; and for $M_{\tilde{\gamma}}, M_{\tilde{\nu}} << M_{\tilde{W}}$, we exclude $M_{\tilde{W}} < 25$ GeV.

We thank Dr. D. A. Dicus, Dr. G. Kane, Dr. O. Nachtmann, Dr. S. Nandi, Dr. A. Reiter, and Dr. E. Reya for useful discussions, and the DESY management and the PETRA machine group for excellent support. This work was supported in part by the Deutsches Bundesministerium fur Forschung und Technologie, and by the Pakistan Atomic Energy Commission.

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