The Z° Factory

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The Z° Factory subgroup met to study the programs for an e^+e^- machine that could explore the energy range 40 to 120 GeV (beam energy 20 to 60 GeV). The group assumed LEP and SLC will be operating by 1988. Therefore, it was important to consider whether the physics program is rich enough to justify the construction and operation of an additional e^+e^- machine such as CESR II. The characteristics of these colliders are given in Table 1.

Table 1

Operating Characteristics of the e^+e^- Colliders

	SLC	LEP-1	CESR-2
Proposed Completion Date	1987	1988	1988
Nominal Energy (GeV)	100	140	100
Peak Luminosity per Interaction Point ($\times 10^{31}$ cm^{-2} sec^{-1})	0.6	$2\times(W/100)^2$	$6\times(W/100)^2$
Number of Interaction Points	1	6	4
Energy Spread at 100 GeV (GeV)	0.50	0.08	0.13

We first discuss the main features of the physics program. A list of experiments is presented that 'Test the Standard Model' and search for evidence of new phenomena ('Beyond the Standard Model'). In addition to the Z°, there is another structure, Toponium, which may play a leading role in clarifying many issues. At this time we do not know at what energy (mass) Toponium will be observed. We assume it has a mass less than the Z° mass and discuss a set of experiments one would perform.

To obtain some idea of how much time is required to perform a particular measurement, we will assume an average machine luminosity of 2×10^{31} cm^{-2} sec^{-1} and assume a data recording time of 2×10^7 seconds per year. For each topic we give a brief description of the process and its significance, the signature by which one can identify and measure the process, the relevant cross section or branching fraction, and the integrated luminosity needed to make the measurement. At the conclusion of the discussion of the physics program, we examine what experiments each machine can perform and recommend construction of another e^+e^- collider.

The Standard Model of the Electro-Weak Interaction predicts the existence of a neutral vector meson, the Z°, at a mass of ~ 90 GeV, that couples directly to e^+e^-. The total cross section for e^+e^- annihilation at that energy is predicted to increase by a factor of $\sim 10^3$ due to Z° production. A study of the final states at and near the Z° can provide stringent tests of the standard model. Deviations from predictions of this theory will either point out the road to some subset of the numerous alternative models or indicate the need for a major revision to the Gauge Theory of weak interactions.

The SU(2) x U(1) model of Weinberg and Salam relates the coupling strength of the electromagnetic interaction to that of the weak interaction. The ratio of these couplings is $\sin\theta_W$, where θ_W is called the Weinberg angle. Various definitions of this parameter have evolved. W. Marciano[1] defines the renormalized weak mixing angle, $\theta_w(0)$, by

$$\sin^2\theta_w(0) = \pi\alpha/(\sqrt{2}G_\mu M_w^2) \tag{1}$$

where $\alpha = 1/137.036$, $G_\mu = 1.16632 \times 10^{-5}$ GeV^{-2}, and M_w is the mass of the W vector boson. According to Marciano, the mass of the Z° is related to the W mass by $M_z = M_w/\cos\theta_w(0)$ plus corrections of order α. Using this, we write

$$\sin 2\theta_w(0) = [4\pi\alpha/\sqrt{2}G_\mu M_z^2)]^{1/2} \tag{2}$$

$$\sin 2\theta_w(0) = 74.563/M_z(\text{GeV}) \tag{3}$$

The weak mixing angle has been determined from several experiments. The average of the best of these,[1] the ν_μ-hadron scattering cross sections and the e-D asymmetry, give

$$\sin^2\theta_w(0) = 0.207 \pm 0.012 \tag{4}$$

We use this to calculate the expected value of the Z° mass and obtain $M_Z = 92.0 \pm 2.1$ GeV. With an e^+e^- collider, one will look for a resonance in the annihilation cross section around this energy. In the absence of any resonant structure, the total cross section for one photon e^+e^- annihilation into hadrons at center of mass energy, W, is

$$\begin{aligned} \sigma_{had}(W) &= R\sigma_{point} \\ &= 4\pi/3\ R\ \alpha^2/W^2 \\ &= 433 \times 10^{-33}/W^2\ \text{GeV}^2\ \text{cm}^2 \end{aligned} \tag{5}$$

