First Measurement of the Left-Right Cross Section Asymmetry in Z Boson Production by e^+e^- Collisions

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We present the first measurement of the left-right cross section asymmetry (A_{LR}) for Z boson production by e^+e^- collisions. The measurement was performed at a center-of-mass energy of 91.55 GeV with the SLD detector at the SLAC Linear Collider which utilized a longitudinally polarized electron beam. The average beam polarization was $(22.4 \pm 0.6)\%$. Using a sample of 10224 Z decays, we measure A_{LR} to be $0.100 \pm 0.044(\mathrm{stat}) \pm 0.004(\mathrm{syst})$, which determines the effective weak mixing angle to be $\sin^2\theta_W^{\mathrm{eff}} = 0.2378 \pm 0.0056(\mathrm{stat}) \pm 0.0005(\mathrm{syst})$.

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This Letter presents the first measurement of the left-right cross section asymmetry (A_{LR}) in the production of Z bosons by e^+e^- collisions. The measurement was performed in 1992 by the SLD Collaboration at the SLAC Linear Collider (SLC).

The left-right asymmetry is defined as [1]

$$A_{LR} \equiv (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R) , \tag{1}$$

where σ_L and σ_R are the e^+e^- production cross sections for Z bosons (at the Z pole) with left-handed and right-handed electrons, respectively. To leading order, the standard model predicts that this quantity depends upon the vector (v_e) and axial-vector (a_e) couplings of the Z boson to the electron current,

$$A_{LR} = \frac{2v_e a_e}{v_e^2 + a_e^2} = \frac{2[1-4\sin^2\theta_W^{\text{eff}}]}{1+[1-4\sin^2\theta_W^{\text{eff}}]^2} , \tag{2}$$

where the effective electroweak mixing parameter is defined [2] as $\sin^2\theta_W^{\text{eff}} \equiv (1 - v_e/a_e)/4$. Note that A_{LR} has the following properties: It is a sensitive function of $\sin^2\theta_W^{\text{eff}}$, it is expected to be large (0.10–0.15), and it does not depend upon the couplings of the Z to its final states.

We measure A_{LR} by counting hadronic and $\tau^+\tau^-$ decays of the Z boson for each of the two longitudinal polarization states of the electron beam. The measurement requires knowledge of the absolute beam polarization, but does not require knowledge of the absolute luminosity, detector acceptance, or efficiency [3].

The SLC has recently been upgraded to produce, accelerate, and collide a spin-polarized electron beam [4,5]. Pulses of longitudinally polarized electrons are produced by photoemission from a gallium arsenide cathode [6] that is illuminated by a circularly polarized laser beam [7]. The circular polarization of each laser pulse (and hence, the helicity of each electron pulse) is chosen randomly. A spin rotation system [8] is used to orient the electron spins into the vertical direction to preserve polarization in the electron damping ring and to adjust the spin direction upon extraction from the ring to achieve longitudinal polarization at the SLC interaction point (IP). The polarization of the electron beam at the IP was typically 22%. The mean e^+e^- center-of-mass energy ($E_{\text{c.m.}}$) was measured with precision energy spectrometers [9] to be 91.55 ± 0.04 GeV.

The longitudinal beam polarization ($\mathcal{P}_e$) is measured by a Compton scattering polarimeter [10] located 33 m downstream of the IP. After it has passed through the IP and before it is deflected by dipole magnets, the electron beam collides with a circularly polarized photon beam produced by a frequency-doubled Nd:YAG laser of wavelength 532 nm. The scattered and unscattered electron beams remain unseparated until they pass through a pair of dipole magnets. The scattered electrons are dispersed horizontally and exit the vacuum system through a thin window. Multichannel Cherenkov and proportional tube detectors measure the momentum spectrum of the electrons in the interval from 17 to 30 GeV/c. The polarization of the laser beam ($\mathcal{P}_\gamma$) is measured to be $(93 \pm 2)\%$ and the sign of the circular polarization is changed randomly on sequential laser pulses.

