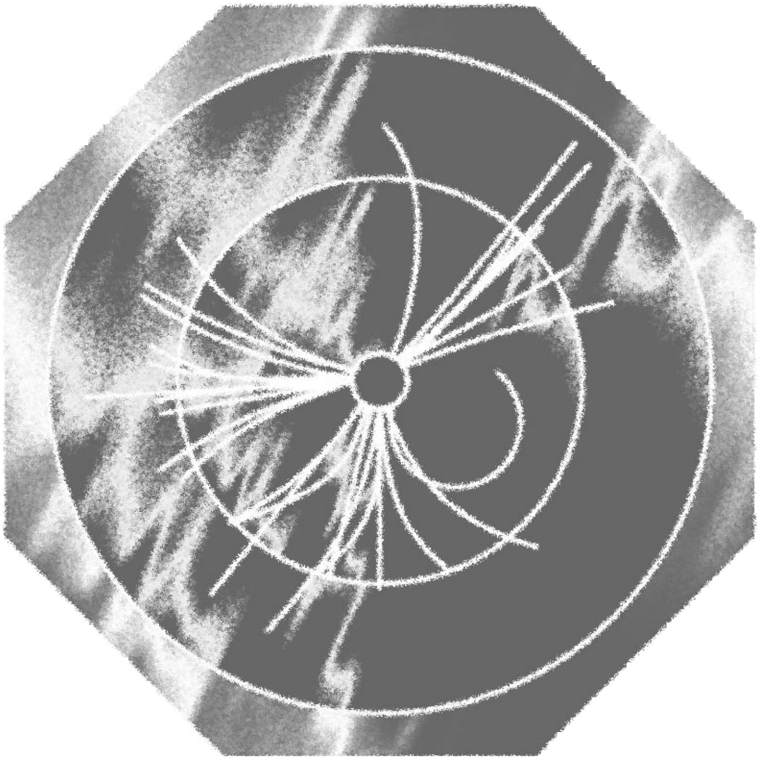
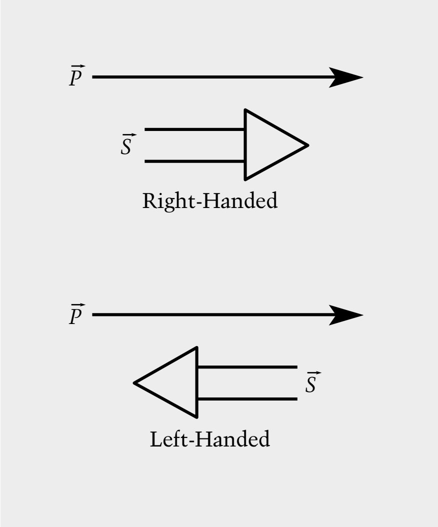
PUTTING A NEW SPIN ON PARTICLE PHYSICS

by MORRIS SWARTZ



Polarized electron beams allow a precision measurement of a key Standard Model parameter.

IN 1991 A HUGE NEW state-of-the-art detector replaced the older and smaller Mark II detector at the interaction point of the Stanford Linear Collider. This detector—named the SLD for SLAC Large Detector—together with the accelerator forms a unique facility for doing experiments in high energy physics. The world's only linear collider, the Stanford Linear Collider or SLC, is also the only $e^+ e^-$ machine to operate routinely with a spin-polarized electron beam.



Left- and right-handed helicity states of a particle with spin $\vec{S}$ traveling with momentum $\vec{P}$.

The SLD was specifically designed to make optimal use of the unique features of a linear collider. Recently the SLC has begun to achieve its goal of producing large numbers of Z particles using highly polarized electron beams; in fact, this collider has substantially exceeded its design goal for beam polarization.

Largely because of these advances, the SLC Collaboration has begun to produce interesting and world-class physics results. The most prominent of these is the world's best single measurement of a key parameter of the Standard Model—the dominant theory of particle physics today. Called the weak mixing angle, this parameter determines the degree of mixing between the weak and electromagnetic forces in this theory. Precise measurements of this parameter are used to search for subtle effects due to physical entities and processes that may lie *beyond* the Standard Model.

MUCH OF THE SLD physics program involves the spin of elementary particles. In 1925, George Uhlenbeck and Samuel Goudschmidt postulated that electrons must have intrinsic angular momenta or *spin*. In order to explain the spectrum of photons emitted by hot hydrogen atoms, they suggested that electrons behave like spinning tops carrying an angular momentum of $\hbar/2$, where $\hbar$ is Planck's constant h divided by 2π. We now believe that all the matter in the Universe is composed of particles (generically called *fermions*) that carry half a Planck unit of intrinsic angular momentum, or spin-1/2. The protons and neutrons inside atomic nuclei are themselves composed of spin-1/2 particles called quarks.

