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A SEARCH FOR SINGLE ELECTRON PRODUCTION IN ELECTRON POSITRON ANNIHILATION AT $E = 29 \text{ GeV}^*$

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Abstract

This thesis presents experimental results from the ASP detector which took data on e^+e^- interactions in the PEP storage ring at SLAC. Its design was particularly suitable for searching for production of supersymmetric particles. The motivations for and phenomenology of Supersymmetry are discussed. In particular, the production of a single supersymmetric electron ("selectron", \tilde{e}) in combination with a supersymmetric photon ("photino", $\tilde{\gamma}$) would result in events in which a single electron and no other particles are observed in the detector at an e^+e^- collider such as PEP, provided the masses of these particles are not too large. Such events would also result from the production of a single supersymmetric W-boson ("wino", \widetilde{W}) in combination with a supersymmetric neutrino ("sneutrino", $\tilde{\nu}$). These processes make it possible to search for selectrons and winos with masses greater than the beam energy. Observation of these unusual events would distinctly indicate the production of new particles.

The ASP detector was designed to be hermetic and to provide efficient event reconstruction for low multiplicity events. The detector is described and its performance is evaluated; it is found to be well-suited to this study. The data sample collected with the detector was thoroughly analyzed for evidence of single-electron events. The various possible background processes are considered and Monte Carlo calculations of the distributions from single selectron and single wino production are presented. Using this information an efficient off-line event selection process was developed, and it is described in detail.

No evidence for single-electron events was observed, allowing the following limits (95 % CL) to be set on the supersymmetric particle masses:

$$\begin{split} \mathbf{m}_{\tilde{e}} &> 20.5 \ \mathrm{GeV/c^2}, \qquad \mathrm{for} \qquad \mathbf{m}_{\tilde{e}_L} = \mathbf{m}_{\tilde{e}_R}, \qquad \mathbf{m}_{\tilde{\gamma}} = 0 \\ \mathbf{m}_{\tilde{e}} &> 19.5 \ \mathrm{GeV/c^2}, \qquad \mathrm{for} \qquad \mathbf{m}_{\tilde{e}_L} \gg \mathbf{m}_{\tilde{e}_R}, \qquad \mathbf{m}_{\tilde{\gamma}} = 0 \\ \mathbf{m}_{\widetilde{W}} &> 20.6 \ \mathrm{GeV/c^2}, \qquad \mathrm{for} \qquad \mathbf{m}_{\tilde{\nu}} = 0 \end{split}$$

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Introduction

1

The study of Elementary Particle Physics during this century has lead to an understanding of the basic constituents of matter and their properties which is known as the **Standard Model**⁽¹⁻³⁾. This theory assumes that the fundamental constituents of all of matter are the quarks and leptons, with these particles interacting through the exchange of vector guage bosons which arise from symmetry under local transformations within the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ (see Table 1.1). This description of Nature has been enormously successful in accounting for the multitude of phenomena that have been observed in a wide variety of experiments, at presently accessible energies. For instance, it predicted the existence of the W^{\pm} and Z^0 bosons before they were discovered. There are presently no experimental results in conflict with this theory.

However, the Standard Model cannot be a complete theory of the fundamental particles and their interactions: it has a number of shortcomings, most notably the large number of arbitrary parameters, the many unrelated fundamental particles, and its lack of explanation of the relation of gravity to the other forces. The main problems which are not accounted for by the Standard Model are the issues of Unification, Flavor and Mass.

The Unification problem arises from the desire to have a single unified mathematical structure that encompasses all of the variety of known forces of Nature, viz. the strong and the weak nuclear forces, electromagnetism and gravitation. Although the Standard Model has provided a means for unifying the weak force and electromagnetism, complete unification has not been obtained. Currently there are the theories of Grand Unification, Supergravity and Superstrings, which hope to resolve this issue. While these theories may make predictions for new phenomena that may be currently observable, such as proton decay, none of these has yet been discovered; instead, the main feature of all of these theories is that they predict new interactions at very high energies ($\geq 10^{15}$ GeV) which are well beyond the reach of current experiments.

The *Flavor* problem refers to the proliferation of quark and lepton species that have been discovered. The observation of sequential generations of particles is clearly reminiscent of the periodic table of the elements, and of the families of mesons and baryons, and so leads to the hypothesis that the quarks and leptons in turn may be composites made of more elementary constituents. This has motivated various theories of compositness, which predict new four-fermion contact interactions, form factors for quarks and leptons which would no longer be point-like, and excited leptons, quarks and possibly vector bosons. While we have as yet no clear idea as to what the scale of such compositness might be, the agreement of so many measurements with the Standard Model, which assumes that these particles are point-like, indicates that it must exceed O(1) TeV.

The Mass problem arises from the lack of understanding of the origin of the masses of the fermions and vector bosons. Unlike the previous two problems, this one requires a solution through the appearance of new physics at a scale that must be below 1 TeV. This makes it the most interesting problem to tackle as it is the one that should be solved soonest. In order for the Standard Model to be consistent with non-zero vector boson and fermion masses, there must exist at least one physical spin-0 particle, the Higgs boson, H, with a mass $m_H = O(m_W) = O(100)$ GeV/c², and which couples to other particles with a strength proportional their mass. However, the Higgs boson has not been observed yet, so this aspect of the theory remains untested.

If the Higgs boson is elementary then including it in a more unified theory containing large mass scales leads to a serious inconsistency. In the absence of new physics below some high scale Λ , radiative corrections due to loops of light particles make a contribution to the Higgs boson mass which is proportional to Λ . Consequently, in the Standard Model there is no way of preventing the elementary Higgs boson from acquiring masses of order the unification scale due to these radiative corrections. But the Higgs mass cannot be too large compared to the weak scale, otherwise it is unable to account for symmetry breaking at this scale, since the weak vector bosons would acquire large masses of the same magnitude. This is known as the gauge hierarchy problem⁽⁴⁾. It arises since the weak scale is vastly different from the scales of grand unification: $m_W/m_{GUT} \sim O(10^{-13})$,

and of gravity: $m_W/m_{Planck} \sim O(10^{-17}).$

Thus it is not confined to grand unified models, since it is essentially a problem of two widely different energy scales, and the Planck scale, where gravity becomes a strong force, is unavoidable. This is also known as the *naturalness* problem, since it takes an unnatural fine-tuning in the Standard Model to maintain the Higgs mass at $O(m_W)$ rather than $O(m_{Planck})$.

One way around this problem is to assume that the Higgs boson is composite. This scenario is known as *Technicolor*⁽⁵⁻⁷⁾. It postulates that the Higgs boson is composed of fermions bound together by a new interaction which becomes strong at an energy scale $\Lambda \sim 1$ TeV. This avoids elementary scalars altogether and consequently eliminates the hierarchy problem. This is referred to as dynamical symmetry breaking. Technicolor would lead to many new technimesons and technibaryons with masses around 1 TeV. Many extended technicolor models give masses to fermions as well as to gauge bosons and contain at least some spin-0 technipions with masses $\leq 100 \text{ GeV/c}^2$ that would be observable at present or planned accelerators. While the original idea of Technicolor is very attractive, realistic models appear to have too many difficulties to be viable.

An alternative approach which retains a fundamental Higgs boson is the theory of **Supersymmetry**⁽⁸⁻¹⁰⁾(SUSY) which postulates a fundamental symmetry between bosons and fermions. This theory alleviates many of the shortcomings of the Standard Model and has great potential for providing a framework for constructing a unified

field theory. It introduces new physics in the form of a supersymmetric partner for each known particle, which has a spin differing by $\frac{1}{2}$ but otherwise is identical to the known particle, viz. it has the same mass, quantum numbers and gauge couplings. Thus there are bosons to partner fermions and vice versa. This resolves the hierarchy problem entirely since the quadratically divergent one-loop radiative corrections to the Higgs mass have the opposite sign for fermions than for bosons. So the introduction of superpartners leads to an exact cancellation of these corrections on a particle-byparticle basis in a supersymmetric theory.

Ideally, each known particle would be the superpartner of another known particle, effectively halving the total number of particles. However, since there is no known boson-fermion pair of particles with otherwise identical quantum numbers, no known particle can be the superpartner of any other known particle. The most obvious instance of this is that no spin-zero elementary particles are known, which are required as superpartners of the quarks and leptons. Consequently, since boson-fermion pairs of particles degenerate in mass are not observed, supersymmetry, if it is indeed a symmetry of Nature, must be broken. Then the SUSY particles will have different masses from their known partners. Since the details of the symmetry breaking are unknown, there is no convincing theory for the masses of the superpartners (as is the case for the known fermions). Given that SUSY is not exact, the loop diagrams giving radiative corrections to the Higgs mass are cut off at an energy corresponding to the mass splitting between the known particles and their superpartners. Then for the cancellation to solve the hierarchy problem the mass splitting between the particles and their superpartners must not be much larger than the weak energy scale. Consequently it is expected that SUSY particles would have masses less than about 1 TeV, within the energy range of current or next generation accelerators.

In addition to solving the hierarchy problem, supersymmetry is very exciting because it has fewer divergences than other quantum field theories and may lead to a finite quantum theory of gravity and the unification of all interactions. Supersymmetry allows a connection to be made between the Poincarè group of space-time transformations and internal groups. By making supersymmetry a local symmetry, a new gauge field is introduced. Since the classical theory of local Poincarè symmetry is the theory of general relativity, this new gauge field is identified to be the graviton, the quantum of gravity. Such a theory is known as *supergravity*. The combination of the spin-2 graviton with its spin- $\frac{3}{2}$ superpartner, the gravitino, yields theories of quantum gravity in which a number of divergences are eliminated, analogously to the manner in which boson-fermion pairing eliminates the hierarchy problem. These are the first quantum gravity theories which are finite at the few loop level when couplings to matter are included⁽¹¹⁾. Supersymmetry is also a necessary ingredient of *superstring* theories which describe the fundamental constituents of matter as strings rather than . as point particles. These theories have generated a great deal of excitement recently as promising candidates for the ultimate theory of matter.

This thesis describes an experimental search for superparticles performed at the PEP e^+e^- storage ring at SLAC using the ASP detector. It was the first detector specifically designed to search for production of these particles. Its name was derived from the title **Anomalous Single Photon** experiment since the initial primary motivation was to search for single photon events. This thesis covers an alternative and complementary approach to searching for superparticles, namely by searching for single electron events. The remainder of this chapter covers the theoretical background for the experiment, while the details of the apparatus, the data analysis and the results are given in subsequent chapters.

1.1 Phenomenology of Supersymmetry

During the early part of this decade there has been considerable theoretical interest in models of low energy supersymmetry. Attention will be confined here to *minimal* supersymmetry, *i.e.* the theory contains only one (N=1) generator of SUSY transformations, Q, such that:

 $Q |Boson\rangle = |Fermion\rangle$ and $Q |Fermion\rangle = |Boson\rangle$. Such a theory contains the fewest particles possible.

The particle spectrum in such a theory is shown in table 1.1. A supersymmetric particle is indicated by the presence of a tilde over the symbol (*e.g.* \tilde{e} for the *selectron*,

the superpartner of the electron). Since the quarks and charged leptons each have both a left-handed and a right-handed component, there are two spin-0 partners of these particles, which have different couplings with respect to the weak interactions, just like their known partners. They are labeled with subscripts L and R, although these spin-0 particles obviously cannot themselves be left- or right-handed; this is simply a convenient notation, referring to the component of the spin- $\frac{1}{2}$ partner. The Higgs sector has to be enlarged to include two Higgs doublets⁽¹⁰⁾: one is required to generate masses for the charge $-\frac{1}{3}$ quarks and another for the charge $+\frac{2}{3}$ quarks. Thus SUSY predicts the existence of physical charged Higgs bosons. The two doublets are also required to provide an equal number of bosonic and fermionic degrees of freedom for the weak gauge bosons and Higgs bosons, and their superpartners. A spontaneously broken theory also contains a fermionic Goldstino associated with the super-Higgs mechanism, while supergravity models contain a gravitino which absorbs the Goldstino to obtain its spin $\pm\frac{1}{2}$ polarization state⁽¹²⁾. In either case there is a neutral weakly interacting particle \tilde{G} present.

Unfortunately, supersymmetry does not directly predict the masses of the superpartners, or even the sequence of the masses. Specific predictions do arise from different symmetry breaking mechanisms used in specific models. Very often many superpartners are predicted to have masses below that of the weak bosons, and so would be accessible to the current generation of accelerator experiments. But these models require a number of assumptions, so that while they can give some guidance about the SUSY masses, in general the masses should be taken as unknown. However, the sequence of masses is crucial, in particular, which is assumed to be the lightest SUSY particle; this is discussed below. Additional ambiguity arises since the mass eigenstates can in general be mixtures of the weak eigenstates having the same quantum numbers. This mixing also depends on the details of the model of symmetry breaking. In particular, the $\tilde{\gamma}, \tilde{Z}^0, \tilde{H}_1^0$ and \tilde{H}_2^0 can mix to form *neutralinos*, and the \tilde{W}^{\pm} and \tilde{H}^{\pm} can mix to form *charginos*. This allows a great deal of variety in the couplings of these particles and the predicted phenomenology. It is assumed here that this mixing is small, so that the mass eigenstates and weak eigenstates are essentially

Table 1.1. The weak eigenstates in a minimal supersymmetric theory. The generic particle symbols denote the quark species q = (u, d, c, s, t, b) and the lepton species $l = (e, \mu, \tau)$; and i = 1,2 for the two Higgs states. The mass eigenstates can in general be mixture of $(\tilde{q}_L, \tilde{q}_R), (\tilde{l}_L, \tilde{l}_R), (\tilde{\gamma}, \tilde{Z}^0, \tilde{H}_i^0)$ and $(\widetilde{W}^{\pm}, \tilde{H}_i^{\pm})$.

Standard Model					Supersymmetric
Particle	symbol	spin	spin	symbol	Partner
lepton	l_L, l_R	$\frac{1}{2}$	0	\tilde{l}_L, \tilde{l}_R	slepton
neutrino	$-\nu_l$	$\frac{1}{2}$.	0	$\tilde{\nu}_l$	sneutrino
quark	q_L, q_R	$\frac{1}{2}$	0	$ ilde{q}_L, ilde{q}_R$	squark
gluon	g	1	$\frac{1}{2}$	\widetilde{g}	gluino
photon	γ	-1	$\frac{1}{2}$	$ ilde{\gamma}$	photino
Z-boson	$Z^{\mathfrak{o}}$	1	$\frac{1}{2}$	$\widetilde{Z}^{\mathfrak{o}}$	Zino
Higgs	$H^{0}_{m{i}}$	0	$\frac{1}{2}$	$\widetilde{H}^{\scriptscriptstyle 0}_{\pmb{i}}$	Higgsino
W-boson	W^{\pm}	1	$\frac{1}{2}$	\widetilde{W}^{\pm}	Wino
Higgs	H_i^{\pm}	0	$\frac{1}{2}$	\widetilde{H}_i^{\pm}	Higgsino

the same. Since the superparticles interact with the same coupling constants as the known particles, it is possible to calculate cross-sections for different SUSY processes, and the production cross-sections for some particles are large unless suppressed by mass effects. Given the uncertainty in the SUSY mass spectrum the cross-sections need to be determined as functions of the masses involved.

In most models of supersymmetry there is a multiplicatively-conserved quantum number^(13,14)known as *R-Parity*. The known particles have R = +1 while their superpartners have R = -1. This quantum number can be defined by

$$R = (-1)^{2J+3B+L}$$
(1.1)

where J = spin, B = baryon number and L = lepton number. As is almost always the case, it is assumed here that R-parity is conserved. Although other models can be constructed in which R-parity is not conserved, their phenomenology is quite different

from conventional SUSY theories. Such theories contain interactions which violate lepton number or baryon number, which allows the lightest SUSY particle to decay and leads to many different unusual multilepton or multijet signatures ⁽¹⁵⁾.

R-parity conservation is very significant in determining the properties of SUSY theories. The first consequence is that superparticles produced from known particles must be produced in pairs since the initial state must have R = +1. Secondly, and most importantly, the lightest SUSY particle (LSP) has to be stable, since no combination of only R = +1 particles can be formed from an R = -1 parent. Furthermore all other superparticles must eventually decay to the LSP. Cosmological arguments and searches for anomalously heavy protons indicate that the LSP cannot be charged or strongly interacting⁽¹⁶⁾. Consequently the LSP must be neutral and non-strongly interacting. Possible candidates for the LSP are the photino ($\tilde{\gamma}$), the sneutrino ($\tilde{\nu}$), the neutral Higgsino (\tilde{H}), and the Goldstino or gravitino (\tilde{G}). As is most commonly the case, it will be assumed here that the LSP is the photino. If the sneutrino were the LSP, then the phenomenology would be essentially the same as if the photino is the LSP (see sec. 1.3).

Since the coupling of the photino is the same as that of the photon, *i.e.* it interacts electromagnetically, it might be expected to interact in a detector. In fact, its interactions with quarks or leptons are very weak compared to those of the photon since these interactions require the exchange or production of the SUSY partners of the quarks or leptons, which are known to be massive since they have been unobserved at present energies. For instance, the cross-section for the SUSY analog of Compton scattering: $\tilde{\gamma}e^- \rightarrow \tilde{\gamma}e^-$ (see fig. 1.1) is⁽¹⁷⁾:

$$\sigma_{\tilde{\gamma}e^-} = \frac{8\pi\alpha^2}{3} \frac{s}{m_{\tilde{e}}^4} \tag{1.2}$$

So the ratio of this to the similar neutrino interaction, $\bar{\nu}_{\mu}e^{-} \rightarrow \bar{\nu}_{\mu}e^{-}$ is⁽¹⁸⁾:

$$\frac{\sigma_{\tilde{\gamma}e^-}}{\sigma_{\bar{\nu}e^-}} = \left(\frac{78 \text{ GeV/c}^2}{m_{\tilde{e}}}\right)^4 \tag{1.3}$$

As will be discussed shortly the selectron mass has been limited to be greater than

at least 20 GeV/c^2 , so the photino interaction cross-section is comparable to that of neutrinos.



Figure 1.1. Feynman diagram for the Compton-like scattering of a photino and an electron.

Consequently the photino behaves like a neutrino in its interactions with matter, and cannot be directly detected in collider experiments. The only way that photinos can be *detected* is by observation of the missing energy and momentum that they carry away. Since photinos are the final decay product of every process, the general signature for SUSY processes is **missing energy and momentum**.

Naturally, it is most sensible to search first for what are expected to be the lightest of the superparticles: viz. the photino and the selectron, and also the sneutrino. Consideration is now given to searches for these particles in the clean, low background environment of e^+e^- interactions.

1.2 Production of Photinos and Selectrons

1.2.1 Photino Pair Production

With the photino assumed to be the LSP, it is obviously the first SUSY particle that should be searched for. For instance, photinos could be pair produced in $e^+e^$ interactions by the *t*-channel exchange of a selectron, *i.e.* $e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$, as shown in fig. 1.2. But, as has been discussed above, photinos would be weakly interacting



Figure 1.2. Feynman diagram for the pair production of photinos in e^+e^- interactions.

and could not be detected in conventional detectors, so that this reaction would go undetected.

However, if a photon is radiated during the interaction, *i.e.* the process becomes $e^+e^- \rightarrow \gamma \tilde{\gamma} \tilde{\gamma}$, as shown in fig. 1.3, then that photon alone could be detected, so that just a single photon would be observed in a detector⁽¹⁷⁻²³⁾. This is quite a spectacular signature. The original motivation for the ASP experiment was to search for such anomalous single photon events. Clearly this process can only occur if $m_{\tilde{\gamma}} < E_{beam}$. This process is also limited by the selectron propagator, which suppresses the cross-section relative to the large cross-section for the analogous reaction for the known particles, *i.e.* $e^+e^- \rightarrow \gamma\gamma\gamma$, even if the photino is light. The only unknown parameters in the cross-section are $m_{\tilde{\gamma}}$ and $m_{\tilde{e}}$, so that if such events are not observed in an experimental search, then limits can be set on these masses. Since the selectron occurs only in the propagator this process is sensitive to $m_{\tilde{e}} > \sqrt{s}$.

