First Measurement of the T-Odd Correlation between the Z^0 Spin and the Three-Jet Plane Orientation in Polarized Z^0 Decays into Three Jets

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We present the first measurement of the correlation between the Z^0 spin and the event-plane orientation in polarized Z^0 decays into three jets in the SLAC Linear Collider Large Detector experiment at SLAC utilizing a longitudinally polarized electron beam. The CP-even and T-odd triple product $\vec{S}_Z \cdot (\vec{k}_1 \times \vec{k}_2)$, formed from the two fastest jet momenta $\vec{k}_1$ and $\vec{k}_2$ and the Z^0 polarization vector $\vec{S}_Z$, is sensitive to physics beyond the standard model. We measure the expectation value of this quantity to be consistent with zero and set 95% C.L. limits of $-0.022 < \beta < 0.039$ on the correlation.

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Polarization is an essential tool in investigations of fundamental symmetries in particle physics. Parity violation was first discovered in β decays from polarized ^{60}Co, and T, CP, and CPT violations were searched for using polarized neutrons [1] and positronium [2]. The recent development of high-polarization electron sources based on strained-lattice GaAs photocathodes [3], in conjunction with the high luminosity achieved at the SLAC Linear Collider (SLC), has allowed production of highly polarized Z^0 bosons by e^+e^- annihilation, enabling investigations of symmetries at the Z^0 resonance.

The Z^0 bosons produced using longitudinally polarized electrons have polarization along the beam direction $A_Z = (P_{e^-} - A_e)/(1 - P_{e^-}A_e)$, where P_{e^-} is the electron-beam polarization, defined to be negative for a left-handed beam, and $A_e = 2v_e a_e/(v_e^2 + a_e^2)$ with v_e and a_e the electroweak vector and axial vector coupling parameters of the electron, respectively. Since 1993 the SLC has run with a strained-lattice GaAs electron source; an electron-beam polarization at the e^+e^- interaction point of approximately 0.77 in magnitude was achieved in the 1994–95 run, yielding $A_Z = -0.83(+0.70)$ for $P_{e^-} = -0.77(+0.77)$ and $\sin^2\theta_w = 0.23$. The electron spin direction was randomly reversed pulse by pulse, reducing systematic effects on polarization-dependent asymmetries. For polarized Z^0 decays to three hadronic jets one can define the triple product:

$$\vec{S}_Z \cdot \left(\vec{k}_1 \times \vec{k}_2\right), \tag{1}$$

which correlates the Z^0 boson polarization vector $\vec{S}_Z$ with the normal to the three-jet plane defined by $\vec{k}_1$ and $\vec{k}_2$, the momenta of the highest- and second-highest energy jets, respectively. Here we report the first experimental study of this quantity.

The triple product (1) is even under C and P reversals, and odd under T_N, where T_N reverses momenta and spin vectors without exchanging initial and final states. Since T_N is not a true time-reversal operation, a nonzero value does not signal CPT violation and is possible in a theory that respects CPT invariance [4]. Similar observables were first proposed for direct experimental observation of the non-Abelian character of QCD in $e^+e^- \to \Upsilon \to ggg$ [5] and in $e^+e^- \to q\overline{q}g$ [6], where a sizable signal is expected at c.m. energies $\sqrt{s}$ below 40 GeV; no experimental measurements have been performed since a longitudinally polarized electron beam is required.

The differential cross section for $e^+e^- \to q\overline{q}g$ for massless quarks may be written [6,7]

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\omega} = \frac{9}{16}\left[\left(1 - \frac{1}{3}\cos^2\omega\right) + \beta A_Z \cos\omega\right], \tag{2}$$

where ω is the polar angle of the vector normal to the event plane with respect to the electron-beam direction. With $|\beta A_Z|$ representing the magnitude [8], the second term is proportional to the T_N-odd triple product (1) and appears as a forward-backward asymmetry of the event plane normal relative to the Z^0 polarization axis. The sign and magnitude of this term are different for the two beam helicities.

Recently, Brandenburg, Dixon, and Shadmi have investigated standard model T_N-odd contributions of the form (1) at the Z^0 resonance [7]. The triple product vanishes identically at tree level [4], but nonzero contributions arise from higher-order processes such as those shown in Fig. 1: (a) QCD rescattering of massive quarks [6], (b) QCD triangle of massive quarks [9], and (c) electroweak rescattering via W and Z exchange loops. Because of various cancellations, these contributions are found to be very small at the Z^0 resonance and yield values of the correlation parameter $|\beta| \lesssim 10^{-5}$ [7]. Because of this background-free situation, measurement of the cross section (2) is sensitive to physics processes beyond the standard model that give $\beta \neq 0$.