When such matter particles interact with each other, they exchange force-carrying particles called *gauge bosons* which always carry one Planck unit of angular momentum (particles with whole-number values of angular momenta are called bosons). In the Standard Model, the different forces or interactions—weak, electromagnmetic, and strong—are mediated by different gauge bosons. The familiar electromagnetic force is mediated by a gauge boson called the photon. The strong interaction that binds the quarks into protons and neutrons (and protons and neutrons into atomic nuclei) is mediated by a family of eight gluons. The part of the weak interaction responsible for radioactive beta decay and for many of the nuclear processes that occur in solar (and stellar) fusion is mediated by massive W bosons. Last but not least, the weak "neutral-current" interaction, which was not discovered until the mid-1970s, is mediated by the Z boson. The SLD physics program is based principally upon the study of the Z and its interactions with quarks and leptons.

The Standard Model describing elementary particle interactions is actually composed of two conjoined theories. The strong interactions of quarks (mediated by gluons) are described by a theory known as quantum chromodynamics. The electromagnetic and weak interactions are unified in an electroweak theory also known as the Weinberg-Salam or Glashow-Weinberg-Salam theory. In the electroweak theory, the spins of the elementary particles play a fundamental role. In general, the spin axis of a spin-1/2 particle such as an electron can be oriented in any direction in space. However, the two cases for which the spin axis lies parallel to the particle's direction of motion are particularly interesting. If the angular momentum vector is parallel to this direction (the sense of the spin would drive a right-handed screw along this direction), the particle is said to have right-handed helicity. If the angular momentum vector is antiparallel to the direction of travel, the particle is said to have left-handed helicity (see figure at left).

What is interesting about the two helicity states is that they are regarded as *distinct particles* in the electroweak portion of the Standard Model. They have *different* quantum numbers, weak charges, and interactions! This difference is the consequence of the 1958 discovery that the weak "charged-current" interaction—that part mediated by W bosons—involves only left-handed

THE ELECTROWEAK THEORY

THE ELECTROWEAK THEORY is constructed by assigning each fermion two weak charges: the third component of weak isospin I_3, and the weak hypercharge Y_W. The electric charge of each particle (in units of the electron charge) is related to the weak charges by the expression, $Q = I_3 + Y_W/2$. The weak charges of each particle in the first generation of fermions in the Standard Model are listed below along with the gauge bosons that they are coupled to.

THE WEAK CHARGES AND INTERACTIONS OF THE FIRST GENERATION OF FERMIONS

Fermion	I_3	Y_w	Gauge Bosons
ν_L	+1/2	–1	W_1, W_2, W_3, B
e_L	–1/2	–1	W_1, W_2, W_3, B
u_L	+1/2	+1/3	W_1, W_2, W_3, B
d_L	–1/2	+1/3	W_1, W_2, W_3, B
ν_R	0	0	—
e_R	0	–2	B
u_R	0	+4/3	B
d_R	0	–2/3	B

The symbols ν, e, u, and d refer to the neutrino, electron, up quark, and down quark, while the subscripts L and R refer to left- and right-handed helicity. Note that all of the left-handed particles come in doublets of weak isospin and couple to three W bosons. Both left- and right-handed particles couple to the hypercharge-sensitive boson B. The physical gauge bosons are linear combinations of the W_i and B states:

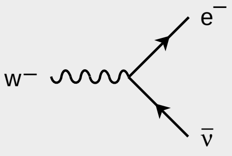
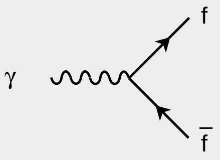
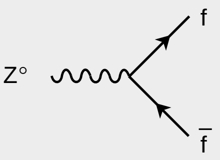
$$W^{\pm} = 1/\sqrt{2}\left[W_1 \mp iW_2^{-}\right]$$
$$Z = W_3 \cos\theta_W - B \sin\theta_W$$
$$A = W_3 \sin\theta_W + B \cos\theta_W$$

where $W^{\pm}$ are the charged gauge bosons that mediate ordinary weak processes such as beta decay, Z is the carrier of the neutral weak interaction, A is the ordinary photon that mediates electromagnetic force, and θ_W is the weak mixing angle. The weak mixing angle is also related to the strengths g' and g of the interactions that depend on hypercharge and weak isospin,

$$\tan\theta_w = \frac{g'}{g}.$$

Numerically, the size of the weak mixing angle is approximately 0.5 radian.