Here we have set R = 5, the theoretical value at energies above the threshold for $t\bar{t}$ quark production. At $W = M_Z$ one calculates $\sigma_{had}(W) = 0.051$ nb (1 nb = 10^{-33} cm^2). If the Z° exists, the hadronic cross section is supposed to increase at energies near Z° mass. This increase is described by a Breit Wigner function of width Γ_Z. The cross section has a maximum value of ~ 50 nb at the mass of the Z° ($W = M_Z$). Assuming the existence of only the three generations of lepton and quark families, the width of the Z° is calculated to be $\Gamma_Z = 2.84$ GeV (the calculation assumes a top quark mass of 20 GeV).[2] A measurement of the hadronic cross section vs. energy around the Z° resonance will provide a precise measurement of M_z and Γ_Z. Two days of energy scanning (~ 2000 nb^{-1}) will produce over 2×10^4 events which is statistically adequate. The major uncertainty to the mass measurement is the calibration of the machine energy. R. Siemann[3] describes three independent methods for making this calibration to a precision $\delta W/W = \pm 10^{-3}$. The peak of the cross section is shifted by initial state radiation. The width is also affected. Siemann finds the peak is shifted by $0.16\Gamma_z = 0.45$ GeV and the width is decreased by 13%. Assuming the radiative effects can be calculated to 10% accuracy, the Z° mass can be measured with an accuracy of ± 100 MeV and the width can be measured with an accuracy of ± 50 MeV. This measurement of M_Z will provide a new value of $\sin^2\theta_W(0)$ with an error $\delta(\sin^2\theta_W(0) \sim \pm 0.62 \times 10^{-3}$, a factor of 20 smaller than the error in the current value (equation (4)). The comparison of this new determination of the weak mixing angle and the value given in equation (4) provides a severe test of the standard model.

The width of the Z° resonance is a measurement of the total decay rate of the state. Within the framework of the standard model, the main decay modes of the Z° are

$$Z^\circ \rightarrow \ell^-\bar{\ell}^+,\ (\ell = e,\ \mu,\ \tau)$$

$$Z^\circ \rightarrow \nu_\ell\bar{\nu}_\ell,\ (\ell = e,\ \mu,\ \tau)$$

$$Z^\circ \rightarrow q\bar{q},\ (q = d,\ u;\ s,\ c;\ b,\ t)$$

The coupling strength of each of these channels is uniquely defined in terms of $\sin^2\theta_W$ and the decay rate for each two-body final state is calculable. The total width of the Z° is the sum of these partial widths. By measuring the cross section for a particular channel at the peak of the resonance and dividing by the total cross section for Z° production, one obtains the branching fraction for that channel. We note that one does not normally measure the total cross section since the neutrino final states are not detected. Later we describe how one can measure the branching fraction to non-interacting final states and make a direct comparison between the measured width of the resonance and the sum of the partial widths. Assume for the moment that this has been done. Then each partial width can be compared with the standard model prediction. A disagreement in any particular channel or set of channels would be an indication of new physics.

The Z° is supposed to decay to each pair of charged leptons 3% of the time. At an average luminosity of 2×10^{31} one produces 10^5 Z° mesons per day. This means one could collect 3000 e^+e^- pairs, $\mu^+\mu^-$ pairs and $\tau^+\tau^-$ pairs per day. Allowing a factor of two for detection and identification efficiencies, one could have $\sim 10^5$ events of each lepton type with a few months of data recording. The ratio of these event samples would provide a test of e, μ, τ universality. The comparison at this level of accuracy would be dominated by the lepton identification efficiency of the detectors. The ultimate accuracy of such a comparison requires more study.

One expects to record data at the peak of the Z° resonance for a long time. In addition to measuring the branching fractions of the lepton and quark pairs, one can extract additional information from the data sample. In the case of the leptonic decays, a simultaneous measurement of the forward-backward charge asymmetry parameter and the cross section allows one to determine the vector and axial vector coupling for each lepton current.[+] The couplings are given in the standard model as

$$v_\ell = (-1/4 + \sin^2\theta_W)/(\sin\theta_W\cos\theta_W) \qquad (6)$$

$$a_\ell = 1/(4\ \sin\theta_W\cos\theta_W) \qquad (7)$$

The asymmetry parameter for lepton ℓ at $W = M_Z$ is related to the couplings by

$$\langle A \rangle = 3(a_\ell v_\ell)(a_e v_e)/((a_\ell^2 + v_\ell^2)(a_e^2 + v_e^2)) \qquad (8)$$