We measure the counting rates in each detector channel for parallel and antiparallel combinations of the photon and electron beam helicities. The asymmetry formed from these rates is equal to the product $\mathcal{P}_e\mathcal{P}_\gamma A(E)$, where $A(E)$ is the theoretical asymmetry function at the accepted energy E of the scattered electrons [11]. The channel-by-channel polarization asymmetry, averaged over a large fraction of the data sample, is shown as a function of the mean channel position in Fig. 1. The curve represents the product of $A(E)$ and a normalization factor ($\mathcal{P}_e\mathcal{P}_\gamma$) that has been adjusted to achieve a best fit to the measurements. The overall detector position and the momentum scale of the spectrometer are calibrated from measurements of the kinematic end point and the zero-asymmetry point.

Polarimeter data are required continually for runs of approximately 3 min. For each run, $\mathcal{P}_e$ is determined from the observed asymmetry using the measured value of $\mathcal{P}_\gamma$ and the theoretical asymmetry function. The absolute statistical precision of each run is typically $\delta\mathcal{P}_e = 0.8\%$. The systematic uncertainties that affect the polarization measurement are summarized in Table I. The total relative systematic uncertainty is estimated to be $\delta\mathcal{P}_e/\mathcal{P}_e = 2.7\%$.

An additional systematic error would arise if the average beam polarization at the electron-photon crossing point differed from the luminosity-weighted average beam polarization at the SLC IP. We have investigated phase space and beam transport effects, depolarization caused by beam-beam interactions at the IP [12], and an effect caused by the possible systematic deviation of the luminosity-weighted mean beam energy from the average

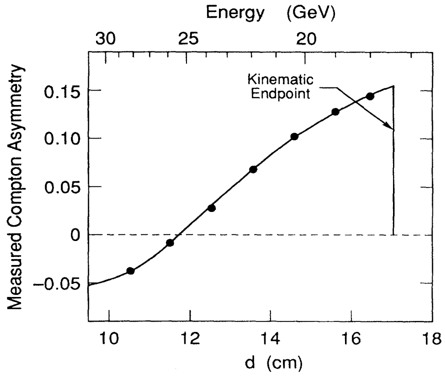

FIG. 1. The average polarized Compoton scattering asymmetry as measured by seven channels of the Cherenkov detector is plotted as a function of the distance (d) from the trajectory of the undeflected beam. The curve represents the product of the asymmetry function and a normalization factor that has been adjusted to achieve a best fit to the measurements.

TABLE I. Systematic uncertainties that affect the A_{LR} measurement.

Systematic uncertainty	$\delta\mathcal{P}_e/\mathcal{P}_e$	$\delta A_{LR}/A_{LR}$
Laser polarization	2.0%	
Detector linearity	1.5%	
Interchannel consistency	0.9%	
Spectrometer calibration	0.4%	
Electronic noise correction	0.4%	
Total polarization uncertainty	2.7%	2.7%
Luminosity asymmetry		1.9%
Background fraction		1.4%
Total systematic uncertainty		3.6%

beam energy [13]. All of these effects cause fractional polarization differences that are smaller than 0.1%.