The asymmetry between left- and right-handed particles survives the mixing of the gauge bosons. The coupling strengths of the left- and right-handed fermions to the physical gauge bosons are given below. The W bosons couple to left-handed fermions only. The photon couples to both left- and right-handed fermions with equal strengths proportional to $e = g \sin\theta_W$. The Z boson also couples to both left- and right-handed fermions but with *different* strengths $g_L{}^f$ and $g_R{}^f$.

	LH Coupling	RH Coupling
	$g/\sqrt{2}$	0
	$Q^f\, g \sin\theta_w$	$Q^f\, g \sin\theta_w$
	$\underbrace{(g^2+g'^2)^{1/2}\ (I_3^f - Q^f \sin^2\theta_w)}_{g_L^f}$	$\underbrace{(g^2+g'^2)^{1/2}\ (-Q^f \sin^2\theta_w)}_{g_R^f}$

The Left-Right Asymmetry

An important parameter measured by SLD physicists, called “the left-right asymmetry” or A_{LR}, is equal to the difference in Z boson production rates when left- and right-handed polarized electrons collide with unpolarized positrons, divided by the sum of these two rates:

$$A_{LR} \equiv \frac{R(e^-_L e^+ \to Z) - R(e^-_R e^+ \to Z)}{R(e^-_L e^+ \to Z) + R(e^-_R e^+ \to Z)}$$

$$= \frac{(g^e_L)^2 - (g^e_R)^2}{(g^e_L)^2 + (g^e_R)^2} = \frac{2(1-4\sin^2\theta_W)}{1+(1-4\sin^2\theta_W)^2}$$

The second step follows from the fact that the individual production rates are proportional to the squares of the respective *Zee* couplings. Note that the value of A_{LR} must lie between 1 (only left-handed electrons produce Z bosons) and –1 (only right-handed electrons produce Z bosons). The Standard Model predicts that A_{LR} should be somewhat positive; more Z’s are produced by left-handed electrons than by right-handed electrons.

The left-right asymmetry is a particularly simple quantity to measure. Since exactly half of the SLC pulses have left-handed helicity and the other half have right-handed helicity, we need only form the asymmetry in the number of Z events detected with left- and right-handed beams, N_L and N_R, respectively. This “raw” asymmetry must be corrected to account for incomplete beam polarization,

$$A_{LR} = \frac{1}{P_e} \times \frac{N_L - N_R}{N_L + N_R},$$

where P_e is the beam polarization, which is the fraction of the beam that is spin polarized (the unpolarized fraction $1 - P_e$ is equally divided between the two helicity states).

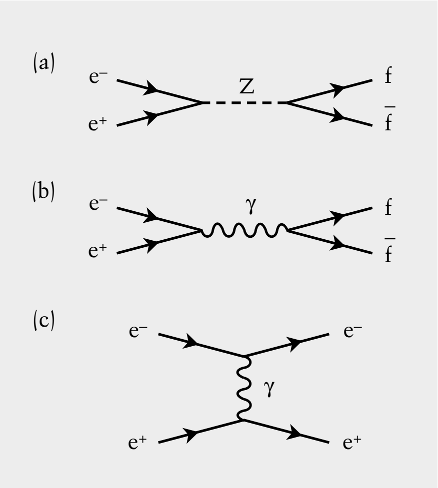
particles; right-handed particles do *not* participate. The architects of the unified electroweak theory therefore had to treat left- and right-handed particles differently. Thus left- and right-handed fermions couple to the Z boson with different strengths, a fact that has crucial implications for experiments with the polarized SLC electron beam.

THE ELECTRON BEAM of the SLC is produced by illuminating a strained gallium arsenide crystal with a circularly polarized laser beam. Depending upon the sign of the laser polarization, mostly right- or left-handed longitudinally polarized electrons are emitted from the crystal and accelerated by the linear accelerator (in 1994–95, about 90% of the beam has the selected helicity and about 10% has the wrong-sign helicity). A number of steps are taken to preserve the beam polarization and to orient it correctly when it collides with the unpolarized positron beam at the SLC interaction point.