Once having demonstrated the couplings are the same for all three lepton types by measuring the individual branching fractions, a precise measurement of $\langle A \rangle$ using muon pairs can provide an independent determination of $\sin^2\theta_W$. In particular, setting $a_\mu = a_e$ and $v_\mu = v_e$, the asymmetry becomes

$$\langle A \rangle = 3(v_e/a_e)^2/(1 + (v_e/a_e)^2)^2 \qquad (9)$$

and

$$v_e/a_e = -1 + 4\ \sin^2\theta_W \qquad (10)$$

The uncertainty in $\sin^2\theta_W$ is related to the error in a measurement of A and to our knowledge of the machine energy relative to the Z° mass ($\delta(\sin^2\theta_W) = 0.5\delta A + 0.05\delta W$, W in GeV). The accuracy with which one measures the asymmetry is ultimately dominated by the lack of symmetry in the detector and beam targeting. We assume these asymmetries can be kept under ± 0.005. We take $\delta W = 0.05$ GeV, and obtain $\delta(\sin^2\theta_W) = 0.005$, a factor 2.5 smaller than current measurements (equation (4)). One can measure the asymmetry to a statistical accuracy of ± 0.002 in ∿40 days of data recording. However, many consistency checks must be made. We estimate 160 days running is required to do a careful experiment.[+] The importance of such a measurement has been stressed at this conference. The theorists tell us there are corrections to the above expressions for a_e and v_e which they have under control, but nonetheless want to test at this level of accuracy.

The Z° is predicted to decay into quark-antiquark pairs with a charge dependent coupling. The standard model predicts all the decay rates unambiguously except for $t\bar{t}$. Since the mass of the top quark is as yet unknown, one does not even know whether $Z^\circ \rightarrow t\bar{t}$ is energetically allowed. This introduces a 10% uncertainty in all branching fractions. The quark-antiquark pair from Z° decay will fragment, producing narrow jets of hadronic particles. There should be little confusion between quark ($q\bar{q}$) and lepton ($\ell\bar{\ell}$) final states. However, it will be very difficult to distinguish the quark jet flavors. Only top quark jets have a unique signature. If top quark jets are produced, one will be able to identify a subset of them by selecting events in which there is a lepton with high transverse momentum relative to the jet axis. This event set can provide an unbiased sample of t quark jets, namely the jet not associated with the lepton. From this sample one can obtain the lepton branching fraction, $Br(t \rightarrow \ell\nu x)$, and the lepton momentum spectrum. Once these quantities are fixed, they can be used, together with the number of events in the $t\bar{t}$ subset, to calculate the branching fraction $Br(Z^\circ \rightarrow t\bar{t})$. Knowledge of the latter branching fraction can be used to estimate the mass of the t quark in case toponium has not yet been found.

The decay width of the Z° into a $\nu_\ell\bar{\nu}_\ell$ pair is 0.176 GeV, where ℓ is a lepton, e, μ, or τ. If there are only three lepton families and no other non-interacting particles into which Z° can decay, the total width into non-interacting final states would be 0.53 GeV or six times the partial width into $\mu^+\mu^-$. A precise measurement of $\Gamma_{Z \rightarrow \nu\nu}$ would uniquely determine

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[+] These measurements do not fix the relative sign v_ℓ and a_ℓ. The sign of $v_e a_e$ can be determined by measuring the sign of the final lepton polarization.[4] This can be done in the case of $e^+e^- \rightarrow \tau^+\tau^-$. Once the sign of $v_e a_e$ has been determined, the relative sign of all the other couplings is fixed.