This technique of searching for an otherwise invisible process through radiative photon tagging is not limited to photino pair production; any long-lived, weakly interacting neutral particle (e.g. $\tilde{\nu}$, \tilde{H}^0) can be searched for in this manner. The non-observation of a significant signal thus limits the total contribution of all such light particles to the e^+e^- total cross-section. Any such search for the production of new particles is ultimately limited by the Standard Model background from radiative neutrino pair production which is also a source of single photon events. Since the



Figure 1.3. Feynman diagrams for the radiative production of photinos pairs in e^+e^- interactions. The amplitude for the lower diagram is substantially smaller than the other two, since the massive \tilde{e} propagator enters twice in it.

cross-section for this process⁽²³⁻²⁶⁾has essentially a linear dependence on the number of light neutrino generations (N_{ν}) the non-observation of an anomalous number of single photon events allows limits on N_{ν} to be obtained. The details and results of the ASP single photon search have been described elsewhere⁽²⁷⁻³⁰⁾.

1.2.2 Selectron Pair Production

Alternatively to searching for indirect evidence for the selectron through radiatively tagged photino pair production, it is possible to search for the production of selectrons directly. The selectron is assumed to decay rapidly to an electron and a photino, as shown in fig. 1.4, with a branching ratio of 100 %. As mentioned earlier, there are two \tilde{e} mass eigenstates. In some models the \tilde{e}_L is expected to be heavier than the \tilde{e}_R due to additional weak radiative corrections. Thus, as is conventional, the two extreme cases will be considered: \tilde{e}_L is much heavier than \tilde{e}_R , so that only \tilde{e}_R can be produced; or that they are degenerate in mass, which leads to a doubling of the cross-section compared to the other case.



Figure 1.4. Feynman diagram for the decay of a selectron to an electron and a photino.

Selectrons can be pair produced in e^+e^- interactions through single photon annihilation and t-channel exchange of a photino as shown in fig. 1.5. This process was first calculated by Farrar and Fayet⁽³¹⁾ for the case of a massless photino. The effect of a non-zero photino mass has been taken into account by later calculations^(32,33). Obviously, searches for this process are limited to probing masses $m_{\tilde{e}} < E_{beam}$. Although it does not probe as large a $m_{\tilde{e}}$ range as the other processes considered here, it is able to obtain limits that are valid for higher values of $m_{\tilde{\gamma}}$ than the other processes.

The signature from this process, *i.e.* $e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$ followed by the rapid decay $\tilde{e} \rightarrow e\tilde{\gamma}$, would be a pair of electrons that would tend to have marked acoplanarity, with missing energy. This is a very clean signature. The main backgrounds arise from the QED processes $e^+e^- \rightarrow e^+e^-\gamma$ and $e^+e^- \rightarrow e^+e^-e^+e^-$, which can be straightforwardly eliminated by requiring that the two detected electrons have some minimum acoplanarity, and that no other particles are observed. A number of experiments have searched for this process⁽³⁴⁻⁴⁰⁾. No evidence for an anomalous rate for this signature has been observed. Since this process is limited by the available energy of the accelerator, not by statistics, it is possible to set limits on $m_{\tilde{e}}$ very close to E_{beam} . This



Figure 1.5. Feynman diagrams for the pair production of selectrons in e^+e^- interactions. Two additional diagrams with the γ replaced by a Z^0 and the $\tilde{\gamma}$ replaced by a \tilde{Z}^0 also contribute to this process, but their contribution is negligible at the energy of PEP or PETRA.

gives experiments at PETRA an advantage over those at PEP, and limits of $m_{\tilde{e}} > 23$ GeV/c² for $m_{\tilde{e}_L} = m_{\tilde{e}_R}$, and $m_{\tilde{e}} > 22$ GeV/c² for $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$, both for $m_{\tilde{\gamma}} = 0$, have been obtained.

1.2.3 Single Selectron Production

It was first suggested by Farrar and Fayet⁽³¹⁾ that it would be possible to produce a single supersymmetric lepton in association with the corresponding spin- $\frac{1}{2}$ lepton and a photino (or goldstino) *i.e.* through associated production. Thus single selectrons could be produced by the process $e^+e^- \rightarrow e^{\pm}\tilde{e}^{\mp}\tilde{\gamma}$ followed by the rapid decay $\tilde{e} \rightarrow e\tilde{\gamma}$. Although this process has a lower cross-section (proportional to α^3) than the pair-production process (proportional to α^2), it makes possible the production of SUSY leptons in e^+e^- collisions even though they have a mass greater than the beam energy; *i.e.* it allows probing the mass region: $m_{\tilde{e}} > E_{beam}$, provided that $m_{\tilde{e}} < 2E_{beam} - m_{\tilde{\gamma}}$.

The first calculation of the cross-section for this process was performed by Gaillard, Hall and Hinchliffe⁽⁴¹⁾ for the case of a massless photino. It was later recalculated including the effect of a non-zero photino $mass^{(42)(33)}$. All of these calculations employed the equivalent photon approximation (EPA)^(43,44), which assumes firstly that the dominant contribution to this process arises from only the two Feynman diagrams shown in fig. 1.6. Furthermore, one of the initial state electrons is assumed to radiate a quasi-real photon and that electron is then forward scattered, so that it continues down the beam line and is undetected since it remains within the beam pipe. The photon interacts with the other electron to form a selectron and a photino (in the SUSY analog of Compton scattering). The selectron then decays immediately into an electron and a photino, with the electron being energetic and distributed almost isotropically for high mass selectrons, while the two photinos are undetected. The signature is thus a single hard electron from the decay of the selectron; it has a high p_t since it balances the p_t of the two photinos, with no other particles detected. This is a very distinct signature, with little background, as is discussed in detail in chapter 4.



Figure 1.6. Feynman diagrams for the production of a single selectron in the Equivalent Photon Approximation.

A number of experimental groups have reported performing searches for single selectron production in e^+e^- interactions at PEP and PETRA⁽³⁹⁾⁽⁴⁰⁾⁽⁴⁵⁻⁴⁸⁾. They are summarized in table 1.2. However, the results of all but one of these searches were based on approximate calculations of this process using the EPA, which appear to have overestimated the cross-sections. A calculation including the effect of a non-zero scattering angle for the forward-going e^{\pm} has been performed⁽⁴⁹⁾, however, it was restricted to a massless photino.

More recently a complete calculation of this process which is valid for all e^{\pm} scattering angles and a non-zero photino mass has been performed by Martinez^(50,51).

Table 1.2. Summary of previous single electron searches at PEP and PETRA and the limits set on $m_{\tilde{e}}$ and $m_{\tilde{W}}$. EPA indicates the results were obtained using the equivalent photon approximation; MM indicates the results were obtained using the complete calculations of M. Martinez *et al.* The $\Delta \phi_{loss}$ value is the region of ϕ that is lost from the acceptance due to poor detector coverage.

Experiment	Mark II	MAC	MAC	JADE	CELLO	MARK-J
Reference	(46)	(47)	(48)	(40)	(41)	(49)
Monte Carlo	EPA	EPA	MM	EPA	EPA	MM
$\sqrt{s}~({ m GeV})$	29.0	29.0	29.0	32.0 - 38.6	38.3 - 46.6	$\langle 39.5 \rangle$
$\int Ldt \; (pb^{-1})$	123.	36.4	206.	72.8	37.6	49.
Acceptance		-				
$E_e ~({ m GeV})$	>9.4	>6.0	>3.5 - 7.0			
P_t/E_{beam}				>.65	>.3	>.2
$ cos \theta $	<0.7	<0.75	< 0.75	<0.7	< 0.85	<0.996
$\Delta \phi_{loss} \; (^{o})$	43.		-	100.	27.5	_
Limits on $m_{ ilde{e}}$					-	
$m_{ ilde{e}_L}=m_{ ilde{e}_R}$	22.2	22.4	24.1	25.2	30.0	25.5
$m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$	18.3		22.8	21.8	26.8	-
$(95\% \text{ CL}) (\text{GeV}/\text{c}^2)$						
Limits on $m_{\widetilde{W}}$						
$(95\% \text{ CL}) (\text{GeV/c}^2)$	-	_		_	26.2	26.5
$(90\% \text{ CL}) (\text{GeV/c}^2)$			22.0			

This calculation incorporates all 14 first-order Feynman diagrams: in addition to the two diagrams shown in fig. 1.6, there are the 6 diagrams shown in fig. 1.7, all of which contribute at lower energies, and an additional 6 diagrams which include a Z^0 , which have very little effect at the energy of PEP. The additional diagrams are not negligible; for instance, if the photino is light, then the fourth diagram in fig. 1.7 involving the exchange of a photino in the *t*-channel is important.

Using this calculation the MAC collaboration⁽⁴⁷⁾found that including all the



Figure 1.7. Additional Feynman diagrams for the production of a single selectron. There are also diagrams involving a Z^0 , but their effect is very small at the energy of PEP.

diagrams and the effects of the e^{\pm} scattering angle "reduces the single selectron production cross-section by 40 % for the cuts and masses used in (their) previous publication⁽⁴⁶⁾." The failure of the EPA in this case is due to the fact that for large

selectron masses the virtual photon has to take almost all of the energy of the incoming electron which is a situation in which the EPA can break $down^{(52)}$.

This work makes use of the same complete calculation by Martinez for determining the cross-sections expected in this experiment. The total cross-section for single selectron production at PEP from this Monte Carlo calculation is shown in fig. 1.8 as a function of selectron mass and of photino mass. The cross-section decreases increasingly rapidly as $m_{\tilde{e}}$ or $m_{\tilde{\gamma}}$ approaches the kinematic boundary. For a typical data set with an integrated luminosity of 100 pb⁻¹, a high efficiency search for single selectron production should be able to set mass limits close to $m_{\tilde{e}} > 24 \text{ GeV/c}^2$ for $m_{\tilde{\gamma}} = 0$, and $m_{\tilde{\gamma}} > 12.5 \text{ GeV/c}^2$ for $m_{\tilde{e}} = 15 \text{ GeV/c}^2$. Although with current data sets the sensitivity of such a search is determined by statistics, for a factor 10 increase in integrated luminosity the limits would be close to saturation and the search would become limited by the beam energy. The detailed predictions of this Monte Carlo calculation are presented in chapter 5.

1.3 Production of Sneutrinos and Winos

Since the production of sneutrinos and winos in e^+e^- interactions can lead to the same signatures as those for photinos and selectrons, the searches described above can also look for evidence of the production of these particles.

Only left handed neutrinos are observed, so minimal SUSY contains a single scalar neutrino $\tilde{\nu}_L \equiv \tilde{\nu}$. Sneutrinos can be produced in decays and also directly in e^+e^- annihilation. With the photino being the LSP the $\tilde{\nu}$ decays almost entirely by $\tilde{\nu} \rightarrow \nu \tilde{\gamma}$, which can only occur via triangle diagrams, and the sneutrino will be undetected.

In many models of supersymmetry the sneutrino mass is similar to the selectron mass. However it will be assumed here that the sneutrino is light. In some models the $\tilde{\nu}$ is the LSP, in which case it would be stable. It interacts with the known particles through the weak force only, mediated by the W^{\pm} and Z^0 or their superpartners the \widetilde{W}^{\pm} and \widetilde{Z}^0 . The \widetilde{W}^{\pm} and \widetilde{Z}^0 have been limited experimentally to be massive, so the $\tilde{\nu}$ interaction cross-sections must be of the same order of magnitude as those of the



Figure 1.8. Total cross-section for single selectron production as a function of (a) selectron mass, and (b) photino mass. The solid curves are for $m_{\tilde{e}_L} = m_{\tilde{e}_R}$, while the dashed curves are for $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$.

neutrinos. Consequently the sneutrino will be undetected. If the sneutrino were the LSP, the photino would decay according to $\tilde{\gamma} \rightarrow \nu \tilde{\nu}$, and the photino would also be unobservable in this case, since the $\tilde{\nu}$ and ν would both be undetected. Consequently the phenomenology discussed above assuming the photino to be the LSP is unchanged if instead the sneutrino is the LSP.

1.3.1 Sneutrino Pair Production

Sneutrinos could be pair produced in e^+e^- interactions *i.e.* $e^+e^- \rightarrow \tilde{\nu}\tilde{\nu}$, through the formation of a single Z^0 in the *s*-channel, or the *t*-channel exchange of a $\widetilde{W}^{(53,54)}$. Since the sneutrino would be weakly interacting, this process would be undetectable just like photino pair production. However, the radiatively tagged version of this process will contribute to the single photon cross-section⁽⁵⁵⁾. So single photon searches can also obtain limits on $m_{\tilde{\nu}}^{(30)}$; in addition, the presence of the \widetilde{W} propagator in one diagram makes this process sensitive to $m_{\widetilde{W}} > \sqrt{s}$.

1.3.2 Wino Pair Production

Although the weak vector bosons W^{\pm} and Z^0 are too heavy to be produced at PEP and PETRA, a wide class of SUSY models predicts that one of the partners (\widetilde{W}^{\pm} and \widetilde{Z}^0) of each of them will be lighter and the others heavier, than the corresponding known bosons⁽⁵⁶⁾. There are a number of possible decay modes for the wino^(57,58). Due to the unknown masses of the particles involved in such decays, (particularly the $\tilde{\nu}$ and \tilde{g}), and the complete ignorance about chargino mixings, predictions for the \widetilde{W} decay and any resulting limits on its mass, are very model-dependent. As mentioned above, it is assumed here that the chargino mixing is small, so that the light chargino state is essentially a pure weak eigenstate, the wino, and the heavier chargino state a pure Higgsino. Having assumed that the sneutrino is light, the wino decays exclusively according to the two body decay: $\widetilde{W} \to l\tilde{\nu}_l$, with the $\tilde{\nu}$ escaping undetected. Assuming that the three generations of sneutrinos are degenerate in mass, the branching ratios into the three known leptons will be equal, so that the branching ratio for the decay in to an electron, $\widetilde{W} \to e\tilde{\nu}_e$, is $\frac{1}{3}$. Winos can be pair-produced in e^+e^- interactions through single photon annihilation and t-channel sneutrino exchange^(59,60) as shown in fig. 1.9. Since the wino has spin- $\frac{1}{2}$, its production cross-section is enhanced compared to that of the squarks or sleptons, which have spin-0, except compared to selectron pair production where the electromagnetic coupling in the t-channel photino exchange diagram (fig. 1.5) makes a much larger contribution than the weak coupling in the t-channel sneutrino exchange diagram (fig. 1.9) for wino pair production.



Figure 1.9. Feynman diagrams for the pair production of winos in e^+e^- interactions.

With the assumptions made here, the signature from this process, *i.e.* $e^+e^- \rightarrow \widetilde{W}^+\widetilde{W}^-$ followed by the rapid decay $\widetilde{W} \rightarrow l \tilde{\nu}_l$, would be a pair of acoplanar (not necessarily identical) leptons with missing momentum, which is very similar to that of pair production of new heavy leptons. This process has been searched for at PETRA^{(40)(61,62)}. As for selectron pair production, limits very close to E_{beam} have been obtained, *i.e.* $m_{\widetilde{W}} > 23 \text{ GeV/c}^2$.

1.3.3 Single Wino Production

The single electron experimental signature discussed above is not an unambiguous signature for single selectron production. It would also result from the production of single winos in a process analogous to single selectron production: *i.e.* $e^+e^- \rightarrow e^{\pm}\widetilde{W}^{\mp}\widetilde{\nu}$, followed by the rapid decay $\widetilde{W} \rightarrow e\widetilde{\nu}_e$. This process has a lower cross-section than that from wino pair production, but it makes possible the production of winos in e^+e^- collisions, even though they have a mass greater than the beam energy; i.e. it allows probing the mass region: $m_{\widetilde{W}} > E_{beam}$, provided that $m_{\widetilde{W}} < 2E_{beam} - m_{\widetilde{\nu}}$.

This process results in an electron scattered forward, dominantly at low angles, so that it is mostly undetected as it will usually remain within the beam pipe, and a single hard lepton $(e, \mu \text{ or } \tau)$, together with an undetected sneutrino, from the wino decay. Since the ASP detector was optimized for the detection of electrons and photons, only the single electron signature will be considered here. Just like for single selectron production, the signature is a single electron with high p_t , since it balances the p_t of the two sneutrinos, with no other particles detected.

Approximate calculations of this process have been performed⁽⁴²⁾⁽⁶³⁾ using the EPA which takes into account only the first two diagrams in fig. 1.10. Such a calculation was used by the CELLO collaboration⁽⁴⁰⁾ to obtain results for their search for single wino production. However, the approximation used in these calculations is apparently inaccurate⁽⁴⁷⁾, as discussed above for the case of single selectron production, and overestimates the cross-section so that the CELLO limit is probably too high. More recently a complete calculation of this process which is valid for all e^{\pm} scattering angles and a non-zero sneutrino mass has been performed by Martinez, Grifols and Pascual⁽⁶⁴⁾. It incorporates all 12 first-order Feynman diagrams: there are the 6 diagrams shown in fig. 1.10, all of which contribute at lower energies and an additional 6 diagrams which include a Z^0 , which have very little effect at the energy of PEP. The additional diagrams are not negligible; for instance, if the sneutrino is light, then the fifth diagram in fig. 1.10 involving the exchange of a sneutrino in the *t*-channel is important. Both the MAC collaboration⁽⁴⁷⁾ and the MARK-J collaboration⁽⁴⁸⁾ have used this calculation to obtain results for this process. All previous experimental searches are summarized in Table 1.2.

This work makes use of the complete calculation by Martinez *et al.* for determining the cross-sections expected in this experiment. The total cross-section for single wino production at PEP from this Monte Carlo calculation is shown in fig. 1.11 as



Figure 1.10. Feynman diagrams for the production of a single wino. There are also diagrams involving a Z^0 , but their effect is very small at the energy of PEP.

a function of wino mass and of sneutrino mass. The cross-section is quite similar to that for single selectron production (fig. 1.8) and decreases increasingly rapidly as $m_{\widetilde{W}}$ or $m_{\tilde{\nu}}$ approaches the kinematic boundary.



Figure 1.11. Total cross-section for single wino production as a function of (a) wino mass, and (b) sneutrino mass.

For a typical data set with an integrated luminosity of 100 pb⁻¹, a high efficiency search for single wino production should be able to set mass limits close to $m_{\widetilde{W}} >$ 23 GeV/c² for $m_{\tilde{\nu}} = 0$, and $m_{\tilde{\nu}} > 12.5$ GeV/c² for $m_{\widetilde{W}} = 15$ GeV/c². Although with current data sets the sensitivity of such a search is determined by statistics, for a factor 10 increase in integrated luminosity the limits would be close to saturation and the search would become limited by the beam energy. The detailed predictions of this Monte Carlo calculation are very similar to those for single selectron production, and are also described in chapter 5.

1.4 Experimental Requirements

The cross-sections for single selectron and single wino production shown above indicate that the single electron events being searched for are expected to be rare. To establish a positive result, or set a significant limit on the possible cross-sections requires a detector which can veto essentially all events due to potential backgrounds. This necessitates complete solid angle coverage down to as close to the beam line as possible, with charged particle detection and electromagnetic calorimetry in order to provide the required level of event containment. While the detector does not have to allow as detailed an event reconstruction as other more general purpose e^+e^- detectors do, it cannot have any holes or cracks in its coverage, if it is to perform this search successfully. Also, to maximize the detectable signal expected from these small crosssections, it is necessary for the detector to trigger on, detect and cleanly recognize electromagnetic showers over a wide range of polar angles. As will be described in the next chapter, the ASP detector was optimized taking these factors into consideration.