The ability of the SLC to collide a polarized electron beam with unpolarized positrons at a center-of-mass energy that is sufficient to produce real Z bosons gives the SLD experiment a unique capability. By changing the dominant beam composition from left-handed to right-handed electrons and back, the SLD experimenter can effectively change the *types* of particles in the beam and compare the rates at which they interact with positrons to produce Z bosons. The electron beam is changed from a dominantly left-handed beam (with one set of weak charges) to a dominantly right-handed beam (with a different set) simply by changing the sign of the voltage on an electro-optical cell (called a Pockels cell) in the polarized electron source. To excellent precision, only the helicity of the beam is changed; all other parameters are insensitive to the sign of the Pockels cell voltage. It is therefore possible to compare very precisely the production rates of Z bosons with left- and right-handed electron beams and extract the so-called left-right asymmetry A_{LR} (see box at left).

SLD physicists search for events in which a Z boson has been produced by recording extensive information about those collisions in which a large amount of energy has been deposited in the detector. They then subject these data to a series of tests in order to distinguish the actual production of a Z boson from the spurious background events that can mimic this process. Incident electrons and positrons can annihilate to produce real Z bosons or virtual photons [see diagrams (a) and (b) on page 23]. Because the SLC energy is tuned to the Z mass, the Z production rate is resonantly enhanced; it is approximately a thousand times larger than the virtual photon production rate. After about 10^{-26} sec, the Z bosons decay into fermion-antifermion ($f\bar{f}$) pairs. About 70% of the time, the final state consists of a quark and antiquark, which appear in the SLD as a back-to-back pair jets of strongly interacting particles. Each charged lepton species (electrons, muons, and taus) is produced about 3% of the time. Electron-positron final states can also be produced by another process [see diagram (c) on page 23] in which the incident electron and

The dominant physical processes that produce large-energy events in the SLD. Initial states are on the left, and time flows as indicated by the arrow.

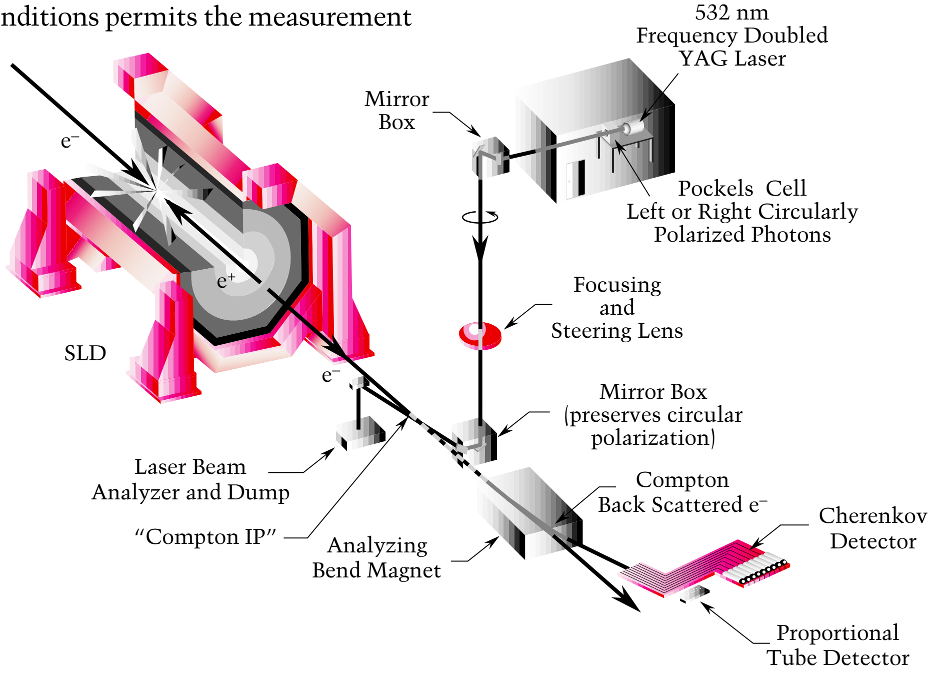


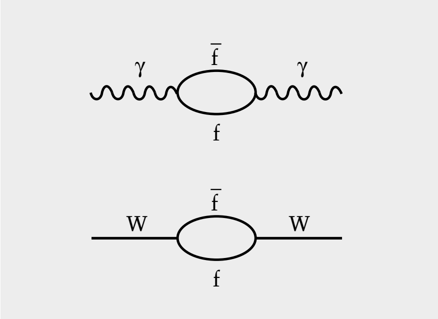
positron exchange a virtual photon as they pass each other; they do not annihilate but deflect each other to large angles. This so-called "t-channel" process leads to about twice as many electron-positron events in the SLD as does the Z decay process alone. Finally, about 20% of all the Z bosons produced decay into neutrino-antineutrino pairs. Since neutrinos interact only very weakly with other matter, they are not detected by the SLD.