[+] Using a polarized e^- beam and an unpolarized e^+ beam allows one to make an order of magnitude more precise measurement of $\sin^2\theta_W$.[5]

the number of neutrinos. A method for making this measurement by observing radiative Z° production,

$$e^+e^- \rightarrow \gamma Z^\circ \rightarrow \gamma\nu\bar{\nu} \qquad (11)$$

has been suggested[6,7], and the realities of a practical experiment have been studied[8,9]. The main idea is to go to an energy above the Z° and look for events in which there is only a single photon in the detector. The beam energy must be sufficiently high so that an observation of events with a single photon of the correct energy and no charged particle tracks would constitute an unambiguous signal of the process one wants to measure. The experiment would consist of measuring the ratio of such events to events with a photon plus a $\mu^+\mu^-$ pair. In other words, one would measure the cross section ratio,

$$\begin{aligned} \rho &= \sigma(e^+e^- \rightarrow \gamma Z^\circ \rightarrow \gamma\nu\bar{\nu})/\sigma(e^+e^- \rightarrow \gamma Z^\circ \rightarrow \gamma\mu^+\mu^-) \\ &= \Gamma(Z^\circ \rightarrow \nu\bar{\nu})/\Gamma(Z^\circ \rightarrow \mu^+\mu^-) \end{aligned} \qquad (12)$$

In the standard model, ρ is twice the number of neutrino families. If one wanted to demonstrate there were 3 and not 4 families, one requires a statistical accuracy in the ratio, ρ, of $\delta\rho = \pm 0.6$, which would be provided by $\sim$100 $\gamma\mu^+\mu^-$ events. At an energy of 15 GeV above the Z°, an integrated luminosity of 6×10^4 nb^{-1} is required. A more accurate measurement would provide a test of whether ρ is really an even integer. A practical goal would be $\delta\rho = \pm 0.2$, which would require 6×10^5 nb^{-1} (1.5 years at our average luminosity) for three families.

After we have measured the cross section for charged leptons, hadrons, and neutrinos at the Z°, we can compute the partial decay widths and compare their sum with Γ_Z, the width of the Z° obtained by scanning over the resonance. To make this comparison, we require the integral over energy of the total cross section for Z° production. Since we do not really measure the total cross section, we define $\sigma_X(W)$ to be the cross section for which the Z° decays into final states that interact in the detector. We define the experimentally measured integral, I_X,

$$I_x = (M_z/(6\pi^2)) \int dW\, \sigma_x(W) \qquad (13)$$

Using a Breit Wigner to describe the Z° resonance, I_x is the combination of decay widths

$$I_x = \Gamma_{ee}\Gamma_x/\Gamma_{tot} \qquad (14)$$

where Γ_X is the decay width into final states that interact in the detector. Defining Γ_n to be the partial width into states that do not interact, we have

$$\Gamma_{tot} = \Gamma_x + \Gamma_n \qquad (15)$$

We have discussed measuring the lepton and hadron branching fractions at $W = M_z$. We actually measure the ratios

$$r_\ell = \sigma_{\ell\ell}(M_z)/\sigma_x(M_z) = \Gamma_{\ell\ell}/\Gamma_x, \quad \ell = e,\mu,t \qquad (16)$$

$$r_q = \textstyle\sum_q \sigma_{q\bar{q}}(M_z)/\sigma_x(M_z) = \Gamma_Q/\Gamma_x, \quad q = d,u,s,c,b,t \qquad (17)$$

To determine the branching fraction of $Z^\circ \rightarrow \nu\bar{\nu}$ one actually measures

$$r_n = \sigma(\gamma Z^\circ \rightarrow \gamma + \text{nothing})/\sigma(\gamma Z \rightarrow \gamma\mu^+\mu^-) = \Gamma_n/\Gamma_{\mu\mu} \qquad (18)$$

From I_x and the measured ratios r_e or r_μ, and Γ_z, we obtain Γ_x.

$$\Gamma_x = (I_x\Gamma_z/r_e)^{1/2} = (I_x\Gamma_z/r_\mu)^{1/2} \qquad (19)$$

Then the various partial widths are given by,

$$\Gamma_{\ell\ell} = r_\ell\Gamma_x, \quad \ell = e,\mu,t \qquad (20)$$

$$\Gamma_Q = r_Q\Gamma_x \qquad (21)$$

$$\Gamma_n = r_n r_\mu \Gamma_x \qquad (22)$$

The sum of these must equal the total width,

$$\Gamma_z = (3r_\ell + r_Q + r_n r_\mu)(I_x\Gamma_z/r_\mu)^{1/2} \qquad (23)$$

From the definition of σ_x and Γ_x, we are guaranteed $3r_e + r_Q = 1$ and our equation for Γ_z becomes

$$\Gamma_z = (1 + r_n r_\mu)^2 I_x/r_\mu \qquad (24)$$

At first sight, it appears that the $q\bar{q}$ final states are missing. Their presence is contained in the integral over the detectable cross section, I_x. If relation (24) is not satisfied, either the resonance can not be described by a Breit Wigner function, or there is an experimental inconsistency in the data. In table 2 we estimate how well we are constrained by equation 24. According to this estimate, equation 24 allows one to calculate the Z° width to an accuracy of ± 130 MeV. This value would be compared to the measured value whose accuracy should be ±50 MeV[3].