Experimental Apparatus

Following discussions between John Ellis, Bob Hollebeek and Dave Burke late in 1982, the ASP experiment was proposed in 1983 as the first experiment designed specifically to search for events resulting from the production of supersymmetric particles in e^+e^- collisions. It was designed and built by a collaboration of physicists and technicians from SLAC, MIT and the University of Washington. Compared to other experiments mounted at major accelerator facilities, the ASP detector was fairly compact, relatively inexpensive (costing approximately \$ 1 million for all equipment) and was the work of a small group (14 full-time physicists). In order to be able to utilize the last two running periods at the Positron-Electron Project (PEP) storage ring before its operation was suspended for construction and commissioning of the SLAC Linear Collider (SLC)[†], the detector had to be designed, built, installed and running on a tight schedule. The experiment was approved in May 1983 and the first part of the apparatus was already installed by Spring 1984. The data analysed in this work were taken between January 1985 and April 1986, after which time the PEP ring was temporarily shut down and the ASP detector was dismantled.

After a brief discussion of the PEP ring, the various detector subsystems are described in detail in the following sections. Then the trigger, on-line data-acquisition, calibration and monitoring system and diagnostic events are discussed.

[†] A new accelerator project for obtaining e^+e^- collisions at $\sqrt{s}\sim m_Z$

2.1 The PEP Storage Ring

The PEP e^+e^- storage ring ⁽⁶⁵⁾ is a large colliding beam facility located at SLAC. It has a circumference of 2.2 km, and is situated largely underground at the end of the SLAC linear accelerator. Accelerated electrons and positrons supplied by the linear accelerator are stored in tight bunches in the ring, where they are confined and kept focussed by magnets as they circulate. Three equi-spaced electron bunches collide with three positron bunches which travel in the opposite direction, so that collisions may be observed at 6 separate interaction regions, every 2.4 μ s. The machine was run at a center-of-mass energy of $\sqrt{s} = 29$ GeV during the entire period of this experiment. It had a typical luminosity of $1 - 2 \times 10^{31}$ cm⁻² sec⁻¹, so that when the machine was running well the integrated luminosity was about 1pb⁻¹ per day.

The ASP detector was located in interaction region 10 of the PEP ring. This region is 20 m underground, and has no direct access to it other than through the storage ring tunnel. However, the overlying earth and rock filters all primary hadrons from the cosmic-ray flux and reduces the overall intensity by a factor of roughly 2.7. This section of the storage ring is also immediately downstream from the electron injection line, so that special consideration had to be given to the high level of radiation present during the filling of the ring.

2.2 Overview of the ASP Detector

The ASP detector (see fig. 2.1) consisted of two main sections: a central region with basic charged particle tracking and a lead-glass/proportional wire chamber calorimeter; and a forward region with lead-scintillator calorimeter modules and drift chambers for tracking charged particles.

Since it was a fairly simple, special-purpose detector, it did not have the broad range of application that more conventional, larger, general-purpose detectors have. Lacking the complexity of a general-purpose detector, ASP had some disadvantages: the absence of a magnetic field prevented charge determination for charged particles, and the absence of a central drift chamber and additional instrumentation such as time-of-flight counters and muon chambers made it impossible to perform detailed


Figure 2.1. A vertical cross-section of the ASP detector through the beam axis. The apparatus is 8.8 m long and 1.2 m wide.

particle identification. However, ASP's unique features gave it a number of advantages over more conventional detectors. Firstly, it had nearly complete solid angle coverage (99.98 % of 4π): the only gaps were beam line holes within the forward angular cutoff at 21 mrad. This was necessary in order to perform both the single photon and single electron searches, since the presence of any gaps or cracks in the detector coverage could lead to other events (*e.g.* radiative Bhabhas) faking these signatures. Secondly, the good central calorimeter segmentation, both along and transverse to the beam line, provided details of the development of electromagnetic showers, which served for track reconstruction as well as for discrimination of clean events from backgrounds. Thirdly, the absence of a magnetic field had the advantage that low energy charged particles originating from the beam line could be observed, whereas with a magnetic field present they would have curled up inside the beam pipe.

The detector will be described here using a coordinate system centered on the interaction point(IP). The positive x axis points radially towards the center of the PEP ring, while positive y points vertically upwards. The z axis then lies along the beam line, with the positron beam moving towards +z. Angles will be given in terms of the usual spherical co-ordinate system: theta is the angle between a line and the z axis, while phi is measured in the xy plane counterclockwise from the x axis. Because of the quadrant geometry of the lead-glass stacks, the acceptance of the central detector is given by a particular value of projected theta (θ_p), rather than

theta alone. Projected theta is the angle between the z axis and the projection of a shower onto the xz or yz plane. The relationship between θ and θ_p is

$$\tan \theta_{p} = \tan \theta \cdot \max(|\cos \phi|, |\sin \phi|) \tag{2.1}$$

2.3 Central Detector

2.3.1 Beam Pipe

The beam pipe consisted mostly of thin aluminum in order to minimize photon conversion probability. In addition, a tungsten mask was accommodated in a special indentation in the beam pipe (see fig. 2.1), so that the mask covered the region $12 < \theta < 20$ mrad, in order to shield the central calorimeter from off-energy beam particles that were over-focused by the insertion quadrupoles. The indentation also served to minimize the amount of material traversed by particles between 21 and 27 mrad. This window allowed an accurate study of low angle tracks to be made, so that $e^+e^- \rightarrow e^+e^-\gamma$ events with photons of $p_t \approx 0.75$ GeV/c in the central detector could be studied to verify QED calculations near the trigger threshold. The materials in the beam pipe are summarized in table 2.1.

Angle	Material	Thickness in
(mrad)		Radiation Lengths
> 100	120 mil Al	0.034
50 - 100	100 mil Al	0.029
45 - 50	Al-stainless weld	_
30 - 45	stainless flange	3.5
27 - 30	60 mil stainless	0.027
21 - 27	60 mil stainless @ 30°	0.027

Table 2.1. Summary of the Materials in the ASP Beam Pipe.

2.3.2 Central Tracker

The beam pipe was surrounded by two systems for the detection of charged particles. The inner one, the central tracker (CT)⁽²⁹⁾ consisted of 192 aluminum proportional wire tubes of dimension $2.4 \times 1.1 \times 220$ cm³, lying parallel to the beam line. To minimize the material in the CT, their walls were thinned by etching to 0.3 mm. The tubes were glued together to form four quadrants of 45 tubes each, in such a way that radial lines from the beam axis did not pass through tube walls, and three extra tubes were added in each corner to ensure that all central tracks passed through at least 5 layers (see fig. 2.2). The quadrants were mounted on a 1 cm thick -Hexcell backplate, then combined to form 2 L-shaped units which were assembled around the beam pipe. Each tube was strung with a $50\mu m$ Stableohm 800 stainless steel resistive sense wire which was read out at both ends, to provide redundancy and also to measure the z-coordinate of tracks by charge division. The wires were run at 2400 Volts in an atmosphere of 48.3% argon, 48.3% ethane and 3.4% ethyl alcohol by volume. The veto efficiency, defined as the fraction of charged particles tracked by the CT, was measured to be 99.6% using cosmic rays that were selected to go through the IP.

2.3.3 Veto Scintillators

A set of veto scintillators (VS) enclosed the CT on all sides to within 100 mrad of the beam and provided the second charged particle detector. They were constructed from 1 cm thick sheets of Kiowa SCSN-38 scintillator, two of which were sandwiched together to form modules 2 cm thick. The central VS modules were of dimension $2 \times 33.5 \times 225$ cm³. They covered the sides of the CT (see fig. 2.2) at a distance of 16 cm from the beam line, immediately in front of the lead-glass quadrants, with their edges overlapping so that there were no dead spaces. The forward VS modules were of dimension $2 \times 32 \times 60$ cm³, having a semi-circular area of radius 13 cm, centered at a point 2 cm from the edge, cut from the middle of one of the long sides. Two of them were placed at each end of the CT with a 4 cm overlap so that they formed a 60 cm square unit with a 13 cm circular hole in the middle, and were mounted on



Figure 2.2. Cross section in the x - y plane through the Central Tracker and surrounding Veto Scintillators.

the front face of each inner forward shower counter. Each central VS module was read out at each end with a Kiowa Y7 wavebar (0.5 cm thick, 2.2 cm wide) leading to a Amperex XP2212PC photomultiplier tube (PMT), permitting an approximate measurement of the z-position of the shower. Each forward VS module was read out on the 3 outside edges by wavebar leading to 2 PMT's, one at each outer corner of the unit. Thus 2 PMT's viewed each module to ensure redundancy in case of PMT failure. The pair conversion probability of a photon in the material between the IP and the VS was 4.5 % at $\theta_{\gamma} = 90^{\circ}$.

2.3.4 Lead-Glass Calorimeter

The major component of the detector was the central calorimeter, consisting of layers of lead-glass bars separated by planes of proportional wire chambers. There were 632 lead-glass bars in total, arranged in 4 separate quadrants, which completely surrounded the IP in azimuth leaving no gaps in the calorimeter between quadrants (see fig. 2.3). Each quadrant contained 5 layers: the odd layers had 32 bars, while the two even layers had 31 bars, stacked so that there was a half-bar offset in z-position of the bars between adjacent layers, to prevent the cracks between bars lining up, and to provide optimal position resolution. The bars, which were $6 \times 6 \times 75$ cm³ in size, were extruded from F2 (Schott) type lead glass. Each bar had a single Amperex XP2212PC 12-stage photomultiplier tube (PMT) glued to one end, for collecting the Čerenkov light from particles passing through the lead glass. The good segmentation provided accurate reconstruction of the origin, direction and shape of electromagnetic showers, as well as tracks from minimum ionizing particles in the *xz*- or *yz*-plane. (Further details on the lead glass and the construction, calibration and monitoring of the calorimeter are given in Appendix A.)

A lead-glass/PMT calorimeter has the desirable characteristics of low noise, good intrinsic resolution and stability. However, lead glass is susceptible to radiation damage which could seriously degrade the resolution with time. As mentioned above, the detector was immediately down-stream from the e^- injection line, so steps had to be taken to reduce this danger. The first was to use lead glass doped with 0.35 % cerium which has been shown to reduce its sensitivity to radiation⁽⁶⁶⁾. Secondly, to shield the glass, the calorimeter quadrants were combined into two L-shaped halves which could be moved away from the beam line using a hydraulic drive. They were retracted behind 10 cm thick lead walls prior to each injection of beam into PEP, then moved into the closed position before data taking began. Even though dosimeters on the exterior of the central calorimeter facing the beam pipe measured radiation levels around 10³ rad, no change in the response of the calorimeter was observed during the entire course of the experiment, showing that the above strategies were successful.

In order to determine the operating voltages of the photomultiplier tubes, their



Figure 2.3. Cross-section in the x-y plane of the central calorimeter and tracking system. Only a section of the central tracker is shown; it completely surrounds the interaction point (IP).

gains were initially calibrated using a green LED. During the course of the experiment, cosmic ray events were logged and these were used off-line to find correction factors that reduced the remaining tube-to-tube variation to less than 2%. The overall energy scale was determined using kinematically fitted radiative Bhabha events.

The energy resolution of the calorimeter, averaged over all values of phi in the central region $20^{\circ} < \theta_p < 160^{\circ}$, was^(67,68) $\sigma_E/E = 10\%/\sqrt{E}$ (*E* in GeV). The angular resolution was $\sigma_{\theta_p} = 4.4^{\circ}$. Timing information from the lead glass signals allowed

event time to be determined with a σ_t that ranged from 1.2 ns for a 1 GeV shower to 1.0 ns above 2.5 GeV. Resolution of the z-origin was $\sigma_z = 0.03$ m. These resolutions, and those of the central PWC described below, were measured with the fully reconstructed and kinematically-fitted radiative Bhabha events discussed in Sec. 3.2.

2.3.5 Central Proportional Wire Chambers

Planes of proportional wire chambers (PWC's) were interleaved between the layers of lead glass (see fig. 2.3). The chambers were oriented with their length parallel to the beam line, (i.e. perpendicular to the lead-glass bars) to provide information in - the xy-plane. Thus the lead glass and central PWC's together provided information for the three-dimensional reconstruction of tracks in the calorimeter. Each PWC plane was assembled from four closed-cell aluminum extrusions which each contained eight chambers measuring $1.23 \times 2.36 \times 200$ cm³ in size, with walls 0.18 cm thick. The chambers were each strung with a single 48μ m gold-plated tungsten sense wire and were operated at 1600 Volts in a gas mixture of 95% argon and 5% carbon dioxide by volume. Since the response of the chambers was sensitive to the atmospheric pressure, the gain was normalized off-line frequently by using Bhabha events. These chambers measured the angle ϕ with a resolution of $\sigma_{\phi} = 3.2^{\circ}$.

2.3.6 Time-of-flight Counters

The central region was covered by a time-of-flight (TOF) system that was attached to the roof of the interaction region, forming an "umbrella" over the detector. The TOF system served primarily to reject cosmic ray events. It was assembled from 48 scintillator counters, of dimension $2.54 \times 20 \times 345$ cm³, that had originally been used for the Mark II† detector time-of-flight system. The counters were positioned with their length parallel to the beam line. To cover all of the central region, half of the counters covered the +z end of the central calorimeter, while the other half

[†] A general-purpose detector that also took data at PEP and was upgraded for running at the SLC.

covered the -z end, with the two sets overlapping in the middle to ensure complete coverage. Each counter had a photomultiplier tube at both ends, providing a measurement of the z-position of a track with a resolution of $\sigma_z = 26$ cm. The timing resolution, after compensating for flight time from the IP, was $\sigma_t = 3$ ns.

2.4 Forward Detector

2.4.1 Forward Shower Counters

The forward shower counters (FSC) provided ASP with complete forward coverage above 21 mrad from the beam line. These calorimeters were constructed in 1.2 m square modules, 15 cm thick, of lead-scintillator sandwich. A module consisted of six 1.27 cm thick layers of Polycast PS-10 acrylic scintillator alternated with five layers of 0.64 cm thick lead alloy (94% Pb + 6% Sb); layers of 1.27 cm thick aluminum formed the front and back outer covers (see fig. 2.4). Each layer of scintillator was sandwiched between two reflective aluminum sheets (.64 mm thick), which served to cut down on losses of scintillation light. Consequently a module was 6 radiation lengths (X_0) thick. Each edge of a module was covered by a sheet of Rohaglas GS1919 wavelength shifter which transmitted the scintillation light to an Amperex XP2212PC PMT. Two pairs of modules formed the inner FSC's at $z = \pm 1.5$ m, which overlapped the central calorimeter, extending the coverage to $\theta = 100$ mrad from the beam line. Another two sets of three modules formed the outer FSC's at $z = \pm 4.1$ m; they covered the region $\theta_p < 120$ mrad and $\theta > 21$ mrad (see fig. 2.1). The extra material in the outer FSC's was required to reduce the probability of photons escaping detection at low angles due to non-conversion in $e^+e^- \rightarrow e^+e^-\gamma$ and $e^+e^- \rightarrow \gamma\gamma\gamma\gamma$ events. Each module was built in two halves so that it could be easily installed around the beam pipe, but had a 4 cm overlap in the joint between the halves, which ensured that there were no cracks in the forward coverage (see fig. 2.4).

These calorimeters served to measure the energies of particles in the small angle region; their resolution was $\sigma_E/E = 25\%/\sqrt{E}$ (*E* in GeV). Also, coincidences between discriminated pulses from the FSC's were used to obtain an on-line measurement of the specific luminosity of the PEP ring. Due to large radiation doses received



Figure 2.4. Front and side views of a forward shower counter module. The inset shows details of the construction of a corner of the module.

by the FSC's during electron injection, they suffered radiation damage which caused the scintillator to darken. Since the luminosity measurement was sensitive to the FSC gain, the photomultiplier tube voltages were increased every two weeks or so to compensate for the loss in light yield. Even so, the non-uniformity of the darkening across the scintillator resulted in a deterioration of the energy resolution. Application of heat lamps to the scintillator between the two data taking periods led to a significant curing of the damage and improved light transmission through the scintillator.

2.4.2 Forward Proportional Wire Chambers

Between the first and second modules of both the inner and outer FSC's were two planes of proportional wire chambers, one plane with wires along the x-direction, the other with wires along the y-direction. These PWC's thus measured the spatial location of showers in the FSC's at a depth of $6X_0$. They were constructed from closed-cell aluminum extrusions identical to those used in the central calorimeter and were assembled and operated in the same way. There were 48 chambers per plane (six sets of eight chambers), each chamber having an active length of 102 cm. The central tubes in each plane were truncated in the middle to form a circular cut-out so that the PWC fitted tightly around the beam pipe. The angular resolutions were $\sigma_{\theta} = 2.5$ mrad and $\sigma_{\phi} = 28$ mrad.

2.4.3 Forward Drift Chambers

Four planes of drift chambers were located between the inner and outer FSC's to provide accurate tracking of charged particles in the angular range from 21 – 100 mrad. Each plane consisted of 2 rectangular chambers with circular cut outs, so that together they formed a square surrounding the beam pipe. Each chamber had 2 layers of alternating field and sense wires, spaced 1.5 cm apart, all running in either the x- or y-direction. The sense wires were 30 μ m gold-plated tungsten and the field wires were 150 μ m copper-plated beryllium. To minimize the material traversed by particles passing through the chambers, their walls were constructed from copper-clad G-10. The chambers were operated at 2000 Volts in an atmosphere of 49.2% argon, 49.2% ethane and 1.6% ethyl alcohol by volume. A set of two crossed planes with an inner radius of 8 cm was located at $z = \pm 1.9$ m, while a second set with an inner radius 5.5 cm was located at $z = \pm 3.0$ m (see fig. 2.1). They measured x and y with a resolution of $\sigma = 0.4$ mm.

2.5 Trigger

The beam crossing frequency in the PEP ring is 408 kHz, but it is not feasible to record data at such a high rate. However, most of the collisions are uninteresting, so it is only necessary to have a fast trigger that can identify the occasional good events during the 2.4 μ s between successive beam crossings, so that they can all be logged. The timing for the ASP trigger system ⁽⁶⁹⁾ is shown in fig. 2.5. During data taking the start signal was provided by the PEP RF clock. Analog sums from the lead-glass, VS and FSC signals were used to select good events, by employing a sequence of programmable digital look-up tables, within 1 μ s, so there was no dead time resulting from the trigger decision. If a trigger was satisfied, the data was digitized using a BADC/SHAM IV ^(70,71) system, which required approximately 10 ms. The digitized data from the detector was then read out to a disk by the host VAX 11/750 computer, requiring a further 10 ms. Upon completion of the readout, the VAX re-enabled the trigger system, so it was ready for the next event. The synchronization of the various decision making, data acquisition and event readout processes was controlled by a single central unit, the Global Control Module.

The main triggers were based on the total, quadrant and layer analog sums of the lead-glass pulse heights. Since a lead-glass calorimeter with PMT read-out has a low level of electronic noise, clean triggers could be obtained at low energies. The triggers were formed as follows: the signals from the 632 individual PMT's were fed into Splitter/Summer units which used passive transformer splitters to divide each signal into two. (These transformers also broke the ground loops between the detector and the summing circuits, allowing a lower achievable threshold.) One half of each signal went to the BADC/SHAM IV system, for the primary readout of the calorimeter. The other halves were summed in groups of eight adjacent channels to form a signal from one quarter of a layer which went to both the trigger circuitry and an independent ADC (see fig. 2.6). This ADC provided a redundancy check of the BADC data, and a means to compensate it if a SHAM channel overflowed. The signals were further summed in stages to form layer, quadrant and total sums, which were then integrated and discriminated to provide digital levels for input to



Figure 2.5. Flowchart of the overall trigger timing. The elements of the chart enclosed in dotted brackets could have been implemented if necessary.

the Memory Logic Units (MLU) which could recognize patterns of hits in the various detector elements. The summary outputs from the MLU's were fed into the input latches of the Global Control Module, which then recognized specific event patterns and made the trigger decision.