All of the observed Z final states can be used to measure A_{LR} except for the e^+e^- final state (which cannot be separated from the unwanted t-channel contribution). A very simple event selection procedure based upon the liquid-argon calorimeter of the SLD is sufficient to identify Z events with very small backgrounds (less than 0.2%) from beam halo, cosmic rays, and unwanted e^+e^- events. Unlike many of the precise electroweak measurements performed at other high energy accelerators, this measurement does not require any knowledge of the efficiency of the detector and the event selection criteria (because it appears in both the numerator and denominator of the asymmetry and therefore cancels out in the ratio). Systematic uncertainties associated with efficiency corrections are therefore not present.

It is, however, important to measure accurately the average polarization of the electron beam, which is accomplished by performing a second colliding-beam experiment 30 m downstream of the first. After interacting with the positron beam at the center of the SLD, the 45.65 GeV electron beam collides with a beam of 2.33 eV circularly-polarized photons from a frequency-doubled Nd-YAG laser (see drawing below). About 1 electron in 10^7 interacts with a laser photon (this process is called Compton scattering). The scattered electrons emerge at tiny angles with respect to their incident direction (the maximum scattering angle is 9.6 microradians). However, the energies of the scattered electrons are significantly degraded; those that ricochet backwards in the electron-photon center-of-mass frame emerge with energies of only 17.36 GeV as viewed in the laboratory. These backscattered electrons are separated from the rest of the beam by a dipole bending magnet; they produce a signal in a Cerenkov detector downstream of this magnet. The number of backscattered electrons is roughly seven times larger when the helicities of the laser photon and electron are opposite (spins parallel) than when they are the same (spins antiparallel). A comparison of the counting rates measured under these two different conditions permits the measurement

A schematic diagram of the Compton polarimeter used to measure the polarization of the SLC electron beam.





Feynman diagrams for vacuum polarizaton corrections.

of the electron beam polarization with a precision of about 1%.

IN 1993, THE SLD experiment logged a total of more than 50,000 Z events with an average beam polarization of 63%. After applying a small correction for the photon exchange backgrounds, the SLD experimenters found the left-right asymmetry to be

$$A_{LR} = 0.1637 \pm 0.0075$$

This value of A_{LR} translates directly into an effective value of the all-important weak mixing angle (see box on page 21) $\sin^2\theta_W$,

$$\sin^2\theta_W = 0.2294 \pm 0.0010$$

This result constitutes the single most precise determination of this key Standard Model parameter yet performed. This quantity has also been extracted from 30 measurements performed by the four LEP experiments at CERN. The average value of this compilation is $\sin^2\theta_W = 0.2321 \pm 0.0004$, which differs from the SLD value by more than two standard deviations.

Why are these results interesting? What are the consequences of one value or the other?

Both A_{LR} and $\sin^2\theta_W$ are sensitive to a number of virtual electroweak processes. The dominant corrections come from the so-called vacuum-polarization effects (see above figure). Gauge bosons can change (briefly) into virtual particle-antiparticle pairs, especially at high energies. These processes alter the electroweak coupling strengths and in turn affect the measured value of these parameters. New particles that are too heavy to be produced directly at the SLC or LEP can still signal their existence by their effect on precisely measured quantities such as A_{LR} and $\sin^2\theta_W$. Unfortunately, these higher-order corrections depend upon all of the particle charges and masses in the Standard Model, including those of the unobserved Higgs boson and the recently observed top quark. They could also hint at the existence of other particles not included in the Standard Model. The measurement of a single electroweak observable does not, in general, test this theory. Measurements of several different observables that depend differently on the top quark and Higgs boson masses are required to carry out detailed tests. The SLD measurement of A_{LR} and $\sin^2\theta_W$ is therefore part of a world-wide program of electroweak testing.

The SLD and LEP values of $\sin^2\theta_W$ are both compatible with Standard Model expectations and other precise electroweak measurements. The SLD value is consistent with heavier top quark masses and lighter Higgs boson masses, while the combined LEP result prefers a lighter top quark and a heavier Higgs boson. We hope that the recent 1994–1995 run of the SLC and SLD will resolve this issue. The SLD Collaboration acquired a sample of more than 100,000 new Z events with an average electron beam polarization of nearly 80%. The uncertainty on the SLD measurement of $\sin^2\theta_W$ should improve by a factor of 2, to the point where it is competitive with the combined LEP uncertainty. A persistent discrepancy with the LEP measurements of this key Standard Model parameter would have interesting implications for particle physics.