Table 2

Estimated Precision by Which One Can Test The Consistency of the Partial Width Measurements

Measured Quantities	Γ_z	r_n	r_μ	I_x	$(1+r_n r_\mu)^2 I_x/r_\mu$
Expected Value	2.84	6.0	.038	.072	2.84
Estimated Accuracy	0.05	0.2	.002	.002	0.13

The Higgs boson is a necessary ingredient of the standard model. In the simplest version of the theory, it is a single neutral scalar. Coupling of the Higgs to other particles is fixed by the theory. However, the mass of the Higgs is not predicted. Consequently, the Higgs may be heavier than the Z° and inaccessible. Assuming this is not the case, several studies have been made on how to observe the Higgs in Z° decay[10,11,12]. The favorite decay modes are

$$e^+e^- \rightarrow Z^\circ \rightarrow \ell^+\ell^- H^\circ, \quad \ell = e, \mu$$

$$e^+e^- \rightarrow Z^\circ \rightarrow \gamma H^\circ$$

The branching fraction, $Br(Z^\circ \rightarrow \ell^+\ell^- H^\circ)$, is strongly dependent on the Higgs mass. It varies from $\sim 3 \times 10^{-5}$ at $M_H = 10$ GeV to $\sim 3 \times 10^{-7}$ at $M_H = 60$ GeV. The experiment consists of using the leptons to compute the missing mass and demonstrating a peak in the mass spectrum. At the agreed luminosity, the experiment is sensitive for Higgs mass below 40 GeV. After one year of data recording (4×10^5 nb^{-1}), one would have 120 events at $m_H = 40$ GeV (No allowance has been made for the detection efficiency.). The branching fraction for $Z^\circ \rightarrow \gamma H^\circ$ is low, $\sim 2.4 \times 10^{-6}$ at $M_H = 10$ GeV and $\sim 6 \times 10^{-7}$ at 60 GeV. In this case one is looking for a monochromatic photon and one can imagine a high efficiency, good resolution detector. For Higgs mass below 40 GeV, the total production per year is only 30 to 50 events.

Z° decays are a potential source of some of the new particles that have been predicted by models which attempt to resolve questions raised by the standard model. An e^+e^- storage ring provides a clean environment in which to observe these particles. As an illustration, we summarize the sensitivity for testing models of Technicolor, Super Symmetry, and Heavy Leptons (a fourth quark-lepton family).

Technicolor is a dynamic theory of breaking the Electroweak symmetry group SU(2) x U(1). The theory[13] predicts the existence of spinless mesons, technipions, of charge ±1 or 0 and mass between 5 and 40 GeV. The predicted branching fraction for $Z^\circ \rightarrow p^+p^-$ is large. The technipions couple to fermion-antifermion pairs in proportion to their mass. Consequently, they prefer to decay to the heaviest fermions that are kinematically allowed. A choice signature for observing technipions is[13,14].

$$p \rightarrow \tau\nu_\tau \rightarrow e\nu_\tau\nu_\tau\nu_e \text{ or } \mu\nu_\tau\nu_\tau\nu_\mu$$

$$\bar{p} \rightarrow \text{Hadrons}$$

The topology would consist of a high energy lepton in one direction and a hardon jet in the opposite direction. Since $\bar{p}$ would decay to $b\bar{t}$, $b\bar{c}$, or $s\bar{c}$, we would expect the hadronic jet to have high multiplicity and many kaons. In table 3 we list the predicted rates vs technipion mass[14]. A null result of a search for technipions in Z° decay would rule out Technicolor as a symmetry.