The primary trigger was based on the total energy visible in the lead-glass calorimeter, *i.e.* from the sum of all of the PMT signals. The threshold on this trigger was limited by the coherent noise, which was insignificant on individual channels, but became large when summed over all 632 channels. It was set at 1.5 GeV. In order to obtain the lowest possible threshold for single central prong events, without increasing the trigger rate above manageable levels, there were additional triggers employing layer and quadrant sums to select events with signatures from single showers in the calorimeter, which were programmed into the MLUs. Their thresholds were at about 0.7 GeV.

There were also special independent triggers for logging diagnostic events which were used for the off-line calibration of various detector components and also to measure the performance of the detector. They were as follows:

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- The forward Bhabha (e⁺e⁻ → e⁺e⁻) trigger required a coincidence between large signals (greater than about 7 GeV) in the FSC's on opposite sides; prescale factors of 600 for the outer FSC's and 20 for the inner FSC's were needed to reduce the high rate of these events to a level that did not swamp the data acquisition system. These events were used to study the performance of the forward systems and to measure the luminosity not only for this experiment, but also for the PEP ring. The luminosity was determined rapidly on-line by just counting the number of times this trigger fired. The integrated luminosity of the data sample was determined off-line by comparing the measured and QED predicted rates for these Bhabha events (see sec. 3.2.1).
- o The radiative Bhabha (e⁺e⁻ → e⁺e⁻γ) trigger required a coincidence between large signals in FSC's on opposite sides and at least a small amount of energy (> 0.3 GeV) in the lead glass. These events were particularly useful since they had a single electron or photon in the central region of the detector, which had all the same characteristics as signal events, while the other two final state particles were confined to the forward regions. They were kinematically fitted, and then used for calibrating the detector and for studying its performance as a function of the energy and angle of the central track.
- The cosmic ray trigger required a coincidence between two central veto scintillator modules during a narrow gate (15 ns wide) ending 5 ns before beam crossings. This yielded a sample of minimum-ionizing tracks roughly in time with the beam crossing. They were used for calibrating and monitoring the responses of the central detector systems.
- The random trigger was provided by a free running oscillator, which logged random beam crossings. These random events provided a means of monitoring occupancies in each detector system during data-taking.

By setting the trigger thresholds at appropriate values, as indicated above, it was possible to combine all triggers and yet still reduce the 408 kHz crossing rate to an overall trigger rate of approximately 4.5 Hz. The precise value varied depending upon the specific luminosity and beam steering in PEP, but was never over 7 Hz, which was within the capabilities of the data acquisition system. The rate from the lead-glass energy triggers was about 4 Hz and from the monitoring triggers it was about 1 Hz.

2.6 On-line Data Acquisition and Monitoring

The data acquisition was performed using a CAMAC-based system, interfaced to a dedicated VAX 11/750 computer. The acquisition software running on the VAX was split into a set of independent processes, each performing specific tasks. Experimenter control was provided by an interactive process which communicated with all the other processes, which were run in batch, via mail and global sections. The interface was a pseudo-touch panel from which commands could be selected by toggling a cursor over "buttons" drawn on a terminal screen. As a result of the sophistication of the data acquisition system, the experiment could be run by a single physicist from one terminal. Consequently, the experiment was operated by one person for an eight hour shift at a time, so that despite its small size, the ASP collaboration proved quite adequate for running a full-scale experiment at PEP. Throughout the data taking the detector and acquisition system were monitored in a number of different ways to ensure that they were functioning correctly.

The main acquisition process (ASPACQ) was responsible for data-taking, including handling begin-run and end-run sequences, and CAMAC initialization. It stored event information in individual event buffers which were then written to disk by a logging process (ASPLOG). This created a run file for each data-taking run, which usually lasted for one to two hours. The 1 gigabyte disk provided sufficient storage for data from about 2 days of running. As the disk filled, the run files could be copied to tape by the operator between runs, during the periods when the PEP ring was being filled. The copying was performed by an independent TAPECOPY process, which took about 5 minutes to write out a full tape of data in IBM readable form for subsequent analysis by an IBM mainframe computer.

Every four minutes during data-taking runs, an interrupt was issued to run a separate monitoring process (ASPMON). This was responsible for checking a wide variety of detector parameters, such as the low and high voltages, wire chamber currents, beam noise monitors, gas flow monitors and even the positioning of the central calorimeter modules. If a parameter was measured to be outside the required tolerance, the operator was sent an error message. Problems encountered by this or other processes were all handled by a separate process (ASPERR), which wrote the messages both to the screen and to a file for error logging. To provide a summary of the status of the detector, an additional process (ASPSTATUS) maintained a color display on a dedicated color monitor. This showed the status of all detector subsystems (e.g. voltages, currents, etc.) and acquisition processes, as well as the values of storage ring parameters read from the PEP control room by another process (ASPPEP).

To check the quality of the data as events were being logged, there was also an analysis process (ASPANL) which analyzed a sample of selected events obtained from the memory buffers shared with the data acquisition process. The number of events analyzed depended on the extra VAX time available for this processing, and was usually at least a few percent. The analysis of these events provided a check of the performance of the various detector subsystems. At the end of each run the results were checked and a summary was printed out. If any significant deviations from expected values were found, an error message was sent to the operator. It was also possible to request that a selection of one event displays be drawn as events were logged, providing a further visual check of detector performance. The final data acquisition process (ASPSEP) monitored the injection line to PEP to provide a signal for tripping the high voltages and warning the operator should the injection septum be activated. Information from the ASPACQ, ASPLOG, ASPMON and ASPANL processes was written to a data base for maintaining information for each run.

The data acquisition system could be activated by a calibration signal in order to calibrate the detector subsystems. The calibration was performed once per eight hour shift, at the beginning of a run, while beams were present in PEP. It was timed to occur between beam-crossings so that there would be no interference from signals from beam interactions. All subsystems of the detector were calibrated simultaneously, at a selection of points as specified by a database: different charge levels were injected into the wire chambers and the PMT's were flashed with LED systems at various levels. The operator was provided with a summary of results for all systems, showing warnings or failures for channels that had gains or pedestals out of tolerance. It was also possible to examine the values of the constants, compare them with old ones and modify them if necessary. For the wire chamber systems, the results of the calibration were saved as new constants in the run images of the BADC's, so that they applied the updated corrections to the data as it was recorded. For the CT system a fitting procedure was used to extract the splitting fractions for the sharing of charge between the two amplifiers on a single wire as required for its measurement of z by charge division. The PMT-based systems were much more stable and their calibration levels were less well known, so their calibration results were used to monitor their stability but not for determining on-line gain corrections. Their pedestals were determined from the no-excitation calibration point and corrected for off-line.

Offline Data Analysis

The raw data used in this analysis were accumulated over two running periods at PEP, from February 1985 through May 1985, and from November 1985 through February 1986. The center-of-mass energy was fixed at 29 GeV throughout both periods. There were close to 30 million events logged to tape during this time, which filled 359 computer tapes (2400' 9-track 6250 bpi). This is clearly a large amount of information, and it required the full power of the IBM mainframe computer at SLAC in order to process this raw data before it could be used in a physics analysis. This processing entailed initial filtering in order to eliminate uninteresting events before the remainder were subjected to a detailed reconstruction process that required a large amount of computer time.

The main categories of events expected in the raw data set were:

- ▶ the e^+e^- interactions: most notably the basic QED events $(e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \gamma\gamma \text{ or } e^+e^-\gamma \text{ and higher order radiative events})$, but also hadronic events produced through $e^+e^- \to q\bar{q}$ and two-photon events $(e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-X)$
- events from the interaction of beam particles with residual gas molecules remaining in the beam pipe (beam gas events) and from beam particles lost from the beam pipe
- non-beam related events due to cosmic ray interactions in the detector.
 The trigger described in the previous chapter provided the initial crude event

selection: all events satisfying a trigger criterion were logged to tape. The triggers were designed to select all good events above certain thresholds, but due to the simple nature of the trigger setup, many other uninteresting events were logged as well. In order to filter out the events of interest, the events logged to tape were then subjected to detailed offline selection procedures which included complete event reconstruction. The event reconstruction involved forming tracks from the individual hits in the different detector systems, and determining their energies from the signals associated with them. Other information such as shower shapes and event timing were extracted from the data too. In this chapter the tracking procedures are discussed, the use of the diagnostic events is described, and details of the basic event selection are given.

3.1 Event Tracking

The tracking of each event was accomplished in several stages. Initially the different detector systems were each tracked separately with individual procedures to find all track segments in each of them. For example, the tracking of the lead-glass system proceeded as follows: first a cluster-finding algorithm was used to determine the boundaries of each shower within each quadrant. There can be fluctuations in the development of an electromagnetic shower which create gaps in the pattern of energy deposition, while on the other hand two showers which are close together in the plane of a quadrant may overlap. Therefore the clustering algorithm allowed small gaps, but was also sensitive to maxima and minima in the energy distribution along a layer, and would define a new cluster when sufficiently large fluctuations in signal were encountered. Clusters were not continued across quadrant boundaries; clusters from a single shower split between two adjacent quadrants were combined at a later stage of the tracking.

A two-dimensional total least squares fit was then performed for each cluster. This fit found the axis about which the sum of the squares of the perpendicular distances to each bar, D_i , was minimized. The signal in each bar corrected for PMT gain, S_i , was used to weight each term. The quantity to be minimized was:

$$M_{W^2} = \sum_{i} S_i D_i^2 \quad . \tag{3.1}$$

A slope and intercept in the plane of the quadrant (xz or yz) were extracted from this fit.

The signals observed in the central PWC's, the central tracker, and the forward PWC's and shower counters were all tracked independently in a similar fashion and then combined with the lead-glass clusters to reconstruct an event topology. To accomplish this, the track segments from each system were reduced to vector and error matrices. A topology finding routine then identified the segments from each system which could belong together in a track. A least-squares fit was performed, and if the χ^2 was satisfactory a track was created utilizing all the information from the various systems. If the χ^2 was unsatisfactory, the segment which contributed the most to the χ^2 was dropped and the fit was tried again. Clusters from a shower which crossed the boundary between two quadrants were combined in a similar fashion. The clusters were required to match based on a χ^2 formed from their θ values and errors, and information from the other central tracking systems was used in the fit. Tracks from minimum-ionizing particles were treated in the same way as electromagnetic showers; the tracking code worked equally well for both.

Ambiguities arose in matching lead-glass clusters and PWC clusters when there were multiple tracks per quadrant. For charged tracks this could usually be resolved by using information from the central tracker. However if there were multiple neutral tracks in a quadrant, the tracking algorithm had to rely on a comparison between the signals deposited in each of the layers of the lead-glass and the PWC clusters. From this comparison a χ^2 was extracted which indicated how well the patterns of energy deposition in the two systems matched. When two showers had very different patterns this method worked well; however if they were similar it was difficult to correctly assign the PWC clusters to the lead-glass clusters. Because of this limitation the tracking worked best for low multiplicity events.

3.2 Diagnostic Events

Various sets of diagnostic event types were filtered directly from the raw data tapes to provide specialized data samples for calibrating and checking the performance of the different detector systems. These events were logged by the special triggers described in sec. 2.5, and consequently were easy to filter from the data tapes as they could be selected simply by checking if the appropriate trigger bit was set.

3.2.1 Forward Bhabha Events

Low angle Bhabha events that had tracks in the outer forward shower counters were used off-line to determine the precise value of the integrated luminosity by comparing the measured events with the rates predicted by QED calculations. Forward Bhabha events also provided a means for measuring the angular resolutions of the forward PWC's and drift chambers.

The forward systems provided excellent luminosity monitors since there was only a small amount of material between them and the IP, the FSC's had good forward coverage and the forward PWC's provided accurate tracking capability at small angles. The combination of these factors with the large Bhabha cross-section enabled the integrated luminosity to be determined⁽⁷²⁾ with a precision of 1.1 %. The angular acceptance used for this analysis was chosen to be the region where the forward detectors performed best. One track was required within the interval $55 < \theta < 95$ mrad on one side (+z or -z), and a second track was required within the interval $50 < \theta < 100$ mrad on the other side in z. These cuts avoided the flange in the beam pipe below 45 mrad and the overlap region between the inner and outer forward shower counters above 100 mrad where the energies and angles of tracks could not be well measured. The two tracks also had to be colinear to within 20 mrad.

The angular distribution of forward Bhabha events from this analysis is shown in fig. 3.1. Clearly, the data and the Monte Carlo prediction are in excellent agreement. For the data sample used in this work the integrated luminosity was determined to be:

 $109.56 \pm 0.48(stat) \pm 0.83(syst) \pm 0.79(QED) \text{ pb}^{-1}$.

The first uncertainty is the statistical counting uncertainty, the second is the systematic measurement uncertainties combined in quadrature and the third is the uncertainty in the QED prediction found from the difference between the two Bhabha Monte Carlo programs that were used.



Figure 3.1. Distribution of Bhabha events in the forward region. The data are plotted as points with errors, while the QED Monte Carlo calculation is shown as a histogram.

3.2.2 Radiative Bhabha Events

The radiative Bhabha events logged by the special trigger described in sec. 2.5 were particularly useful because of their similarity to the events being searched for. They had only a single electromagnetic shower in the central detector, with all the same characteristics as signal events, while the other two final state particles were confined to the forward regions, where the long lever arm afforded a precise measurement of their angles. Good events were carefully selected without making any cuts on information from the lead-glass or central PWC systems so that they would be unbiased for checking the performance of the central calorimeter. They were fully reconstructed and then fitted using the kinematic-fitting program SQUAW⁽⁷³⁾. Because the center-of-mass energy in e^+e^- collisions is known ($\sqrt{s} = 29$ GeV at PEP), the fit to a three-particle final state was over-constrained. Consequently the detector performance could be studied by performing different fits while removing particular variables of interest from the fit. These events were essential for calibrating the central detector systems and for measuring the resolutions and analysis efficiencies in the central region as functions of energy and angle. They were also very useful for developing and evaluating many of the software algorithms required for data analysis.

The selection of good radiative Bhabha events without making any requirements on the energy and angular measurements of the central calorimeter that would bias the event sample proceeded as follows:

An initial basic selection procedure was used to reject the main backgrounds present in the set of events that were logged by the radiative Bhabha trigger:

- The raw lead-glass energy was required to be > 0.2 GeV. This low threshold cut is well below the energy range to be studied in the calorimeter, but rejected events where there was a trigger with only a small signal in the lead glass from noise in the trigger electronics or a noisy PMT.
- Events where a beam gas interaction overlapped with a Bhabha in the forward region were eliminated by requiring < 70 hits in the CT, or < 50 hits in the CT if both of the outer FS counters were above threshold.
- ▷ There was required to be at least one PWC point in each of the forward directions.
- Most of the remaining non-radiative Bhabha events in the sample were Bhabha events where one or both of the tracks hit the edge of the central calorimeter before entering the inner FS counter modules. Consequently if either of the outer FS was above threshold, the event had to be good and was saved.
- ▷ For the remaining events, if both inner FS counters had good forward PWC points, with the maximum signal track lying below $\theta_p = 163$ mrad for the -z side and below $\theta_p = 160$ mrad for the +z side, then the forward tracks were

not near enough to the central calorimeter to have hit it, and the event was saved. (The angular cut was slightly different on the two sides because the beam spot was biased slightly towards -z with respect to the center of the detector.)

Next the signals in the end bars of the first layer of each lead-glass quadrant were checked. If there was a good forward PWC point then the energy in the end bars of the two closest adjacent quadrants were summed, otherwise, all 4 end bars at that end were summed. If the end sums at one or both ends were below 45 MeV, then the event was saved. The remaining events were Bhabha events where the tracks hit the edges of both ends of the central calorimeter, and were not saved.

A more detailed selection was then used to obtain a set of good, unbiased events for use in this analysis. First, events with clean, well-measured forward tracks were selected:

- One and only one forward track was required on each side. In addition, the forward PWC raw signal was required to be > 3.5 GeV on each side, and the FS energy on each side was required to be > 5 GeV and < 18 GeV.</p>
- The forward tracks were restricted to angular regions with good tracking, by requiring that they were:
 - o at $\theta_p < 180$ mrad from the beam line to avoid the region of overlap with the central calorimeter.
 - o not in the region $100 < \theta < 130$ mrad from the beam line to avoid the overlap region between the inner and outer FS counters.
 - o not in the region $30 < \theta < 45$ mrad from the beam line to avoid the flange at very low angles.
- ▷ The angular errors of the FP points on the tracks were required to be small:
 - o $d\theta < 5 \text{ mrad and } d\phi < 200 \text{ mrad for } \theta < 30 \text{ mrad}$
 - o $d\theta < 15 \text{ mrad}$ and $d\phi < 150 \text{ mrad}$ for $45 < \theta < 100 \text{ mrad}$
 - o $d\theta < 35$ mrad and $d\phi < 200$ mrad for $\theta > 100$ mrad and $\theta_p < 180$ mrad

Bhabha events in the forward region coincident with events such as cosmic rays which deposited energy in the central calorimeter, were eliminated by requiring the forward tracks to be acolinear by at least 10 mrad.

Secondly, to select events where there was a single electron track in the central calorimeter, with well-measured angles, without making any requirements on the measurements made by the lead-glass or PWC elements of the calorimeter, a number of cuts were made on the CT information:

- There was required to be one and only one CT track having 12° < θ_p < 168° and satisfying the following criteria:</p>
 - o at least 4 clusters in the xy-fit,
 - o no more than 12 hits on the xy-track,
 - o at least 3 good z-clusters in the z-fit,
 - $\chi^2 < 3$ for the *xy* and for the *z*-constrained fits,
 - o the projected z-intercept had to be within 0.4 m of z=0 and
 - the difference between the unconstrained fit and constrained fit CT angles had to be reasonable: $\Delta \theta \leq 50^{\circ}$ and $\Delta \phi \leq 30^{\circ}$.
- ▷ To attempt to verify that the CT track was indeed consistent with a central electron in a radiative Bhabha event, and was not just one of many central tracks, it was required to be coplanar with the two forward tracks to within 12°.

These requirements yielded a final set of very clean events: scanning a selection of them indicated that the contamination from events other than radiative Bhabhas was less than 1 %. They were kinematically fitted using as input values the measurements and errors of the angles of the forward tracks, and of the angles of the central track as measured by the central tracker. The fit resulted in a prediction of the energy and angles of the shower in the lead glass. A small fraction of events with a poor fit were rejected by making a cut on the χ^2 of the fit, leaving a final sample of 62140 events with a central electron having E > 1.0 GeV. This sample of good fitted events, and the values of the parameters found by the fit, were unbiased by the resolutions or possible inefficiencies of the central calorimeter, since no lead-glass or central PWC information was used in selecting or fitting them. Consequently this event sample could be used for measuring resolutions and efficiencies, including the trigger efficiency, since the radiative Bhabha trigger threshold was much lower than that of the lead-glass energy trigger.

3.2.3 Cosmic Rays

The penetrating muons in the cosmic ray events provided a set of minimum ionizing tracks to complement the electromagnetic showers in the radiative Bhabha sample. They were used for calibrating and monitoring the responses of the central detector systems. They were essential for obtaining the final counter-to-counter leadglass energy calibration as is described in Appendix A.