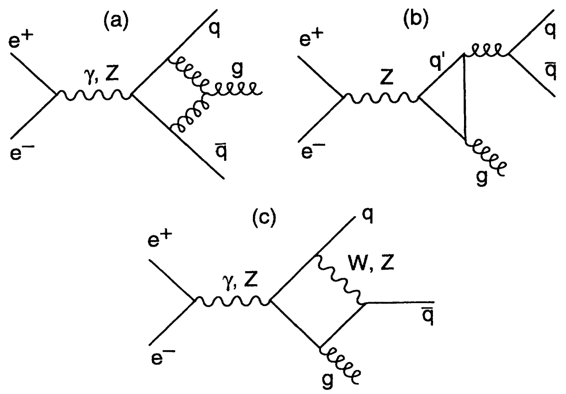

FIG. 1. Representative Feynman diagrams of higher-order interactions with nonvanishing contributions to the triple product: (a) QCD rescattering ($m_q \neq 0$ is required), (b) triangle diagram via quark annihilation ($m_q' \neq 0$ is required), and (c) electroweak rescattering.

The measurement was performed with the SLC Large Detector (SLD) using approximately 50 000 Z^0 decays into multihadrons collected in 1993 and 100 000 decays collected in 1994–95, for which the magnitude of the average electron-beam polarization was 0.63 and 0.77, respectively. A general description of the SLD can be found elsewhere [10]. In the present analysis the hadronic event selection and three-jet reconstruction were based on the topology of energy depositions in the liquid argon calorimeter (LAC), taking advantage of its large solid-angle coverage. The LAC is a lead liquid argon sampling calorimeter composed of barrel and endcap sections, covering the angular ranges $|\cos\theta| < 0.82$ and $0.82 < |\cos\theta| < 0.98$, respectively. It is segmented radially into projective towers of constant solid angle with 192 azimuthal and 96 polar-angle segmentations. The longitudinal segmentation comprises two electromagnetic sections with a combined thickness of 21 radiation lengths and two hadronic sections, giving a total thickness of 2.8 interaction lengths.

The calorimetric analysis must distinguish Z^0 events from backgrounds; in addition, it should remove any background hits coincident with Z^0 events. The dominant source of beam-related backgrounds in the LAC was high-energy muons produced in the SLC that were characterized by small amounts of energy in a large number of towers parallel to the beam direction. An algorithm was used to identify this characteristic signal, and background hits were removed before the hadronic event selection [11].

Although the LAC offers a uniform energy response over most of its solid-angle coverage, the response is degraded around $|\cos\theta| \approx 0.82$, where the barrel and endcap sections meet. In order to achieve a uniform response over the whole acceptance in θ, the detected energy of each tower was corrected. Using the recorded energies E^i_{em} and E^i_{had} in the electromagnetic and hadronic sections of each polar angle segmentation, the total detected energy was expressed as the weighted sum [12]

$$E_{\mathrm{detect}} = \sum_i \left(a_i E^i_{\mathrm{em}} + b_i E^i_{\mathrm{had}}\right). \tag{3}$$

The a_i and b_i correction factors were determined by minimizing the sum

$$\sum_{\mathrm{events}} \frac{(E_{\mathrm{detect}} - E_{\mathrm{c.m.}})^2}{\sigma^2}, \tag{4}$$

where $E_{\mathrm{c.m.}}$ is the e^+e^- collision energy corrected for the detector acceptance and for the undetectable energy carried by neutrinos, and σ is the measured LAC energy resolution for hadronic Z^0 events as a function of thrust axis polar angle θ^{thrust}. The sum was taken over recorded back-to-back two-jet events that form a statistically independent sample to the three-jet events used for this study.