The polarized e^+e^- collisions are measured by the SLD detector which has been described elsewhere [14]. For this measurement, the triggering of the SLD and the selection of Z events were based solely upon calorimetry. The liquid argon calorimeter (LAC) [15], which covers 98% of the full solid angle, is segmented in depth into two electromagnetic sections (21 radiation length thickness) and two hadronic sections (2.8 interaction length thickness for the entire LAC), each of which is transversely segmented into projective towers of constant solid angle (there are approximately 17000 towers in the first electromagnetic section). The calorimetric analysis must distinguish Z events from several backgrounds that are unique to the operation of a linear collider and differ from those encountered at e^+e^- storage rings. The backgrounds fall into two major categories: those due to low energy electrons and photons that scatter from various beam line elements and apertures, and those due to high energy muons that traverse the detector parallel to the beam axis (due to the low average current in the SLC, backgrounds caused by beam collisions with residual gas in the beam line are negligible). The beam-related backgrounds in the calorimeters are characterized by small amounts of energy in a large number of towers parallel to the beam direction. In order to suppress these backgrounds, all towers used in the analysis are required to satisfy a combination of threshold cuts and criteria that select against longitudinally localized energy deposition in a combined electromagnetic-hadronic tower. Each candidate event must contain fewer than 3000 accepted towers (of the 40000 total) and the total energy observed in the end cap region of the warm iron calorimeter [16], where beam backgrounds are large, must be less than 12 GeV. All events are required to have at least 20 GeV in the LAC and be energy balanced.

We estimate that the combined efficiency of the trigger and selection criteria is $(90\pm2)\%$ for hadronic Z decays and about 30% for tau pairs. Because the event selection is calorimeter based, muon pairs are not included in our sample. Comparing this selection procedure with one that is based upon charge particle tracking information, and by applying the selection procedure to Monte Carlo events, we estimate that the residual beam-related background in the Z sample is less than 0.7%. The contribution of two-photon processes to the Z sample has been estimated by a Monte Carlo simulation to be less than 0.1%. Final state e^+e^- events are explicitly removed since the presence of the t-channel photon exchange subprocess dilutes the value of A_{LR}. We apply an e^+e^- identification procedure which searches for large and highly localized energy deposition in the electromagnetic section of the LAC. The residual e^+e^- background in the Z sample is estimated to be approximately 0.7%.

The sign of the electron beam helicity is supplied to the SLD data acquisition system via two redundant data paths. The synchronization of the helicity signals with triggered and logged events was verified on several occasions.

A total of 10224 Z events satisfy the selection criteria. We find that 5226 (N_L) of the events were produced with the left-handed electron beam and 4998 (N_R) were produced with the right-handed beam [17]. The measured left-right cross section asymmetry for Z production is defined as

$$A_m \equiv (N_L - N_R)/(N_L + N_R) = (2.23\pm0.99)\times10^{-2}.$$

The measured asymmetry A_m is related to A_{LR} by the following expression which incorporates a number of small correction terms in square brackets:

$$A_{LR} = \frac{A_m}{\mathcal{P}_e} + \frac{1}{\mathcal{P}_e}\left[A_m f_b + A_m^2 A_{\mathcal{P}} - E_{\mathrm{c.m.}}\frac{\sigma'(E_{\mathrm{c.m.}})}{\sigma(E_{\mathrm{c.m.}})}A_E - A_\varepsilon - A_{\mathcal{L}}\right], \quad (3)$$

where $\mathcal{P}_e$ is the luminosity-weighted average beam polarization; f_b is the background fraction; $\sigma(E)$ is the unpolarized Z cross section at energy E; $\sigma'(E)$ is the derivative of the cross section with respect to E; and $A_{\mathcal{P}}$, A_E, A_ε, and $A_{\mathcal{L}}$ are the left-right asymmetries of the beam polarization, the center-of-mass energy, the product of detector acceptance and efficiency, and the integrated luminosity.

The correction to A_m for background contamination is less than 3.1×10^{-4}. The polarization asymmetry is directly measured to be $A_{\mathcal{P}} = -2.9\times10^{-3}$, resulting in a negligible correction. A left-right beam energy asymmetry would arise primarily from a left-right beam current asymmetry via beam loading of the accelerator. Using the measured left-right current asymmetry, we infer that the A_E correction to A_m is $(1.7\pm0.6)\times10^{-5}$. The SLD has a symmetric acceptance in polar angle [3] which implies that the efficiency asymmetry A_ε is negligible.