Out of the half million cosmic triggers that were logged during data taking runs, good events were selected as follows:

- ▷ The outer forward shower counters were required to have < 0.4 GeV raw energy to remove events coincident with the very copious e⁺e⁻ annihilation events having tracks at low angles.
- \triangleright Noisy events were rejected by requiring < 35 CT hits.
- ▷ Each lead-glass quadrant was required to have < 1.5 GeV raw energy to eliminate events where the cosmic ray had interacted to produce a shower in the calorimeter.
- The events were then tracked and had to have no more than three tracks found.
 At least one track had to satisfy the following criteria:
 - o at least 3 lead-glass layers hit with > .015 GeV raw energy in each.
 - o at least 3 central PWC layers hit.
 - the lead-glass cluster had to have a width and an energy variance between layers consistent with a minimum-ionizing track.
 - o each lead-glass layer in the cluster had to have no more than 3 bars hit.

Using these events, the tracking efficiency of the central tracker was determined to be 99.6 %. They were also used to calibrate the response of the individual veto scintillator counters as a function of position.

3.2.4 Random Triggers

The random triggers provided a means of determining the occupancy in the various detector systems while the beams were colliding during data-taking. Consequently they could be used to determine the efficiency of analysis cuts that required that a given system not have an energy deposition above a certain level. These events were logged by a free running oscillator, so there was approximately 1 random trigger per minute of running time regardless of what the luminosity was. Consequently the full set of random triggers were not luminosity normalized: there were too many random triggers during low luminosity running at the end of runs (when the noise was usually -low) relative to during high luminosity running at the beginning of runs (when the noise was usually high). As a result, using the full data set would have underestimated the average noise per e^+e^- event, so that inefficiencies due to noise determined using the random triggers would have been systematically underestimated.

To overcome this problem, a set of random triggers normalized by the instantaneous luminosity were selected and used for measuring the efficiencies of occupancy cuts in this analysis. This procedure had an efficiency of 32 % for saving events and yielded a useful sample of 26677 random triggers.

3.3 First Pass Event Filter

Since the raw data sample to be processed during off-line analysis was so large, it was necessary to have an initial fast event selection procedure that could rapidly identify and reject the obvious uninteresting events while retaining all classes of interesting events with very high efficiency. In order for the routine to run fast enough to be able to process the entire raw data set in a reasonable number of CPU cycles, it was not feasible (or necessary) to perform the full event reconstruction during this stage. After members of the collaboration had examined the various event types in the raw data, a single routine was written that was designed to keep all annihilation events except forward Bhabha triggers. This algorithm proceeded as follows:

- A very small fraction of the events were logged due to the fact that one or other of the BADC's used for reading out the lead-glass SHAM's very occasionally had a sticky bit in the ADC. They were obvious since essentially all lead-glass channels read out by one of the BADC's then showed hits at the same low level. These were not real triggers and were rejected.
- Next, distinct cosmic ray events were rejected if one of the following criteria were satisfied:
 - o the special cosmic trigger fired.
 - o the raw time measured by the lead-glass system was greater than 5 σ from the beam crossing time.
 - o there was a track in the central PWC system that had 4 or more layers hit, was identified as being a minimum ionizing particle from the layer energy distribution and had a distance of closest approach to the origin in the xy-view > 0.2 m.
 - o there was a track in the lead-glass system that had 4 or more layers hit, was identified as being a minimum ionizing particle from the layer energy distribution and had a z-intercept in the xz- or yz-plane > 0.2 m.
- To eliminate very noisy events, mostly from beam gas interactions, events which had > 80 hits in the central tracker were rejected.
- ▶ In order to retain all events that had a good signal in the detector, events that passed the above cuts and satisfied one of the following criteria were saved:
 - o there was at least one good lead-glass track that had a z-intercept within 0.5 m of the origin and distance of closest approach to the origin < 0.3 m (both as viewed in the xz- or yz-plane). A good lead-glass track was defined by the minimal requirements of > 0.06 GeV raw energy, with hits in 2 or more layers.
 - there were 2 lead-glass clusters in adjacent quadrants, each with an energy > 0.03 GeV and with centroids having a z separation < 0.25 m, provided there was no good lead-glass track present that failed the intercept or distance of closest approach check above. This saved events in which

there was a good lead-glass track in the region of overlap between two quadrants, but which had failed the previous check because the track was split into two clusters in the two quadrants.

- there was at least one CT track found having (in the xy-view) an intercept with the plane through the beam line parallel to the CT quad containing the track ≤ 0.08 m and a lead-glass cluster with raw energy > 0.3 GeV in the quadrant to which the CT track pointed, providing there was no good lead-glass track present that failed the intercept or distance of closest approach check above. This saved events where the CT had a good charged track with energy nearby in the central calorimeter.
- it passed a special routine intended to select events with a single central calorimeter energy deposit and no other energy. It required a lead-glass energy trigger be satisfied, and that 2 adjacent lead-glass quads, the 2 outer FS modules and one of the inner FS modules all have energy less than the 99.5 percentile level determined from random triggers, and that no more than one of these subsystems have an energy above the 97 percentile level. If there were any lead-glass clusters present with raw energy > 0.12 GeV, then the maximum energy cluster was required to have a z-intercept within 0.8 m of the origin and distance of closest approach to the origin < 0.3 m (both as viewed in the xz- or yz-plane.)
- there was at least one lead-glass cluster and at least one forward PWC point found and the total forward shower counter energy was > 5 GeV, but neither the radiative Bhabha nor the forward Bhabha trigger had fired. This saved events such as radiative Bhabhas and singly tagged two-photon events that were not already saved in the diagnostic event samples.
- the event passed the special preliminary routine for selecting radiative Bhabha events discussed in sec. 3.2.2. These events were retained along with the rest of the data to ensure all radiative Bhabhas were available for efficiency checks.
- ▷ If an event failed any of the above cuts other than the sticky BADC bit cut,

the check for a cosmic trigger or for a cosmic track in the central PWC system, but it had total raw lead-glass energy > 3 GeV, with the sum of raw leadglass energy in the back three layers of all quadrants > 0.3 GeV, then it was saved. This final category was to catch events that did not have a good leadglass track, yet had significant energy away from the edges of the lead-glass acceptance, such as could arise from hadronic events.

All other remaining events not flagged as good were rejected. All good events were passed through the remainder of the tracking procedure before being logged to tape.

This first pass filter saved 36.6 % of the raw events. Scanning through a sample of the events indicated that they were almost all good e^+e^- annihilation events. The efficiency of this and the later event selection algorithms was determined by passing the kinematically fitted radiative Bhabha events through the same selection process as the data. The occupancy cuts that could not be checked with these events were checked using the random triggers. The overall efficiency for the first pass filter was 99.8 % for events with single central tracks having E > 1.5 GeV and $\theta_p > 20^\circ$ from the beamline.

3.4 Second Pass Event Filter

The second round of event selection was designed to select events that had only one good track in the central calorimeter, without regard to whether or not there were any forward tracks. There was also no distinction made as this stage as to whether or not the central track was charged. The aim of this selection was to extract a basic data set for further analysis from the output of the first pass filter that would contain all events of interest for this search. Consequently the cuts were fairly loose: the philosophy was to reject any events which clearly did not have just one central track.

Although all events had been tracked initially during the first pass filter, during the early stage of this selection the events were re-tracked. This was done in order to obtain the final version of the tracking code, since after the first pass filtering had been completed, a few improvements to the tracking were made to take care of some minor problems. However even the final version of the tracking code occasionally split a single shower into separate tracks. These were combined by this filter to obtain the best determination of the angles in the central calorimeter, and the energy of the shower was re-calculated to obtain the correct value for these angles.

While the events selected by this routine included those with just one central track and no other tracks, the vast majority of events selected at this stage were radiative Bhabha events where just one of the tracks was in the central acceptance, with the other two tracks at low angles, either in the forward region or down the beam pipe. The algorithm for this second pass filter proceeded as follows:

- ▷ The events had to have fired a lead-glass energy trigger, either the total energy trigger or one that checked for a localized energy deposit in the central calorimeter. The efficiency of this trigger requirement is shown in fig. 3.2 as a function of energy and of theta, as determined from the radiative Bhabha sample. Clearly the trigger was fully efficient except for low energy tracks and the boundaries of the calorimeter coverage.
- ▷ The events were required to have at least one lead-glass track using the original tracking and the two lead-glass quadrants opposite in ϕ to the maximum energy lead-glass track were each required to have less than 0.15 GeV of raw energy, as would be the case if there were only one central track. The maximum energy of two adjacent lead-glass quadrants opposite a randomly chosen ϕ -value for random triggers is shown in fig. 3.3. The random noise in the lead-glass system is seen to be very low. This cut substantially reduced the number of events that had to be retracked as many events present in the data had multiple central tracks with p_t balance (e.g. Bhabha and two-photon events).
- ▷ The events were then retracked, and required to still have at least one track with lead-glass energy present, since the new tracking sometimes found different tracks, although mostly the track reconstruction was very similar to the earlier version.
- All tracks with lead-glass energy were then checked to see whether any combination of them were from a single shower, since the tracking procedure did not always succeed in linking the various track segments, especially when the



Figure 3.2. The trigger efficiency as measured using the kinematically fitted radiative Bhabha events is shown in (a) vs energy for events with $\theta_p > 20^\circ$, and in (b) vs θ_p for events with energy > 2 GeV.



Figure 3.3. The maximum energy per quadrant in two adjacent lead-glass quadrants chosen at random for random triggers.

shower was in a corner region where two quadrants overlapped. If any track was within 20° in θ and within 30° in ϕ of the maximum energy central track, then those two tracks were combined into a single track. However, if either of the pair of tracks did not have a phi value assigned, but they were in the same or adjacent quadrants then they were combined if they were within 20° in θ without checking their ϕ -match. The combined track was assigned new angles by energy-weighting the angles from the separate tracks. These angular association cuts were fairly loose in order to save all potentially good events. Less than 18 % of event passing all cuts in this filter had one or more tracks associated with the main central track. To reject events in which there was more than one distinct central track present, if there was either a central track with a corrected energy > 0.1 GeV or an unassigned lead-glass cluster with a raw energy > 0.2 GeV, that did not have an angular match to the maximum energy central track, then the event was rejected.

- ▷ The event was required to have a phi measurement (from either a CT segment, a central or forward PWC point, or the merging of two lead glass clusters in two adjacent quadrants) for the single central track found above. This was necessary since if no ϕ was measured for a shower, its energy could not be determined properly. Less than 0.5 % of the events failed this cut; they were either bad events or had only a low energy central photon.
- By this stage the events remaining all had one central track with well defined angles. The charge of the track was determined as follows: if there was a CT segment on the track, or an unassociated CT track within 20° in θ and within 15° in φ then it was taken to be charged, otherwise it was taken to be neutral. For neutral tracks, the first layer with lead-glass energy was determined in order to find the approximate point of conversion for photons. Next the energy of the track was recalculated to determine it as accurately as possible by using all information from any tracks that may have been combined. Also the point of conversion was used in determining the energy of photons. For tracks that had forward shower counter energy assigned to them, this measurement was used in determining the total shower energy instead of the estimate of the energy lost from the calorimeter due to leakage.
- To retain only events in which the central track was within the region where the detector performed well, the central track was required to be in the acceptance region:

 $20^{\circ} \le \theta_p \le 160^{\circ}$ $p_t \ge 0.5 \text{ GeV/c.}$

The lead-glass raw time was corrected for the flight time of the track from the interaction point and for the distance the light had to travel down the lead-glass bars to reach the PMT's, using the angles of the central track. Cosmic events which were far out of time with respect to the beam-crossing signal were rejected by requiring that those events with a well measured time be within $5\sigma_t$ of the beam crossing time. The timing resolution σ_t obtained after making these corrections was a slowly decreasing function of energy: $\sigma_t = 1.2$ ns for

a 1 GeV shower decreasing to $\sigma_t = 1.0$ ns for energies above 2.5 GeV. The distribution of lead-glass times for the data and for radiative Bhabha events is shown in fig. 3.4.



Figure 3.4. The corrected event time from the lead-glass signals for the data (points with error bars) and for radiative Bhabha events (histogram). A fit to the radiative Bhabha distribution yields $\sigma = 1.037$. The data events present at early times are due to cosmic ray interactions in the detector.

▷ Events from non beam-beam interactions having the central track originating far from the interaction point were rejected by requiring that the maximum energy central track or any other tracks that might have been combined with it have a z-intercept < 0.3 m from the interaction point. The distribution of z-intercepts for the data and for radiative Bhabha events is shown in fig. 3.5.

Of the events passing the first pass filter, 14.3 % passed these cuts. They were logged to 40 tapes which were used for the final round of event selection cuts presented in chapter 6. The track parameters determined during this second pass filter were saved with the data for later use. The overall efficiency of this procedure varied



Figure 3.5. The z-intercept of central tracks for the data (points with error bars) and for radiative Bhabha events (histogram). A fit to the radiative Bhabha distribution yields $\sigma_z = 0.0297 \text{ m}$. The events with intercepts far from the origin indicate the fraction of the data that is due to beam-gas interactions.

strongly as a function of the low energy cutoff at low energies, due to the trigger efficiency (see fig. 3.2). However, the efficiency was high for events having energy above the trigger threshold: it was measured to be 96.1 % for events with single central tracks having E > 1.5 GeV and $\theta_p > 20^{\circ}$ from the beamline.
Backgrounds

In designing and performing an experiment of this kind, consideration must be given not only to the types of events to be studied, but also to the potential backgrounds to those processes. A number of features of the detector were specifically included in order to enable background events to be distinguished from the signal events, which in this case are single isolated electrons in the central acceptance region. The central calorimeter allowed the position and direction of electromagnetic showers to be determined with good accuracy, so that tracks that originated from the beam-beam interaction point could be distinguished from backgrounds due to non beam-beam sources that have a broad spatial distribution. The pattern recognition and timing information from the calorimeter served to identify non-electromagnetic showers and events that were not in time with the beam crossing time. It also had a high detection efficiency, but unlike many other calorimeters it had essentially no intrinsic noise. Since timing gates of ~ 10 ns were sufficiently wide to assure full trigger efficiencies, a low trigger threshold could be achieved without producing significant dead-time due to triggers from noise or cosmic rays. The full coverage down to low angles provided by the forward shower counters that overlapped with the central calorimeter region allowed additional particles in an event to be detected so that potential multi-particle backgrounds were essentially eliminated.

4.1 Anticipated Backgrounds

The basic classes of events which were expected to be backgrounds for the search for single electron events are as follows:

4.1.1 Cosmic Rays

The high flux of cosmic rays reaching the surface of the Earth could be a potential source of background in this search. Fortunately, unlike most detectors which have a large volume in which cosmic rays can interact, the compact design of the ASP calorimeter presents a smaller active volume. Also, since the ASP calorimeter is a Čerenkov detector, it did not register anomalously large signals from cosmic rays in the way that sampling ionization calorimeters do. In such a device a cosmic ray can travel along the length of a sampling gap, and deposit a large amount of radiation in a single cell. In addition, the location of the ASP detector in IR-10 on PEP placed it underground below 20 m of rock and soil. This covering was sufficient to filter essentially all hadrons from the cosmic ray flux and to attenuate the penetrating muon component by about a factor of 3.

The cosmic ray muons which did reach the detector were still copious, but most could be easily distinguished as muons. They travelled straight through the detector, leaving clear tracks that could be identified as arising from minimum-ionizing particles, as a result of their even energy deposition in both the lead-glass and central PWC systems. In addition, they left clear tracks in the central tracker. However, a small fraction of events were not as easy to distinguish as cosmic rays. These were events in which the muon generated a large signal in the calorimeter by producing an energetic knock-on electron. Although this resulted in a single, isolated shower in the calorimeter, these events could be identified using the tracking and timing capabilities of the detector: the cosmic rays were random in their time of arrival and uniform in their spatial distribution across a horizontal plane through the detector. Thus they could be distinguished from beam-beam interactions in which showers originated from the interaction point and were in-time with the beam crossing signal. The time-of-flight system placed above the central calorimeter provided a further means of distinguishing down-going cosmic rays from beam-beam interactions since it allowed a comparison to be made between the timing signal from the lead glass and from the time-of-flight system. The combination of the pattern-recognition, originreconstruction and timing capabilities of the ASP detector was sufficiently powerful to reject all possible background events arising from cosmic rays.

4.1.2 Beam-Gas Interactions

Another possible source of background for this search comes from the interaction of single beam particles with residual gas molecules in the beam pipe. Since these beam-gas interactions arise when the beam passes through the interaction region, they are in time with the beam crossing, making them harder to reject than cosmic rays. However, the gas molecules are uniformly distributed along the beam line, so these events arise from a line source along the z-axis, so that the tracking capabilities of the calorimeter could be used to reject most of these events on the basis of their z-intercept not being close to the beam-beam collision point.

The two common forms of beam-gas interactions are (see fig. 4.1):



Figure 4.1. Topologies of (a) beam-gas bremsstrahlung and (b) Compton scattering type beam-gas interactions which can produce photons, pions, nucleons and nuclear fragments.

beam-gas bremsstrahlung, where the beam particle radiates a photon when it scatters inelastically off a nucleon. This process has been analyzed⁽⁷⁴⁾ and was found to be quite small (of order 10⁻⁴) relative to the rate due to radiative Bhabha events. Also, it tends to result in a low energy photon scattered at wider polar angles with the incident beam particle being scattered at low polar angles, and thus the particle detected centrally is a photon rather than an electron. Consequently this process is not a background to this search.

Compton scattering type interactions where the beam particle radiates a ⊳ photon which interacts with a nucleon to produce a photon or pions and other nuclear fragments. In these interactions the incident electron is scattered at nearly 0° with respect to the beam line and will consequently not be detected in the central acceptance. As a result, the other particles produced in these interactions must conserve transverse momentum, and so it is unlikely that just a single track will be observed. Also, these particles will have low energy $(\leq 1 \text{ GeV})$. For example, a common interaction that might cause a background to this search is the case where the photon radiated from the beam particle interacts with a proton in a residual gas molecule to produce pions. In this case the overlap of a π^0 with a charged π can leave a signature in the calorimeter that would look like an electron shower. However, the recoiling proton (or nuclear fragment) would have to balance the transverse momentum of the observed pions, and would be observed in the detector. A number of events, where a broad shower in the calorimeter is accompanied by a charged track in the central tracker away from the shower, which has little or no associated calorimeter energy, have been observed in the data set and are presumably from this source. The breadth of the calorimeter shower and the presence of an additional charged track makes it easy to distinguish these events, so that this background is not a problem for this search.

4.1.3 Beam-beam Collision Events

Since events from e^+e^- interactions are from the beam collision point and are in time with the beam crossing, they are potentially harder to distinguish from signal events than the other backgrounds. Of all the various e^+e^- processes, basic QED events are the major source of background, since they are copious sources of electrons. The most important beam-beam process to consider is the low multiplicity forwardpeaked radiative Bhabha scattering process $e^+e^- \rightarrow e^+e^-\gamma$. Two-photon events such as $e^+e^- \rightarrow e^+e^-e^+e^-$ are similar in nature, but are not a source of background here as they tend to have transverse momentum balance between the centrally detected particles.

Fortunately, these types of events may be separated from the signal events by applying the principle of a kinematic veto: if an electron is produced with an energy E at a polar angle θ , then the remaining particles in the final state must balance its transverse momentum. This means that at least one other particle must be above a minimum polar angle θ_{min} . For radiative Bhabha scattering, the configuration which is hardest to veto against is shown in fig. 4.2. From transverse momentum balance it is clear that the minimum polar angle below which both forward going particles must be scattered, in order to balance the p_t of the central electron, is given by

$$\theta_{min} = \frac{(p_t)_e}{2E_{beam}} = \frac{E_e \sin \theta_e}{2E_{beam}} \tag{4.1}$$

For example, if a 3 GeV electron is detected at $\theta = 20^{\circ}$ ($p_t = 1.03 \text{ Gev/c}$), then at least one of the forward going particles must be above $\theta = 35$ mrad. Since the ASP detector completely covers polar angles > 21 mrad from the beam line, all centrally observed electrons with $p_t > 0.61 \text{ GeV/c}$ will have at least one other particle within the detector coverage. So in principle this background can be vetoed provided the observed particle has $p_t > 0.61 \text{ GeV/c}$.