Table 3

Event Rates for New Particle Searches

$$\frac{\text{identified events/year}}{(2\text{x}10^7\text{sec})\text{ x }(2\text{x}10^{31}\text{cm}^{-2}\text{sec}^{-1}))}$$

mass (GeV)	technipions (p^+p^-)	supersymmetry ($\underline{ee}$ or $\underline{\mu\mu}$)	heavy leptons ($e\mu$ events)
20	3250	270 x 10^3	4700
30	1030	140 x 10^3	4000
40	75	40 x 10^3	2000

Supersymmetry is a unification model in which each of our known particles has a supersymmetric partner whose spin differs by $\bar{h}/2$. The lightest scalars in this model are the partners of the electron and muon, the selectron ($\underline{e}$) and smuon ($\underline{\mu}$)[15,16]. As in the case of the Higgs, the coupling of the supersymmetric particles are defined by the model but the mass scale is open. For selectron and smuon masses below 40 GeV, the Z° is a copious source. The selectron and smuon decay to their ordinary partners and a photino. The latter is a non-interacting neutral particle that will leave the detector. An experimental search would be based on[14]

$$e^+e^- \rightarrow Z^\circ \rightarrow \underline{e}^+\underline{e}^- \text{ or } \underline{\mu}^+\underline{\mu}^-$$

$$\underline{e} \rightarrow e\underline{\gamma},\ \underline{\mu} \rightarrow \mu\underline{\gamma}$$

One would look for non-colinear e^+e^- or $\mu^+\mu^-$ pairs that are acoplanar with the beam line. The missing momentum vector would have to point into the detector. The event rate in the mass range covered by Z° decays is given in table 3.

One normally thinks of 3 quark and 3 lepton families when speaking of the standard model. However, there is no constraint on the number of families. As discussed earlier, the branching fraction to $\nu\bar{\nu}$ will tell us the number of lepton families. If the massive member of the next lepton family is lighter than half the Z° mass, we will be able to observe $Z^\circ \rightarrow \bar{L}^+L^-$. The best signature appears to be that used by Perl to find the τ meson. One looks for events with only an electron and a muon coming from the sequence

$$\bar{L} \rightarrow e^+\nu_e\bar{\nu}_L \text{ and } L \rightarrow \mu^-\bar{\nu}_\mu\nu_L \text{(or the charge conjugate decays)}$$

The same conditions are imposed as for the scalar electron search, acoplanarity with the beam and missing momentum pointing into the detector. Additional cuts are needed for a strict kinematic rejection of $\tau^+\tau^-$ events[14,17]. The event rate is given in table 3.

Searching for new particles that are found in 2 body decays of the Z° is uniquely clean. The above examples are especially so because they involve a single lepton in the final state. One might wonder whether there is any more to be learned about the particles from such an event sample other than their existence. For example, can on distinguish the above hypotheses? The answer is clearly in the affirmative. Technipions are distinguished by final states with 1 lepton and a multihadron jet with high kaon content. Th angular distribution with respect to the beam axis is $\sin^2\theta$. In the case of scalar leptons, one observes e^+e^- and $\mu^+\mu^-$, but never $e\mu$. The angular distribution should be $\sin^2\theta$. In contrast, the heavy lepton will produce an $e\mu$ signal as well as ee and $\mu\mu$. The angular distribution must be $1 + \cos^2\theta$. With several thousand events one can obtain an approximate measure of the particle mass from the lepton momentum distribution. A better mass determination will require measuring the production cross section near threshold.

Recent speculations that quark and leptons are composite structures, leads to observable consequences at the Z°. One version has radial excitations of the familiar leptons and quarks. If these excited states were sufficiently light, the Z° would decay to them in pairs as if they were elementary and one would observe a large increase in the Z° width. The excited leptons would decay radiatively to ordinary leptons and one would try to measure the invariant photon-lepton mass. The mass scale of the composite models is currently 1 to 10 TeV. One can probe some of this range by a careful measurement of elastic e^+e^- scattering at 100 GeV. The various composite models make different predictions about the size deviations from the Bhabha cross section. The fractional deviations are a maximum near 90°, and go to zero at forward and backward angles. The Bhabha cross section at $W = 100$ GeV and $\theta=\pi/2$ is $d\sigma/d\Omega = 4 \times 10^{-36}\text{cm}^2/\text{ster}$. For a composite mass scale of 2 TeV, the deviations from the Bhabha cross section for $W = 100$ GeV and $\theta=\pi/2$ are greater than 5%[14,18] and extends over ~ 3 steradians. The Bhabha rate into this solid angle is 40 events per day. One would require 75 days to collect the 3000 events needed to place a 2.5 standard deviation lower limit on $\lambda = 2$ TeV.