A significant left-right luminosity asymmetry could be produced only by an asymmetry in the beams emitted by the polarized electron source. Such effects are expected to be quite small [7]. We verify this by examining a sample of 25615 small-angle Bhabha scattering events detected by the luminosity monitoring system (LUM) [18]. Of these, 12832 events were produced with the left-handed electron beam and 12783 were produced with the right-handed beam. Since the left-right cross section asymmetry for small-angle Bhabha scattering is expected to be small ($\sim 3\times 10^{-4}\mathcal{P}_e$ in the LUM acceptance), the left-right asymmetry formed from the luminosity Bhabha events is a direct measure of $A_{\mathcal{L}}$. We measure $A_{\mathcal{L}}$ to be $(1.9\pm 6.2)\times 10^{-3}$. A more precise determination of $A_{\mathcal{L}}$ follows from a study of the three parameters of the electron beam (all defined at the IP) that determine the SLC luminosity: the beam current, the electron-positron beam offset, and the beam size (the beam is approximately round). The first two quantities are measured directly. The beam size is not measured directly but can be inferred from the flux of beamstrahlung photons produced by beam-beam interactions at the interaction point. By measuring the left-right asymmetries of each of these quantities, we conclude that $A_{\mathcal{L}}$ is $(1.8\pm 4.2)\times 10^{-4}$.

Since all corrections listed in Eq. (3) are consistent with zero or are extremely small, we do not apply them to A_m but include them in the systematic uncertainty on A_{LR}. Equation (3) then takes the following simple form:

$$A_{LR}=\frac{A_m}{\mathcal{P}_e}=\frac{1}{\mathcal{P}_e}\left[\frac{N_L-N_R}{N_L+N_R}\right]. \tag{4}$$

Because $A_{\mathcal{L}}$ is small, the luminosity-weighted average polarization can be estimated from measurements of the beam polarization made when valid Z events are recorded,

$$\mathcal{P}_e=\frac{1}{N_Z}\sum_{i=1}^{N_Z}\mathcal{P}_i=(22.4\pm 0.6)\%\,, \tag{5}$$

where N_Z is the total number of Z events, and $\mathcal{P}_i$ is the polarization measurement associated in time with the ith event. The error on $\mathcal{P}_e$ is dominated by the systematic uncertainty on the polarization measurement.

Using Eq. (4), we find the left-right asymmetry to be

$$A_{LR}=0.100\pm 0.044(\mathrm{stat})\pm 0.004(\mathrm{syst})\,,$$

where the systematic error has contributions from the uncertainties on $\mathcal{P}_e$, $A_{\mathcal{L}}$, and f_b (see Table I). We use this measurement to derive the following value for the effective electroweak mixing parameter:

$$\sin^2\theta_W^{\mathrm{eff}}=0.2378\pm 0.0056(\mathrm{stat})\pm 0.0005(\mathrm{syst})\,,$$

where we have corrected the result to account for the deviation of the SLC center-of-mass energy from the Z-pole energy and for initial state radiation [19]. These results are consistent with recent measurements of τ polarization and the leptonic forward-backward asymmetries made by other experiments [20] and demonstrate the utility of a new, statistically powerful, and systematically precise technique for testing the standard model.

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[1] A review of the properties of A_{LR} can be found in D. C. Kennedy *et al.*, Nucl. Phys. **B321**, 83 (1989).

[2] We follow the convention used by the LEP Collaborations in Phys. Lett. B **276**, 247 (1992).

[3] The value of A_{LR} is unaffected by decay-mode-dependent variations in detector acceptance and efficiency provided that the efficiency for detecting a fermion at some polar angle (with respect to the electron direction) is equal to the efficiency for detecting an antifermion at the same polar angle. The SLD has an azimuthally symmetric solenoidal magnetic field which ensures the equality of particle and antiparticle efficiencies even in the presence of detector nonuniformities. Additionally, the SLD calorimeter has a high degree of uniformity and polar symmetry.

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