Figure 4.2. The $e^+e^- \rightarrow e^+e^-\gamma$ topology that minimizes the maximum scattering angle of the two forward going particles.

However, given that the calorimeter does not have perfect energy and angular resolution, some electrons from this source that are produced with p_t less than this cutoff will be observed in the detector with a p_t somewhat above the cutoff. This resolution smearing effect has been evaluated in detail by generating Monte Carlo events of this topology using the radiative Bhabha event generator TEEGG7⁽⁷⁵⁾. The generated events were smeared according to the known energy and angular resolutions determined from the kinematically fitted radiative Bhabha sample. In fig. 4.3 the event distributions from this calculation are shown versus p_t and versus energy, both as generated, and with the resolution effects applied, for electrons within the angular acceptance $\theta_p > 20^{\circ}$ from the beam line, and for the integrated luminosity recorded in this experiment (109.6 pb^{-1}). The size of this potential background is clearly very large, but is confined to low p_t and low energy. This calculation predicts that no events having a single electron with $p_t > 0.9 \text{ GeV/c}$ or E > 2.0 GeV, within the central angular acceptance, will be observed without there being another particle within the detector coverage. Consequently no contribution of single electron events from this source is expected in this experiment above these cutoffs.

4.2 Unexpected Background

In addition to the anticipated backgrounds discussed above, there was another event topology that was discovered to be a source of background during preliminary event selection. An initial off-line study of the data indicated the presence of a small number of what appeared to be good single electron events with p_t well above the 0.9 GeV/c cutoff expected from the kinematic veto and with energy around 4 GeV. After puzzling over the origin of these events for a while, considering whether they could be due to any source other than from the production of new particles, it became apparent that it was possible for radiative Bhabha events to result in a background where single electrons with p_t greater than the kinematic veto cutoff could be observed. Such a background arises in the following manner: if a radiative Bhabha event has one electron in the central detector acceptance (providing the desired single electron signature) with the other electron scattered along the beam line so that is un-



Figure 4.3. The distribution of radiative Bhabha background events is shown in (a) as a function of p_t and in (b) as a function of energy. In both cases the histogram shows the distribution without resolution effects, and the points show the distribution after the detector resolution has been applied.

detected, while the photon (which balances the p_t of the electron in the acceptance) passes through a thinner portion of the detector without converting, then a single electron, possibly with high p_t , and no other detected particles, would be observed. This possible background would yield exactly the single electron signature that was being searched for in this analysis!

Is such a background significant in this experiment? This depends on the probability of a photon from radiative Bhabha scattering not converting in the detector. The probability that any particular photon will not convert is given by

$$P_{NC} = exp\left(-\frac{7}{9}R_L\right) \tag{4.2}$$

where R_L is the number of radiation lengths traversed by the photon. In fig. 4.4 the thickness of the detector in radiation lengths is shown as a function of θ and of ϕ . Although the detector is hermetic over the entire angular range down to the small beam line holes at forward angles, there are regions that are not very thick. In particular, the thinnest sections are those around $\phi = 70^{\circ} + n \frac{\pi}{2}$ where two adjacent quadrants of the central calorimeter meet. Barely 8 radiation lengths of material are present there at $\theta = 90^{\circ}$, with a slow increase in thickness as θ moves away from 90°. Although 8 radiation lengths is not thin, the radiative Bhabha process is such a copious source of events that there is a possibility that events could be observed where the photon does not convert. In addition, there is a region around $\theta = 10^{\circ}$ from the beam line where the inner forward shower counters do not overlap with either the central calorimeter or the outer forward shower counters, so that there is only 12 radiation lengths of coverage there. Even though this region is fairly thick, for the radiative Bhabha scattering topology of interest here, where one of the electrons is scattered at wide angles, the photon is dominantly scattered at low angles, so that the non-conversion probability may be high in this region.

To investigate and quantify this background, a detailed Monte Carlo calculation was performed using the TEEGG7 radiative Bhabha event generator. Events were generated with one electron in the central region and the other electron within the



Figure 4.4. The thickness of the detector in units of radiation lengths is shown as a function of (a) ϕ for $\theta = 22.5^{\circ}, 45^{\circ}$ and 90°; and of (b) θ for $\phi = 42.5^{\circ}$ and 71° where the central calorimeter has respectively its maximum and minimum thickness in ϕ

forward angular cutoff ($\theta = 21 \text{ mrad}$) while the photon could be at any angle above this forward cutoff. To allow for the effects of detector resolution, events were generated with the central electron having E > 0.5 GeV and $\theta > 10^{\circ}$ from the beamline. The effects of the trigger and analysis efficiencies as well as the resolutions, all as determined from the kinematically fitted radiative Bhabha sample, were applied to the events. Then those events with an electron within the central angular acceptance $(\theta_p > 20^{\circ} \text{ from the beam line})$ were selected. The energy distribution of the detected electrons in these events is shown in fig. 4.5 (a); as expected the spectrum is peaked at low energies and falls rapidly with increasing energy. To evaluate the magnitude of the background from non-converted photons, each event is weighted with the probability that the generated photon in it would not have converted *i.e.* with P_{NC} from eqn. 4.2. Weighting each event in this way yields the weighted energy spectrum shown in fig. 4.5(b). Although there are relatively few events with higher energy electrons, the photons that balance the p_t in these events are at larger angles, so that they pass through thinner regions of the detector and have larger weights for not converting. The peak observed between 9 and 14 GeV arises from photons that pass through the thinner regions of the central calorimeter, while the peak between 2 and 5 GeV arises from photons that pass through the region of the inner forward shower counters that is not also covered by the central calorimeter or the outer forward shower counters. Summing the weights in this distribution yields the integrated probability for observing events that would have a non-converted photon in this experiment. The integral probability is 1.96 events for the full range of this distribution.

This analysis shows that a small number of single electron events are indeed expected to be observed above the kinematic veto cutoff, as a result of radiative Bhabha events in which the photon does not convert. However, since the origin of such events is understood, it is possible to make a specific cut to eliminate them. Applying four-momentum conservation, the kinematics of a radiative Bhabha event where one electron escapes undetected down the beamline may be described as follows:



Figure 4.5. The energy spectrum for electrons observed in the detector from radiative Bhabha scattering, where the other electron in the event is scattered within the beam pipe, is shown in (a). When each event is weighted by the probability that the photon in it does not convert, the histogram in (b) is obtained. By applying the cuts described in the text, the distribution is reduced to that shown by the points.

$$p_e + p_{\bar{e}} + p_{\gamma} = E_{cm} \tag{4.3}$$

$$p_e \sin \theta_e = p_\gamma \sin \theta_\gamma \tag{4.4}$$

$$p_{\bar{e}} = \pm p_e \cos \theta_e + p_\gamma \cos \theta_\gamma \tag{4.5}$$

where it has been assumed without loss of generality that the electron (e) is detected and the positron (\bar{e}) escapes down the beamline, and that both of them are extremely relativistic so that their rest masses can be ignored. There is an additional transverse momentum balance equation which serves to constrain the three particles to lie in a plane. The sign ambiguity in eqn. 4.5 arises because the direction of travel of the positron lost down the beam line is unknown, *i.e.* it is not known whether it is at $\theta = 0^{\circ}$ or at $\theta = 180^{\circ}$, corresponding to the two configurations shown in fig. 4.6. In actuality, the QED matrix elements strongly favor the positron to be scattered down the beam line in the same direction as its incident direction. However, the ASP detector has no means of identifying the sign of charged particles: since it is not known whether the detected electron is an e^+ or an e^- , the undetected electron could be either an e^+ or an e^- too. Consequently the sign ambiguity represents two possible solutions which cannot be distinguished in this experiment. Fortunately, as will be seen shortly this ambiguity does not lead to a large effect here.



Figure 4.6. The two possible topologies that can occur in radiative Bhabha scattering when one electron is observed and the other electron is scattered down the beam line.

Scaling the momenta to the beam energy, E_b , equations (4.3 - 4.5) can be rewritten in terms of:

$$x_i = \frac{p_i}{E_b}, \qquad c_i = \cos \theta_i, \qquad s_i = \sin \theta_i$$

where $i = e, \bar{e}$ or γ . Assuming that the electron energy and angle, x_e and c_e , have been measured, it is desired to determine the energy and angle of the photon, x_{γ} and c_{γ} . By eliminating $x_{\bar{e}}$ from the equations, the remaining two equations can be solved for x_{γ} and c_{γ} , in terms of x_e and c_e , yielding the following solutions:

$$x_{\gamma} = 1 - \frac{x_e(1 - x_e)(1 \pm c_e)}{2 - x_e(1 \pm c_e)}$$
(4.6)

$$c_{\gamma} = 1 - \frac{x_e^2 (1 - c_e^2)}{2 - x_e (1 \pm c_e)(2 - x_e)}$$
(4.7)

There are two solutions for both x_{γ} and c_{γ} corresponding to the two possible directions of travel of the positron down the beamline. Although these equations have been derived for the case where it is the e^- that is detected, since they depend only on energy-momentum balance, they are equally valid for the case where it is the e^+ that is detected. Applying these equations in the Monte Carlo calculation, it is possible to compare the energy and angle of the photon as generated, with the values calculated from the energy and angle of the observed electron. As shown in fig. 4.7, the agreement is good: 99.9 % of events have an energy difference of less than 0.05 GeV, and 99.9 % of events have a theta difference of less than 1.5°. This quantifies the effects due to the fact that the electron scattered down the beamline is not always exactly along the z-axis (as assumed in the calculation), but may be at a small angle within the forward cutoff of 21 mrad. This assumption is seen to have minimal effect.

Since this background arises only when the photons pass through the thinner sections of the detector, using equations (4.6 - 4.7) it is possible to design a cut that eliminates the events from this source. For each detected single electron event, the measured energy and angles can be used to calculate the angles of the photon that would be present if this were a radiative Bhabha event having the other electron



Figure 4.7. The difference between the calculated and the generated (a) energy and (b) polar angle of the photons in the Monte Carlo calculation.

scattered down the beam line. The cut is most effective when applied to two distinct regions. Firstly, the lower energy background can be eliminated by rejecting events if the photon is in the thinnest region of the forward coverage. The θ_p distribution for the generated photons in the Monte Carlo events is shown in fig. 4.8 (a): most of the photons are at very low angles, balancing the p_t of the lower energy central electrons. When each event is weighted by the probability for the photon in it not to convert, the weighted distribution shown in fig. 4.8(b) is obtained. The background due to the non-conversion of photons is seen to arise from two distinct regions: photons probing the thin regions of the central calorimeter, and those probing the forward regions which are covered only by the inner forward shower counters. Since the latter contribution arises from very narrow angular regions it is efficiently eliminated by the first part of the cut which rejects events if either of the solutions for c_{γ} lies in the range $8^{\circ} < \theta_p < 13^{\circ}$ or $167^{\circ} < \theta_p < 172^{\circ}$.

Secondly, the calculated angles of the photon can be used to determine the number of radiation lengths that the photon would have traversed in passing through the detector. Then the higher energy background can be eliminated by requiring that this number of radiation lengths be greater than a particular value, to be determined from the Monte Carlo calculation. The only complication in this case is that it is necessary to calculate the number of radiation lengths corresponding to both of the possible solutions for c_{γ} , and then assign the lower of the two to the event. Since this background arises predominantly when $c_e \sim 0$ (*i.e.* $\theta_e \sim 90^{\circ}$), where the two solutions coincide, they are similar in this case, so that taking them both into account does not lead to a large effect. Various values of the radiation length cut were evaluated in the Monte Carlo calculation for different lower energy cutoffs. It was determined that the background could be reduced to a low enough level above an energy of 4 GeV by rejecting events where the minimum calculated number of radiation lengths traversed by the photon was less than 13. The effect of both parts of this cut against this background is shown in fig. 4.5(b). After this cut has been applied, this source is predicted to contribute only 0.12 events above the energy cutoff of 4 GeV.

Clearly this cut reduces the acceptance for the single electron search; the amount



Figure 4.8. The theta-projected distribution of photons in the radiative Bhabha Monte Carlo is shown in (a). When each event is weighted by the probability that the photon in it does not convert, the weighted distribution in (b) is obtained.

of the reduction depends on the energy and angular distributions expected for single selectron and single wino production. The details of the Monte Carlo predictions for these distributions are presented in the following chapter.

Monte Carlo Calculations

-In addition to considering the backgrounds to the processes being investigated, it was necessary to study the event distributions expected from these processes before the final event selection could be performed. These distributions were obtained from detailed Monte Carlo calculations which generated events according to the matrix elements obtained from the Feynman diagrams for these processes. Some of these predicted signal distributions vary strongly with the masses of the Supersymmetric particles being generated, so it is necessary to redetermine them for each set of masses being investigated. Consequently, since it was necessary to obtain results as a function of these masses, it was not possible to use detailed detector simulation calculations for each pair of mass combinations, since that would have required excessive amounts of computer time. Instead, the approach that was used was to apply the resolutions as measured by the radiative Bhabha events as a function of energy, theta and phi to the Monte Carlo events to determine the distributions that would be observed in the detector. This method does not depend on the correctness of the many details of detector simulation calculations, and also provides a rapid evaluation of the expected distributions.

In this chapter details of the resolutions as measured using the radiative Bhabha events are presented first. Then the event distributions expected in the detector including these resolution effects are discussed for a selection of representative SUSY mass combinations for single selectron and for single wino production.

5.1 Resolutions for Central Acceptance Region

The radiative Bhabha events that were selected and fitted as described in sec. 3.2 were used to measure the energy and angular resolutions of the central acceptance region as a function of energy and angles. The resolutions were determined for bins of energy, theta and phi and were then used in a lookup table to apply the effects of these resolutions to the data generated by the Monte Carlo calculations. This method was suitable since none of the resolutions vary sharply as a function of energy or angle. For instance, the energy resolution as a function of energy is shown in fig. 5.1; no strong variation as a function of energy is apparent.



Figure 5.1. The energy resolution of the central acceptance region as a function of energy.

In fig. 5.2 (a), the energy resolution is plotted as a function of θ . The resolution is poorer at low angles since that region corresponds to the edge of the central calorimeter acceptance where a fraction of the shower energy leaks into the forward shower counters which have poorer resolution. The resolution is also slightly poorer at higher angles since this is the thinnest part of the calorimeter, so that leakage is



Figure 5.2. The energy resolution for central electrons with energy in the range 1 - 2 GeV as a function of (a) theta and (b) phi (for electrons with $\theta_p > 20^\circ$ from the beam line.)

more significant there; because the leakage was only estimated, on average, and not applied on an event-by-event basis, the resolution is degraded in this region. The energy resolution is also shown as a function of ϕ in fig. 5.2(b). The regular pattern observed is a result of the construction of the calorimeter from four quadrants. The resolution is seen to be poorest in the corners where two quadrants overlap: these are the thinnest regions of the detector and are also the regions in which it is most difficult to accurately reconstruct the electromagnetic showers.

The angular resolutions as a function of energy are shown in fig. 5.3. There is no strong variation with energy, although both the θ and ϕ resolutions improve with increasing energy since the higher energy showers leave hits in more counters of the calorimeter so that the angles can be better determined.



Figure 5.3. The θ and ϕ resolutions of the central acceptance region as a function of energy.

In fig. 5.4, the θ resolution is seen to be fairly flat as a function of ϕ , although some variation due to the quadrant geometry is present. The θ resolution is also fairly flat as a function of θ , with $\sigma_{\theta} = 2.5^{\circ}$ for the central region of the calorimeter,



Figure 5.4. The θ resolution of the central acceptance region as a function of ϕ .

improving to $\sigma_{\theta} = 1.5^{\circ}$ around $\theta = 20^{\circ}$ and 160° where the inner forward shower counters overlap with the central calorimeter, providing a second measurement of the polar angle which yields an improved resolution there. The ϕ resolution as a function of θ is shown in fig. 5.5 which indicates that it improves slightly at higher θ where a shower of given energy penetrates more layers of the calorimeter, so that the central PWC's can make a better determination of the direction of the shower. The ϕ resolution as a function of ϕ shows a regular pattern reflecting the construction of the calorimeter from the separate quadrants: $\sigma_{\phi} \sim 1.8^{\circ}$ in the regions where the track is approximately normal to a quadrant and in the regions where two quadrants overlap; and $\sigma_{\phi} = 1.4^{\circ}$ in the regions around $\phi = 35^{\circ} + n\frac{\pi}{2}$ where a shower hits more central PWC cells than in the other two regions. Overall, no strong dependence of the resolutions of the central acceptance region on any variables is observed.



Figure 5.5. The ϕ resolution of the central acceptance region as a function of θ .

5.2 Supersymmetric Particle Production

As discussed in chapter 1, all but one of the previous searches for the production of single selectrons or winos in e^+e^- interactions reached results based on calculations using the equivalent photon approximation (EPA). As pointed out earlier, it appears that such calculations overestimate the cross-sections by a substantial factor. In this analysis the Monte Carlo programs written by M. Martinez as used by the MAC collaboration for their latest results⁽⁴⁷⁾ have been used. These programs include all the Feynman diagrams for these processes.

The kinematic limits of the mass ranges that could potentially be covered in a search for these processes at the PEP center-of-mass energy of 29 GeV are shown in fig. 5.6. In practice, given the finite amount of data in any experiment, it is not possible to reach these limits since the cross-sections decrease rapidly as the masses approach the kinematic boundary, as illustrated in figs. 1.8 and 1.11.



Figure 5.6. The mass region below and to the left of the line is potentially accessible in single \tilde{e} or single \widetilde{W} production at the energy of PEP. The crosses indicate the mass combinations used to generate events for studying the distributions expected from these processes.

5.2.1 Single Selectron Production

The single selectron production Monte Carlo program was used to generate 10^4 events for a selection of $(m_{\tilde{e}}, m_{\tilde{\gamma}})$ points within the kinematic boundary in order to determine the distributions to be expected if this process were to be observed. The distributions shown here correspond just to the one case where it is the incident positron that is scattered forwards, mostly at low angles, and the incident electron interacts to form a photino and a selectron. The selectron then decays to produce an electron, usually at wide angles, and a photino. The photinos are assumed to be weakly interacting and would not be detected. Similar distributions arise for the charge conjugate case where the electron is scattered forwards and the positron interacts to form a selectron: the distributions of the electron and positron are simply interchanged, but with the θ distributions reflected about $\theta = 90^{\circ}$ due to the different incident directions of the positron and the electron. In these distributions, all events

produced by the SUSY process are shown; although the effects of the ASP detector resolutions have been applied to the events, no cuts have been made and no efficiency effects have been taken into account. As will be seen in the next chapter, the efficiency of the event selection for these searches is high. When cuts were applied to the Monte Carlo events there was found to be very little correlation between the parameters of the particles produced in this process. Consequently, the effect of making a cut on the energy or angle of one particle can be determined directly from the distribution for that parameter.

The most marked variation in the distributions for the different mass sets is in the energy spectra. The energy spectrum of electrons from the selectron decay for $m_{\tilde{e}} = 15 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 0$ (*i.e.* the selectron mass is just above beam energy) is shown in fig. 5.7 (a). The distribution is broad due to the large phase space for the process in this case, and it produces energetic electrons that are easy to detect. When the selectron mass is increased, the spectrum becomes narrower due to the decreased phase space, and harder, since it arises from the decay of a more massive particle, as shown in 5.7(b) where $m_{\tilde{e}} = 25 \text{ GeV/c}^2$ with $m_{\tilde{\gamma}} = 0$ still. When the photino mass is increased, for fixed selectron mass, the energy spectrum also becomes narrower due to the decreased phase space, but it is softer since energy is taken up in producing the massive photino. This is also illustrated in fig. 5.7(b) where $m_{\tilde{e}} = 15 \text{ GeV/c}^2$, as in fig. 5.7(a), but with $m_{\tilde{\gamma}} = 10 \text{ GeV/c}^2$. Consequently, as the mass of the photino increases, it becomes increasingly more difficult to detect the electron as in an increasing fraction of events it will have an energy below the central energy cutoff. At intermediate values of $m_{\tilde{e}}$ and $m_{\tilde{\gamma}}$, the spectrum is slightly broader and more centrally located than for the two extreme cases shown in fig. 5.7(b).