Study of hadron jets at the Z° will reveal whether the t quark mass is less than half of the Z° mass. If t quark jets are observed, a rough estimate of the t mass will be obtained, thereby narrowing the search for toponium. The mechanics of the search, the expected signal size above the continuum background, how long to record data at each energy, and the energy interval needed in the search is well understood[19]. A conservative estimate for finding the $\theta(1S)$ state and measuring Γ_{ee} to ±10% is 100 days. Measuring the mass difference between $\theta(2S)$ and $\theta(1S)$ is a good way to distinguish the variety of heavy quark potential models. The mass difference can be estimated to within 100 MeV and $\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$ is expected to be $\sim$0.3. To locate the $\theta(2S)$ peak, measure its mass, and measure $\Gamma_{ee}(2S)$ to 15% would require $\sim$30 days of data recording. The branching fraction for $\theta(1S) \rightarrow \mu^+\mu^-$ is the next important parameter to determine. $B_{\mu\mu}(1S)$ combined with $\Gamma_{ee}(1S)$ determines the total width of the state. If toponium decays via three gluons as the Ψ and Υ, $B_{\mu\mu}$ may be estimated from the potential model. A significant deviation would indicate new physics. Furthermore, $B_{\mu\mu}$ is one of the few experimental parameters that can be treated reliably by QCD. It is the favorite quantity for determining $\Lambda_{\overline{MS}}$. To estimate the data rate for a measurement of $B_{\mu\mu}$, we assume a toponium mass of 75 GeV. The branching fraction of 8% yields 5 $\theta(1S) \rightarrow \mu^+\mu^-$ events per day. The muon pair rate from the continuum is 17 events per day. Assuming a 75% muon pair acceptance, one obtains a 14% measurement of $B_{\mu\mu}$ with 100 days running on the $\theta(1S)$ peak and 100 days running off the resonance. In addition to questions of spectroscopic structure, toponium may be a source of new physics [19].

We will not know this until we learn the mass of toponium and the mass of the other objects. If toponium is sufficiently heavy (greater than 60 GeV), the weak interaction will play a role in its decay. For example, the t quark lifetime will become comparable with gluonic decay. One will observe the semi-leptonic decay, $t \rightarrow \ell\nu b$, of the bound t quark. The lepton spectrum from this decay will be stiffer than that from B or D meson decay and hence easily recognized. If the Higgs is lighter than toponium, the decay $\theta(1S) \rightarrow \gamma H^\circ$ will have a significant branching fraction. For example, with M_θ = 75 GeV and M_H = 65 GeV, the branching fraction is $\sim$1% and we expect 0.6 events per day. The distinctive monoenergetic 10 GeV photon would be sufficient to recognize these events. They could be the best source for a study of the Higgs. We have discussed the importance of searching for technipions in Z° decay. If the charged technipion mass is less than half the mass of toponium, the $\theta(1S)$ will decay almost exclusively to p^+p^- plus heavy mesons (B or D). The technipions will decay into B or D and lighter mesons. As a consequence, one will have four or more kaons in the final state of almost every event, a unique situation.

Summary

The physics program we have presented is an ambitious one, but is is only the first step. We have limited it to those processes which are considered important and relatively easy to conceptualize, given the absence of data. If predictions of the standard model are found to be incorrect or if new particles are found, further experimentation will be needed. To assess the realism of this first program, we have listed the main items in table 4 together with an estimate of the required running time. The experiments are grouped according to the energy they require. All experiments at the same energy run simultaneously. Looking through the list one observes almost all data recording takes place at the Z° and the $\theta(1S)$. Initially one would limit the Z° running to about one year despite interest in the exotic particles. The Higgs and technipion searches would remain sensitive (100 events) up to masses of $\sim$35 GeV. One year would be sufficient for all other experiments at the Z°. Searching for toponium and measuring $B_{\mu\mu}$ at the $\theta(1S)$ also demands very high integrated luminosity. Altogether the program requires three years at the luminosity and data recording time specified in the introduction. Considering the usual number of false starts, the importance of repeating measurments that give unexpected results, and the need for making background runs, the time could easily double.