The energy spectrum of the forward scattered particle also varies strongly with the masses of the particles being produced. In fig. 5.8 (a) this spectrum is shown for $m_{\tilde{e}} = 15 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 0$, in which case it is seen to be broad, extending all the way from 0 to close to 10 GeV. However, when a massive photino and/or a selectron with mass significantly greater than beam energy is produced, the spectrum becomes softer, since the scattered particle must lose energy in the interaction in order to be



Figure 5.7. The energy distribution of electrons produced in the decay of the selectron (a) for $m_{\tilde{e}} = 15 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 0$, and (b) for $m_{\tilde{e}} = 25 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 0$ and for $m_{\tilde{e}} = 15 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 10 \text{ GeV/c}^2$.



Figure 5.8. The energy distribution of scattered positrons (a) for $m_{\tilde{e}} = 15 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 0$ and (b) for $m_{\tilde{e}} = 20 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 5 \text{ GeV/c}^2$.

able to produce the massive SUSY particles. This is illustrated in fig. 5.8(b), where $m_{\tilde{e}} = 20 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 5 \text{ GeV/c}^2$. Similar spectra are observed for the other two cases since all three heavier mass pairs have a cutoff at 4 GeV, because for each of them $E_{beam} - (m_{\tilde{e}} + m_{\tilde{\gamma}})c^2 = 4 \text{ GeV}$. Thus it becomes more difficult to detect the forward scattered particle as $(m_{\tilde{e}} + m_{\tilde{\gamma}})$ increases, since an increasing fraction of the particles will have an energy below the cutoff for being detected in the forward region.

The angular distributions show little variation with the masses of the SUSY particles. The electron produced in the decay of the selectron is mostly centrally distributed, as shown in fig. 5.9 for $m_{\tilde{e}} = 25 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 0$. This is due to the fact that the selectron is a scalar particle so that it decays isotropically, and since it is heavy it is produced almost at rest, so that there is very little boost given to its decay products. Very similar distributions are observed for the other mass cases, with a slight asymmetry present for lower selectron and photino masses due to the



Figure 5.9. The θ distribution of electrons produced from the decay of the selectron for $m_{\tilde{e}} = 25 \text{ GeV}/c^2$ and $m_{\tilde{\gamma}} = 0$.

boost given to the decay electron. The fact that most of the decay electrons would be observed at wider angles makes this process easier to detect, since most of the electrons would fall within the central acceptance.

The scattered positron is indeed mostly scattered forwards as expected from the EPA prediction, as shown in fig. 5.10 for $m_{\tilde{e}} = 20 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 5 \text{ GeV/c}^2$. However, there is also a finite contribution with the positron scattered at higher angles, that leads to a small fraction of the events having two central tracks observed. Such events would be vetoed by the second track in a search for single electrons such as this one. The angular distribution of the scattered positron is very similar for the different SUSY mass cases; there is a slightly larger fraction of events with this particle at higher angles for cases where the photino is heavy.



Figure 5.10. The θ distribution of scattered positrons for $m_{\tilde{e}} = 20 \text{ GeV/c}^2$ and $m_{\tilde{\gamma}} = 5 \text{ GeV/c}^2$.

5.2.2 Single Wino Production

The single wino production Monte Carlo program was also used to generate sets of 10⁴ events for selected $(m_{\widetilde{W}}, m_{\tilde{\nu}})$ points using the same values as were used for $(m_{\tilde{e}}, m_{\tilde{\gamma}})$ in generating the events discussed above. These calculations yielded event distributions that were very similar to those determined from the single selectron production Monte Carlo for the same input mass pairs (*i.e.* $m_{\widetilde{W}} = m_{\tilde{e}}$ and $m_{\tilde{\nu}} = m_{\tilde{\gamma}}$). The most notable difference between the calculations is in the scattered positron energy spectrum, which covers the same range, but for lower wino masses is harder than the spectrum for production of a selectron of the same mass. This spectrum is shown in fig. 5.11 for $m_{\widetilde{W}} = 15 \text{ GeV/c}^2$ and $m_{\tilde{\nu}} = 0$ and is seen to be harder than that in fig. 5.8(a).



Figure 5.11. The energy distribution of scattered positrons for $m_{\widetilde{W}} = 15 \text{ GeV/c}^2$ and $m_{\widetilde{\nu}} = 0$.

The other distributions are not shown here since they are almost identical to those shown above for the single selectron production Monte Carlo. The close similarity between the distributions for the two different Monte Carlos reflects the similar nature of the diagrams contributing to the two different processes (see figs. 1.6, 1.7 and 1.10) and the strong influence of phase space effects which are the same in both cases.

Results and Conclusions

Having studied the background sources and determined the expected event distributions from Monte Carlo calculations of the single selectron and single wino production processes, the final event selection could be performed. The aim was to isolate any single electron candidate events in the data set with high efficiency, in a region where the backgrounds are not expected to contribute. From the study of the background due to radiative Bhabha scattering presented in chapter 4, it was determined that if appropriate cuts are applied to the data, no events from known sources are to be expected in the central angular acceptance region ($\theta_p > 20^{\circ}$ from the beam line) above the energy cutoff of 4 GeV. This defines the search region for this analysis. Any sizeable number of single electron events observed in this region would constitute evidence for the production of new particle types, and would be a very exciting observation indeed. Alternatively, the absence of any significant level of such events would allow constraints to be placed on the production cross-sections of any new particles that could be expected to result in an observable single electron signature at the energy of the PEP e^+e^- collider. In particular, this can lead to mass limits on such new particles. Although a null result of this type is obviously not as exciting as the discovery of new types of events, it allows constraints to be placed on theories of new physical phenomena, such as Supersymmetry, providing guidance to both theorists in constructing their theories, and to experimentalists in performing searches for these or related particles.

6.1 Third Pass Event Filter

The final event filter ran on the tracked output of the second pass filter. The earlier filter had applied loose cuts in order to select all possible events with one track in the central acceptance region, with high efficiency, without regard to the charge of the track or whether there were additional tracks present in the forward region. This provided a general data sample that was useful for further intensive analysis. The full event tracking had been performed in the second pass filter, so that the topologies of the events were \vec{w} ell-defined by this stage, allowing the final cuts to be implemented easily. Since the majority of events in this sample were radiative Bhabha events with forward tracks present, they were eliminated first in the third pass filter. Then detailed cuts were made on the remaining events to select only those with a single, clean electromagnetic shower in the central acceptance region, that fulfilled the criteria expected for a good single electron event. The selection of events in this third pass filter proceeded as follows:

- First only events having a charged central track were selected based on the central tracker information as determined in the second pass filter.
- Next, events with tracks or energy in the forward system were rejected by making the following cuts on the events:
 - There were required to be no tracks in the region outside the lead-glass coverage ($\theta_p < 12^{\circ}$ from the beam line) having energy > 0.5 GeV.
 - Each outer forward shower counter was required to have less than 0.6 GeV of raw energy present, to eliminate events containing significant forward energy, but in which the tracking had not found any tracks.
 - Each inner forward shower counter was required to have less than 0.2 GeV of raw energy present. However, if the central track had $\theta_p < 30^{\circ}$ from the beam line, this cut was not applied to the shower counter towards which the central track pointed, since in this case there may have been significant leakage of energy from the central calorimeter into that forward shower counter. Harder cuts could be applied to the inner shower counters than to the outer ones, since the noise level was lower in the inner ones.

- ▷ To distinguish electromagnetic showers from other interactions in the central calorimeter, a number of shower shape cuts were used:
 - The width-squared moment of the lead-glass energy deposition was calculated using

$$M_{W^2} = \frac{1}{\sum_i E_i} \sum_i E_i D_i^2$$
(6.1)

where E_i is the energy in the *i*'th bar in the shower, corrected for both PMT gain and attenuation, and D_i is the perpendicular distance from the central axis of the *i*'th bar to the shower axis. The sum was over all bars with significant energy. This moment, M_{W^2} , was larger for broad showers such as those initiated by debris from beam-gas interactions than for single electromagnetic showers. Consequently, non-electromagnetic showers were rejected by requiring that this moment not be too large. The distribution of this moment for the data and for the kinematically fitted radiative Bhabha events is shown in fig. 6.1 (a). Since showers in the corners of the calorimeter, where two quadrants overlapped, tended to be slightly broader, showers having ϕ in the range $(48^\circ - 80^\circ) + n\frac{\pi}{2}$ were required to have $M_{W^2} < .0026$, while showers in the rest of the ϕ range were required to have $M_{W^2} < .0020$.

- Another moment of the lead-glass energy deposition was defined analogously to the width-squared moment, viz. the angular width-squared moment, A_{W^2} . In this case, instead of using the distances D_i to calculate the moment, the angles ψ_i of each bar from the shower axis, with respect to the origin, were used. This serves to distinguish showers in the lead-glass that are wider towards the end of their longitudinal development than is the case for electromagnetic showers. The distribution of this moment for the data and for the radiative Bhabha events is shown in fig. 6.1(b). The events were required to have $A_{W^2} < 0.012$.
- The width-squared moment of the central PWC energy deposition was calculated using a formula of the same form as that for the lead-glass



Figure 6.1. The (a) width-squared moment and (b) angular width-squared moment, for lead-glass showers for the data (points with error bars) and for radiative Bhabha events (histogram). In (a) half the data (13,261 events) is in the overflow bin, while in (b) there are only 594 events in the overflow bin.

moment. This was used to reject events having broad showers in the central PWC's. As for the lead-glass moment cut, since the PWC showers tended to be broader in the corner regions of the calorimeter, wider showers were allowed there by requiring $M_{W_{CP}^2} < 0.020$, while the showers were required to be narrower in the rest of the calorimeter by making the tighter cut $M_{W_{CP}^2} < 0.015$.

- Events having a very uneven deposition of energy in the lead-glass system could be eliminated by checking the layer energy fractions. In particular, showers apparently from beam gas interactions, were observed to deposit most of their energy in the first layer of the calorimeter. These events were rejected by requiring that the layer with the maximum fraction of the energy have less than 0.85 of the total shower energy. The distribution of this maximum layer fraction for the data and for the radiative Bhabha events is shown in fig. 6.2.
- ▷ To select events that were in time with the beam crossing, the cut on the corrected lead-glass time that was applied in the second pass filter was tightened to require events to be within $3\sigma_t$ of the beam crossing time. As seen in fig. 6.3, a fairly small fraction of the events remaining at this stage were due to cosmic ray interactions, as evidenced by the enhanced number of events with times before the beam crossing signal, compared to the distribution for radiative Bhabha events.
- Events which clearly did not originate from the beam-beam interaction point were eliminated by tightening the cut on the z-intercept of the central track to 0.1 m from the interaction point. From the distribution of z-intercepts in fig. 6.4, it is seen that about half of the events remaining at this stage of the analysis must be due to beam-gas interactions.
- ▷ The cut designed to eliminate the background from radiative Bhabha events in which one electron is within the beam pipe and the photon does not convert, as discussed in sec. 4.2, was applied to the events. This rejected events if either solution for the calculated direction of the photon was within the range



Figure 6.2. The fraction of lead-glass energy in the layer having the maximum fraction for the data (points with error bars) and for radiative Bhabha events (histogram). The final data point is off-scale; that bin contains 192 events.

 $8^{\circ} < \theta_p < 13^{\circ}$ of the beam line or the minimum possible calculated number of radiation lengths that the photon would have penetrated was less than 13.

- Finally, to retain only clean events, the level of additional activity in the detector was required to be no greater than that of 99 % of the random triggers:
 - The cut on the signal in each of the two lead-glass quadrants opposite in ϕ to the central track, as made in the second pass filter, was tightened to require less than 0.03 GeV of raw energy in each of them. Although this may seem to be a very tight cut, the lead glass was extremely quiet, as is shown in fig. 3.3. The efficient of this cut was determined from random triggers to be 99.6 %.
 - The signals in the two central VS modules opposite in ϕ to the observed track were each required to be less than that equivalent to 1 minimum ionizing particle.


Figure 6.3. The corrected event time from the lead-glass signals for the data (points with error bars) and for radiative Bhabha events (histogram), just before this cut is applied.

• Events containing additional clear tracks in the central tracker were eliminated by requiring that there be no track in this system that was separated in ϕ by more than 15° from the observed track, and that fulfilled one of the following criteria: at least 5 xy-points and at least 5 z-points found; or at least 4 xy-points found and points from at least one other system (lead glass, central PWC, veto scintillator or forward PWC) be assigned to it. These strict requirements were necessary since the central tracker often picked up random noise hits. This cut was effective in eliminating the remaining beam gas events which contained a single shower accompanied by a charged track with very little energy associated with it.

The efficiency of this final event selection filter was determined to be 88.4 %, using the kinematically fitted radiative Bhabha events to check the track quality cuts, and using the random triggers to check the detector occupancy cuts.



Figure 6.4. The z-intercept for central tracks for the data (points with error bars) and for radiative Bhabha events (histogram) for events passing all earlier cuts.

6.2 Results

The overall procedure for the selection of single electron events is summarized in table 6.1. The energy spectrum of all events passing the full selection procedure is shown in fig. 6.5. The events present at low energies are due to the radiative Bhabha background where two tracks are below the forward angular cutoff (see fig. 4.3(b)) and due to the remnant of the beam-gas background that originates from close to the interaction point. The cutoff at low energies arises from the trigger requirement and the acceptance cut of $p_t > 0.5 \text{ GeV}/c^2$ in the second pass filter. No events were observed within the search region, *i.e.* with energy greater than 4 GeV. The absence of a signal in this region allows limits to be set on possible selectron and photino masses, and also on possible wino and sneutrino masses.

Selection Stage	Number of	Event Fraction	Efficiency
	Events	Passing	$E_e > 3 { m ~GeV}$
First Pass	29,842,391		
Retain only	- ·	-	
physics events:		0.366	0.999
Second Pass -	10,932,099		
Single central track		·	
$p_t > 0.5 \text{ GeV/c}, \ \theta_p > 20^\circ$	• ·	0.143	0.972
Third Pass	$1,\!557,\!872$	•	
Occupancy cuts:			0.929
Track quality:		0.00033	0.951
Final Sample	517		
Overall		0.000017	0.858

Table 6.1. Summary of procedure for selection of single electron events.

6.2.1 Selectron and Photino Mass Limits

The full Monte Carlo event generator for single selectron production was used to generate sets of 10,000 events for different values of $m_{\tilde{e}}$ and $m_{\tilde{\gamma}}$. The effects of the efficiencies of the trigger and analysis cuts, and the effects of detector resolution, all determined using the radiative Bhabha events and random triggers, were applied to the events. Then the number of events remaining in the acceptance that passed all event selection criteria yielded the acceptance corrected cross-section, given the total cross-section determined by the Monte Carlo calculation. The integrated luminosity of the data sample analysed in this search was determined from forward Bhabha events (see sec. 3.2.1) to be 109.56 pb⁻¹. Multiplying this integrated luminosity by the value of the acceptance corrected cross-section predicts the average number of events expected to be observed in this experiment. Since no events were observed in the search region, the 95 % confidence level limit corresponds to 3.00 events, and the 90 % confidence level limit corresponds to 2.30 events. The number of events



Figure 6.5. The energy spectrum of the final event sample after all cuts have been applied. No events are observed in the search region above 4 GeV.

predicted to be observed in this search is shown in fig. 6.6 both as a function of the selectron mass for $m_{\tilde{\gamma}} = 0$, and as a function of the photino mass for $m_{\tilde{e}} = 15 \text{ GeV/c}^2$. As discussed in chapter 1, the relative masses of the two selectron mass eigenstates are in general unknown. Consequently, the two extreme possibilities are considered here: either the two states are degenerate in mass and both are produced, or one state is much heavier than the other, so that only the lighter state can be produced with the available energy.

The mass limits in the $m_{\tilde{e}} - m_{\tilde{\gamma}}$ plane are shown in fig. 6.7. At the 95 % CL selectrons with masses less than 20.51 GeV/c² are excluded for the case of degenerate selectron masses, while selectron masses less than 19.50 GeV/c² are excluded for the non-degenerate case, both for $m_{\tilde{\gamma}} = 0$. The 90 % CL limits are 20.92 GeV/c² and 19.88 GeV/c² respectively. For $m_{\tilde{e}} = 15$ GeV/c², the limits on the photino mass are: 10.70 GeV/c² (10.84 GeV/c²) for the degenerate case and 10.10 GeV/c² (10.37 GeV/c²) for the non-degenerate case at the 95 % CL (90 % CL).



Figure 6.6. The number of events expected to be observed in this search as a function of (a) selectron mass, and (b) photino mass. The 95 % CL limits are indicated.



Figure 6.7. The regions of selectron and photino masses within the contours are excluded at the 95 % CL. The solid contour is for the case where the two selectron mass eigenstates are degenerate in mass, while the dashed contour is for the case when one eigenstate is much heavier than the other.

This experimental search excludes selectron masses substantially greater than the beam energy, while for low mass selectrons photino masses significantly greater than zero are excluded.

6.2.2 Wino and Sneutrino Mass Limits

Mass limits in the $(m_{\widetilde{W}} - m_{\widetilde{\nu}})$ plane were determined using the single wino production Monte Carlo event generator in the same manner as described above for single selectron production. In this case there is only one wino mass eigenstate to be considered. The mass limits obtained are shown in fig. 6.8. At the 95 % CL winos with masses less than 20.56 GeV/c² are excluded for $m_{\widetilde{\nu}} = 0$, while the corresponding 90 % CL limits is 20.95 GeV/c². For $m_{\widetilde{W}} = 15$ GeV/c², the limit on the sneutrino mass is 10.82 GeV/c² at the 95 % CL, and 10.97 GeV/c² at the 90 % CL.



Figure 6.8. The region of wino and sneutrino masses within the contour is excluded at the 95 % CL.

6.3 Systematic Errors

The sensitivity of the SUSY mass limits to systematic errors was determined by modifying the single selectron production Monte Carlo and observing the changes in the calculated cross-section due to different systematic effects. Conclusions derived in this way are also applicable to the limits derived from single wino production, due to the similarity between the two processes. Generally, the limits are not particularly sensitive to changes in the cross-section: this is clear from fig. 6.6 where it is seen that the differences in the mass limits for the two cases $m_{\tilde{e}_L} = m_{\tilde{e}_R}$ and $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$ are only 5 %, despite the difference of a factor of 2 in the cross-section between the two cases. The uncertainty in the mass limits due to the fitting procedure used to extract the limits from the cross-section values as a function of the mass was 0.05 GeV/c².

Two direct sources of error in the cross-section are the uncertainty in the integrated luminosity (1.1 %) and in the overall efficiency (2 %). The less direct sources of error that were evaluated in the Monte Carlo generally did not lead to large changes in the cross-section. A 2° offset in the central angular scale reduces the cross-section by 1.7 %, while a 3 mrad offset in the forward veto angle reduces the cross-section by 3 % due to the additional number of events that are vetoed by the observation of the forward track. A systematic bias in the energy measurement of the central calorimeter leaves the limit on the selectron mass essentially unchanged since the electron energy spectrum in this case is so hard that there are no events near the energy cutoff. However, the electron energy spectrum is much softer when massive photinos are produced, so that a 2 % downwards shift in the energy scale leads to a 10 % decrease in the cross-section for $m_{\tilde{\gamma}} = 10.7 \text{ GeV/c}^2$ with $m_{\tilde{e}} = 15 \text{ GeV/c}^2$. An uncertainty of 0.25 GeV in the forward energy cutoff leads to a 2.5 % shift in the cross-section due to the change in the number of events with forward tracks observed. The uncertainties in the forward and central angular and energy resolutions each contribute only 0.2 - 0.5 % shifts in the cross-section. The calculated cross-section is mostly insensitive to these detector effects due to the smooth nature of the energy and angular distributions resulting from the single selectron or single wino production processes.