Table 4

An Initial Experimental Program with a Z° Factory

Experimental Goals (machine energy and parameter being measured)	Days at $L_{avg}=2\times10^{31}$ $cm^{-2}sec^{-1}$
1. Scan across the Z° (85 to 100 GeV)	
a- Mass and Width of the Z°	1
2. Sit on the Z° resonance peak	
a- Leptonic Branching Fractions To compare e,μ,τ universality (10^5 events of each flavor)	60
b- Lepton Charge Asymmetry without polarization	160
c- Lepton Charge Asymmetry with Polarization	10
d- $e^+e^- \rightarrow \tau^+\tau^-$, to measure τ polarization	200
e- $q\bar{q}$ Branching Fraction (10^5 events)	2
f- $Br(t \rightarrow \ell\nu x)$ and $Br(Z^\circ \rightarrow t\bar{t})$	30
g- Higgs search, $Z^\circ \rightarrow e^+e^-H^\circ$ M_H = 40 GeV, 100 events identified	500^+
h- Technipions search M_P = 40 GeV, 100 events identified	270^+
i- Scalar lepton search (10^3 events)	5
j- Heavy lepton search (15 to 45 GeV, 10^3 events)	20
3. Sit at the Highest Machine energy (at least 15 GeV above the Z°)	
a- $e^+e^- \rightarrow \gamma Z^\circ \rightarrow \gamma\nu\nu$ Count the number of neutrino generations. For N=3, we want $\delta N = \pm 0.2$	75
b- Search for Higgs M_H = 5 to 12 GeV, 100 events	50
c- Rule out composite models for $\lambda < 2$ TeV.	75
4. Scan from 40 to 85 GeV	
a- Search for toponium, $\theta(1S)$, and measure mass and Γ_{ee}	100
b- Scan for $\theta(2S)$ after having found the $\theta(1S)$ and measure its mass and Γ_{ee}	60
5. Sit on $\theta(1S)$	
a- Measure $B_{\mu\mu}$ to ±14%	200
b- Search for γ Higgs up to $M_H = M_{1S}$ (100 events)	500^+
c- Search for p_+p_- (100 events of $c\bar{c}b\bar{b}$)	2

$^+$This measurement will be incomplete if the initial run is limited to one year.

Bottom Line, for each machine energy

on Z°	233
above Z°	75
scanning	160
on $\theta(1S)$	233

Total Time (for $L_{avg}=2\times10^{31}$ and 233 days/yr. 3.0 years

The peak design luminosity of the various machines is listed in table 1. Experience from existing e^+e^- storage rings indicates the average luminosity during periods of scheduled data recording is about 1/3 the peak luminosity . Therefore we expect an average luminosity at LEP of 7 x $10^{30}cm^{-2}sec^{-1}$ at $W \approx 100$ GeV. It has been suggested that SLC will do better because they need not fill, and their luminosity does not decay away. Accordingly, we assume an average luminosity of 3 x $10^{30}cm^{-2}sec^{-1}$ for SLC.

With these average luminosities, we find the experiments listed in table 4 are too demanding. In the case of SLC, the data recording time would be 18 years at 5600 hours per year if SLC could do the entire program. SLC should be able to do an excellent job on the major decay modes of the $Z°$. It will be limited on the rare decay modes because of luminosity and will not be able to do anything on toponium because of the beam energy resolution. Eliminating the toponium program reduces the time to eight years. One should keep in mind that SLC was proposed as a linac collider development project and was not expected to do all of the physics available at the $Z°$.

LEP will be able to investiage the full program described in this report. The time required to accumulate the integrated luminosities given in table 4 is nine years. LEP has been designed to go to a center of mass energy of 250 GeV. It is doubtful that they will dedicate all of their running time to the low energy program after they have developed the RF technology needed for the energy upgrade.

To conclude, we find the physics around the $Z°$ to be exciting. In addition to testing the Weinberg-Salam model of the electroweak interaction, the experiments may discover the Top quark, the scalar Higgs, or new heavy particles such as leptons, technipions, and scalar electrons. Although there will exist two accelerators capable of studying this energy region, neither is optimum. The physics program at these accelerators will either be of limited scope or of extremely long duration. The high energy physics community should consider constructing a high luminosity e^+e^- storage ring optimized to study the physics of the $Z°$.

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