Combining these sources of uncertainty indicates that the systematic error in the cross-section is 11.5 % for the production of massive photinos, but is only 5 % for the production of very light photinos. Due to the relative insensitivity of the mass limits to the cross-section value, these uncertainties correspond to a shift in the selectron mass limit of less than 0.1 GeV/c² for $m_{\tilde{\gamma}} = 0$, and a shift in the photino mass limit of less than 0.15 GeV/c² for $m_{\tilde{e}} = 15 \text{ GeV/c}^2$. Consequently the mass limits found above are rather robust.

6.4 Conclusions

Unfortunately, no evidence for the production of supersymmetric particles has been found in this experiment. This search joins the ranks of the earlier experiments (see Table 1.2) which all obtained null results. Supersymmetry remains a theory with great potential but at this stage without any experimental evidence to support it. However, as discussed in Chapter 1, in order for supersymmetry to provide a solution to the hierarchy problem, the masses of the supersymmetric particles cannot be too large. If supersymmetry is to explain the origin of the scale of the electroweak interaction, then it is natural to expect that this is the relevant scale for supersymmetric masses: if these particles exist, they are likely to be discovered soon.

So much for the theoretical prospects for the future. As R. Barbieri ⁽⁷⁶⁾ has pointed out,

"Needless to say, to prove the relevance of supersymmetry to physics remains (fortunately) an experimental matter."

I agree! We must now wait patiently for results from the next round of experiments at the new, higher energy accelerators.

Appendix A

Lead-Glass Calorimeter

This appendix provides details of the design, construction and operation of the central lead-glass calorimeter, which was the major component of the ASP detector.

A.1 Lead Glass as a Calorimeter Material

Lead glass has been widely used for measurements of electromagnetic showers in high energy physics experiments over the last two decades as a result of its many advantages for this application. The lead content of the glass yields a high density material with a small radiation length. Since the glass transmits Čerenkov light in a frequency range which can be efficiently detected using common photocathode materials, and since the full shower development is visible, lead glass has good intrinsic resolution. It is one of the most precise detectors for electron and photon energy measurements. Combining it with photomultiplier tube readout yields a stable device with very low noise level. Although lead glass has a lower light output than scintillation materials, it is cheaper and easier to work with than scintillators such as sodium iodide.

Of course, large quantities of lead glass are not inexpensive in absolute terms, and this has restricted it use. A major share of the cost of conventional lead-glass blocks or bars is due to the requirements of the surface preparation; typically a raw block, cast or extruded from a molten state, is mechanically cut, ground and polished to produce sharp corners and optically flat surfaces. However, extruded lead-glass bars can be made that have a uniform cross-section with the long sides of the bars flat except for a fairly regular ripple pattern on all four sides. The ripples have an amplitude of about 0.2 mm and a spacing of about 4 mm and are produced as a result of the extrusion process. The surface is otherwise quite smooth on the scale of optical wavelengths. A study⁽⁷⁷⁾ comparing the optical properties of a lead-glass bar that was ground and polished on all surfaces in the usual manner, with an extruded bar that had only its small end surfaces cut and polished, found that the optical properties of the two bars were essentially the same. The extruded bar and the polished bar were found to have the same efficiency for Čerenkov light collection as a function both of length along the bar and of angle with respect to the bar. Consequently, it was concluded that for applications where mechanical tolerances could be relaxed, the use of the unpolished extruded bars could lead to a cost saving of a factor of two or more, without jeopardizing the performance of an electromagnetic shower detector.

A more detailed study using a test calorimeter consisting of 60 of these extruded lead-glass bars in a beam of 15 to 45 GeV/c electrons and pions has been performed⁽⁷⁸⁾. The calorimeter was arranged to have segmentation in both the coordinate along the direction of shower development as well as in one transverse coordinate. The results of this study demonstrated that the energy resolution for this calorimeter was in agreement with previous measurements of more conventional calorimeters. Also, the calorimeter could distinguish electromagnetic showers from hadrons with a hadron rejection factor of 10^{-3} . In addition, overlapping $\pi^{\pm} - \gamma$ events could be discriminated from single electrons at the 10^{-2} level. The success of this study provided a strong motivation for the design of our calorimeter.

A.2 Radiation Damage

Transparent materials such as lead glass used in high energy particle detectors become colored when exposed to radiation *i.e.* they develop one or more optical absorption bands which may occur anywhere in the region of optical transparency⁽⁷⁹⁾. This arises from the fact that when transparent substances are formed they contain both lattice defects (such as vacancies where a single atom is missing) and impurities (which usually occur substitutionally, e.g. an Al^{3+} ion in a site normally occupied by an Si⁴⁺ ion). When exposed to radiation, a few percent of the ionization electrons and electronic holes which are formed are subsequently trapped by defects and/or impurities. A large fraction of the centers formed in this way are optically active; those that absorb light are known as color centers. The most familiar color center, the F-center, is an electron trapped by a single monovalent negative ion vacancy. The stability of the centers varies greatly: some are stable at room temperature, while others may disappear with time either gradually or rapidly.

In many materials the rate of coloring is quite low and so does not impair the detector function. However, lead glass is more sensitive to radiation damage than other materials. Also, if counters having relatively long optical paths are used, even small increases in optical absorption may reduce the detected light appreciably. Consequently, radiation damage to lead glass can cause a decrease in light output with time, leading to a degraded and time-dependant resolution. Radiation damage to the lead glass used in this experiment was a particular concern since the detector was located directly downstream from the electron injection line to PEP, and so was subject to intense radiation during injection periods.

The radiation-induced absorption of lead silicate glasses as used in Cerenkov counters has been previously investigated⁽⁷⁹⁾. In this study, the radiation-induced absorption spectra and the coloring growth curves were measured as a function of radiation. It was found that the absorption extends from the ultraviolet 'edge' to the near infra-red and could be resolved into three broad Gaussian shaped bands. By continuing the absorption measurements after the irradiation was terminated it was found that the largest decay observed was 9 %, and it was concluded that the coloring of these glasses can be regarded as stable to a good approximation.

A significant discovery that was made regarding the sensitivity of lead glass to radiation damage was that the addition of cerium at the level of a fraction of a percent substantially increases its radiation hardness⁽⁶⁶⁾. The presence of cerium causes the lead glass to become slightly yellow, reducing its transmission at short wavelengths, but it protects against the dramatic transmission losses which occur with large doses of radiation. Although the glasses used in the earlier study⁽⁷⁹⁾had very similar properties, different glasses could behave quite differently, and even different batches of the same kinds of glass could have different impurities present which could lead to a variation in their response to radiation. Thus measurements of the effects of radiation on the particular kind of glass selected for use in the ASP detector were performed in order to measure its sensitivity to radiation and to select an appropriate level of cerium doping.

Small samples of the selected Schott F2 type lead glass were obtained from the manufacturer. Both undoped glass and glasses with 0.2, 0.3, 0.4, and 0.5 % cerium content were tested. The transmission spectra of the samples were measured using a Beckman DK-2A Ratio Recording Spectrophotometer prior to any irradiation. The samples were then subjected to incrementally increased doses of radiation from an intense ⁶⁰Co gamma ray source and the transmission spectra were remeasured after each period of irradiation. Between measurements the samples were wrapped in Aluminum foil to shield them from daylight, which otherwise might bleach some of the radiation-induced coloring. Also, the measurements were performed immediately after the irradiation period in case the coloring was unstable. Some typical results are displayed in fig. A.1. While it is clear that the ultraviolet edge in the undoped glass is at shorter wavelengths than in the doped glass, so that the Cerenkov light output would be greater from the undoped glass, it is seen that the undoped glass suffers a much greater loss of transmission for a given radiation dose than does the doped glass. For an integrated dose of 100 rad, the undoped lead glass shows a 5%loss in transmission at $\lambda = 500$ nm (extrapolated to a length of 35 cm) while the lead glass with 0.3% cerium doping shows no loss after 100 rads. For larger doses the transmission of the undoped glass decreases rapidly while that of the doped glass decreases much more slowly.

Preliminary measurements of the radiation level in IR-10 at PEP showed the presence of substantial levels of radiation indicating that radiation damage to the glass was to be expected if no precautions were taken. Tests with sample glass bars indicated that the Čerenkov light output from the doped glass was sufficient despite



Figure A.1. Effect of ⁶⁰Co γ radiation on transmission of light through samples of (a) undoped lead glass and (b) lead glass with .3% cerium doping. Curve A is before exposure to radiation, B is after 1.2×10^2 rads, C is after 1.2×10^3 rads, D is after 1.2×10^4 rads and E is after 5.0×10^4 rads of γ radiation.

the yellowing due to the cerium content. Consequently, lead glass with a .35 % cerium doping was chosen. The composition of the Schott F2 type lead glass that was used is given in table A.1. This lead glass has a radiation length of 3.17 cm and an index of refraction of 1.58. Further precautions that were taken to protect the glass from radiation damage are described in sec. A.3.

Element	Percentage
	Composition
Lead -	41.8
Oxygen	29.7
Silicone	21.5
Sodium	3.7
Potassium	3.3
Cerium	0.35

Table A.1. Composition of the cerium-doped lead glass used in the central calorimeter.

A.3 Construction of the Lead-Glass Calorimeter

The calorimeter was constructed from 632 lead-glass bars arranged in four quadrants of five layers each, as shown schematically in figs 2.1 and 2.3. Alternating layers had 31 or 32 bars, staggered by a half bar-width offset to ensure that the gaps between bars did not line up and to provide optimal position resolution. Interleaved with the lead-glass layers were five planes of proportional wire chambers (PWC).

The extruded lead-glass bars measured $6 \times 6 \times 75$ cm³ in size, and were polished only on both ends. Each bar was read out on one end by an Amperex XP2212PC 12-stage photomultiplier tube (PMT) with high gain, good stability, and low noise. The spectral sensitivity of the bialkali photocathode of these PMT's is a good match to the spectrum of Čerenkov light and the transmission properties of the lead glass. Prior to assembly of the calorimeter, the PMT's were burnt in and calibrated using a green Hewlett-Packard Superbright (HLMP-3950) light-emitting diode (LED), in order to determine the operating voltages necessary to balance their gains. In fig. A.2 the spectral response of the XP2212PC is compared to the Čerenkov spectrum, the spectrum from the calibration LED and the transmission spectra of doped and of undoped lead glass. The PMT's came with an attached printed circuit board base which had to be trimmed to 6×6 cm so that the lead-glass bars could be stacked without any gaps between them. The PMT's were powered by a single LeCroy 1440 multi-channel high voltage supply, which was controlled by the on-line VAX computer via CAMAC. This programmable supply was monitored every 4 minutes to verify the voltage settings and could automatically correct voltages which drifted. It proved to be a very reliable, stable power supply. The PMT calibration data were used to select groups of eight PMT's with roughly similar response to be powered from a single high voltage channel. This voltage was fanned out through a resistive divider which was then adjusted to provide the correct voltage for each tube.



Figure A.2. Comparison of internal transmission curves for 2.54 cm samples of doped and undoped lead glass (solid lines) with the Čerenkov spectrum (dashed line), the spectral sensitivity of the Amperex XP2212PC photocathode (dash-dotted line) and the relative spectral output of the HLMP-3950 LED (dotted line).

The PMT's were glued to the bars using Stycast 6061 optical epoxy; each PMT covered 42% of the surface area of the end of a bar. The bars were wrapped with aluminum foil on five sides and a μ -metal shield was put around each PMT to reduce the effect of external magnetic fields. The five lead-glass and PWC layers in each quadrant were then stacked in a light-tight box made of 0.75 inch thick aluminum. To minimize the non-active material inside the lead-glass calorimeter, the walls of the aluminum box were made half as thick where two quadrants abut. The calorimeter was supported internally by 6.8 cm high aluminum I-beams. Between adjacent layers of PWC six I-beams were used as spacers, creating 'shelves' on which the lead-glass bars were placed between thin layers of foam padding. This was necessary because some of the lead-glass bars were slightly bowed, with a maximum deviation from linearity of 2 mm. This was an artifact of the extrusion process; the bowing occurred only in the horizontal plane as the bars were extruded onto a flat surface. To avoid any small gaps, the bars were stacked with their straight sides together. The weight of the lead glass was then borne by the PWC's and I-beams, and any curvature in the bars was accommodated by the extra height of the I-beams. This arrangement prevented undue stress on the lead-glass bars and bowing of the PWC planes.

Each quadrant measured approximately $1.0 \times 0.5 \times 2.0$ m³ and was an independent unit which was easily dismounted and transported. This was a necessary part of the design, because access to the PEP interaction region where the ASP detector was installed was restricted: every component had to be carried in along the arcs from an adjacent interaction region. The two lower quadrants were mounted on rails and each was then bolted to the quadrant above, to form two complementary L-shaped halves, allowing the detector to be split and retracted from the beam line by a remotelycontrolled hydraulic drive. This provided easy access to the beampipe and detector components whenever necessary. The ASP detector was located directly downstream from the PEP electron injection line, so to avoid excess radiation damage the two halves of the detector were moved away from the beamline whenever electrons were injected into the storage ring. To further protect the lead glass during injection, 10 cm thick lead-brick walls were installed to shield it when it was in the open position. Electronic sensors ensured that the two halves were in the fully-closed position for data taking. Since the detector could not be operated during the three minutes it took to close the calorimeter halves after injection was completed, this safeguard sometimes resulted in a small loss of data.

The PMT's were monitored online with LED's and a light fiber distribution system. There was one LED per quadrant (HLMP-3950, the same type as was used in the initial calibration), each of which could be pulsed by a high-current pulser. The pulser used was similar to that described in ref. 80. Light pulses from the LED shone on the ends of a bundle of light fibers which transmitted the light to each PMT. By the insertion or removal of two filters, four light levels were obtained. The other end of each light fiber was embedded in the epoxy used to glue the PMT's to the ends of the lead-glass bars. The light emitted from the fiber travelled down the bar and reflected from the far end back to the PMT. The output of each LED was monitored by a reference PMT which also viewed a small NaI(Tl) scintillator crystal doped with 241 Am⁽⁸¹⁾ which served as a stable light source⁽⁸²⁾. This system was used to provide a relative calibration of the PMT's for checking their day-to-day stability during data taking. It was not used for an absolute calibration as the transmission of some of the light fiber connections showed long-term drifts, and also the LED spectrum did not cover the full range of the PMT photocathode spectral sensitivity. The reliability of the PMT's was high: fewer than 1% of the tubes failed for any reason over the entire course of the experiment.

A.4 Off-line Calibration of the Lead-Glass Calorimeter

Cosmic ray muons which traversed the lead-glass calorimeter were used to perform an off-line calibration of the PMT response. These events were continuously recorded during data taking runs by a special trigger which fired when a charged particle was detected in the veto scintillators surrounding the central tracker in a 15 ns time window ending 5 ns before the beam crossing. This sample was tracked and the signal deposited in each bar was corrected for path length. The average path-corrected signal displayed a strong dependence on both the distance of the track from the PMT and on the angle of the track with respect to the long axis of the bar as shown in fig. A.3. The dependence on distance was due to reflection losses and attenuation of the signal in the lead glass, modified by geometry- and frequency-dependent increases in light collection when the distance became less than a few cm. The dependence on angle was due to the fact that the Čerenkov light generated by a particle travelling towards the PMT travels a shorter distance in the lead glass than light generated by particles heading away from the PMT, which must travel to the far end and be reflected back. A change in direction also changed the angle of incidence of the light as it traveled down the bar by internal reflection and hence changed the total distance travelled in the glass.



Figure A.3. Attenuation of Čerenkov light in the lead-glass bar, as a function of length along the bar, measured with minimum ionizing tracks from cosmic rays. In (a) the tracks are at an angle $\alpha = 45^{\circ}$ with respect to the bar, pointing toward the PMT. In (b) $\alpha = 135^{\circ}$, pointing away from the PMT.

Due to the different orientations of each lead-glass quadrant, the PMT's in one quadrant pointed up, in another they pointed down, and in the other two they were oriented horizontally. Therefore the angular distribution of the predominantly downgoing cosmic rays with respect to the axis of the lead-glass bars was different in each quadrant. This resulted in a different average path-length corrected signal, due to the attenuation effects described above. To compensate, another correction had to be applied on an event-by-event basis. The correction factor was a function of both the distance of the track from the PMT and the angle of the track with respect to the bar, taken from a look-up table compiled from plots such as those in fig. A.3. After these corrections were applied, a set of normalized energy spectra for all lead-glass counters was obtained. The peak of each spectrum was fitted to obtain a correction factor that was used to normalize the PMT response. The fitting function that was found to fit the peaks of the spectra best was a continuous version of the Poisson distribution:

$$f(x) = \frac{A}{\Gamma(kx+1)} e^{-km} (km)^{kx}$$
(A.1)

This cosmic-ray calibration was more accurate than the one which had been performed with an LED prior to installation (which normalized the PMT responses at the 20 - 30 % level) because the spectral response of the PMT's was integrated over the correct frequency range of Čerenkov light. It reduced the remaining channel-tochannel variation to less than 2 %. In addition, any channel-to-channel variation in the electronics used to read out the PMT's was automatically included in the calibration. This calibration was also used to check for evidence of radiation damage, which would cause a time dependent decrease in the signal from the lead-glass bars. Over the 2 years that the ASP detector was installed at PEP, more than 1 kilorad of gamma radiation and an equal dose in neutrons were recorded by dosimeters affixed to the exterior of the lead-glass calorimeter on the side nearest the beampipe. Dosimeters attached to fixed supports near the beampipe which were not retracted during injection recorded much higher levels. Although a large fraction of the gamma rays must have been absorbed by the 0.75 inch aluminum box surrounding the lead glass, a significant number of neutrons would have penetrated into the calorimeter. Moving the detector away from the beampipe during injection and the installation of lead-brick walls were responsible for a significant reduction in the integrated radiation dose seen by the lead glass, and the addition of cerium to the lead glass reduced the effect of the radiation which was absorbed. These steps to protect the lead glass from radiation were successful, as no significant decrease in response during the entire running period was observed.

The details of the energy calibration of the calorimeter have been published elsewhere ^(67,68). The performance of the calorimeter has been discussed in chapter 5.

A.5 Conclusions

The ASP calorimeter employed 632 extruded lead-glass bars to obtain a compact, hermetic electromagnetic calorimeter with many useful functions. In addition to its good energy resolution, the hermetic design allowed events with missing energy to be identified with high efficiency, due to its low noise level. The good position resolution of the lead-glass bars allowed tracks to be reconstructed and made it possible to distinguish between tracks that originated at the e^+e^- interaction point and those that did not, such as cosmic rays or interactions of the e^+ or e^- beams with residual gas in the vacuum pipe. The segmentation of the calorimeter was fine enough to provide pattern recognition capabilities that permitted electromagnetic showers to be distinguished from minimum ionizing tracks and other interactions and to provide good $\gamma - \pi^0$ discrimination for energies below a few GeV, through the sampling of the shower development. The PMT signals from the device provided event timing and triggering information; the segmentation also allowed triggers for specific event types to be implemented. The precautions taken to protect the lead glass from radiation damage were successful: the response of the detector remained unchanged over the two year period of operation at the PEP storage ring. All in all, it proved to be a truly multi-purpose device, well-suited for detecting low-multiplicity e^+e^- events consisting primarily of electrons and photons.

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