After applying the energy-response correction, calorimeter towers were grouped into clusters. A cluster was selected if at least two towers contributed, its energy E_{cluster} was at least 100 MeV, and the energy correlation in the electromagnetic section $4E_{\mathrm{em1}}E_{\mathrm{em2}}/(E_{\mathrm{em1}} + E_{\mathrm{em2}})^2 > 0.1$, where E_{em1} and E_{em2} are the energies in the front and back electromagnetic sections, respectively [13]. Using the selected clusters the total visible energy E_{vis}, normalized energy imbalance $E_{\mathrm{imb}} = |\sum \vec{E}_{\mathrm{cluster}}|/E_{\mathrm{vis}}$, number of selected clusters N_{cluster}, and $\cos\theta^{\mathrm{thrust}}$ were calculated for each event. Multihadron events were selected by requiring $E_{\mathrm{vis}} > 20$ GeV, $E_{\mathrm{imb}} < 0.6$, and $N_{\mathrm{cluster}} \geq 9$ for $|\cos\theta^{\mathrm{thrust}}| < 0.8$ and $N_{\mathrm{cluster}} \geq 12$ for $|\cos\theta^{\mathrm{thrust}}| > 0.8$. In total 50 144 events from the 1993 run and 99 265 events from the 1994–95 run were selected. The efficiency for selecting hadronic events was estimated to be $(92 \pm 2)\%$, with a background in the selected sample of $(0.4 \pm 0.2)\%$, dominated by $Z^0 \to \tau^+\tau^-$ and $Z^0 \to e^+e^-$ events.

To measure the triple-product correlation for $e^+e^-q\bar{q}g$, three-jet events were selected and the three-momentum vectors of the jets were reconstructed. Although the parton momenta are not directly measurable, at $\sqrt{s} \approx 91$ GeV the partons usually appear as well-collimated jets of hadrons. Jets were reconstructed using the "Durham" jet algorithm [14]. Planar three-jet events were selected by requiring exactly three reconstructed jets to be found with a jet-resolution parameter value of $y_c = 0.005$, the sum of the angles between the three jets to be greater than 358°, and that each jet contain at least two clusters. A total of 44 683 events satisfied these criteria.

Such jet algorithms accurately reconstruct the parton directions but measure the parton energies poorly [15]. Therefore the jet energies were calculated by using the measured jet directions and solving three-body kinematics assuming massless jets, and were then used to label the jets such that $E_1 > E_2 > E_3$. The energy of jet 1, for example, is given by

$$E_1 = \sqrt{s}\,\frac{\sin\theta_{23}}{\sin\theta_{12} + \sin\theta_{23} + \sin\theta_{31}}, \qquad (5)$$

where θ_{kl} is the angle between jets k and l.

Since the energy and angular resolutions of the jet reconstruction procedure determine the sensitivity of the present measurement, a Monte Carlo simulation of hadronic Z^0 decays [16] combined with a simulation of the detector response was used to study the quality of the jet reconstruction. To account properly for beam-related backgrounds in the simulation, real calorimeter hits taken by a random trigger were overlaid on the simulated Z^0 events. These events were then subjected to the same reconstruction, hadronic event selection, and three-jet analysis procedures as the real data. For those events satisfying the three-jet criteria, exactly three jets were reconstructed at the parton level by applying the jet algorithm to the parton momenta. The three parton-level jets were associated with the three detector-level jets by choosing the combination that minimized the sum of the angular differences between the corresponding jets. The directions and energies of jets at the parton level were then compared with those for the corresponding jets at the detector level. Although the detector-jet energies were much degraded, the reconstructed energies agreed well with the parton-jet energies; the average angles between the parton-jet and detector-jet directions were 2.9°, 4.0°, and 7.2°, and the rms energy difference between parton and reconstructed jets was 2.8, 5.2, and 5.2 GeV for the highest, medium, and lowest energy jets, respectively.

Since in this analysis the vector normal to the jet plane is determined by the two highest energy jets, reconstruction of the correct jet-energy ordering is essential. For a three-jet event whose jets are labeled according to the parton-jet energy ordering, six detector-jet energy orderings are possible. For the three cases where the energy ordering of any two jets does not agree between parton and detector levels, the direction of the jet-plane normal vector is opposite between the parton level and detector level, and $\cos\omega$ will be measured with the wrong sign. The probability of this, $P_{\rm mis}(|\cos\omega|)$, was determined from Monte Carlo studies. Although the three-jet rate was largest for $y_c \approx 0.002$, the misassignment probability $P_{\rm mis}$ was found to be smallest for $y_c \approx 0.012$. The experimental sensitivity to the T_N-odd contribution was found highest for the y_c value of 0.005 used in this analysis. For this y_c value $P_{\rm mis}$ was 0.25 around $\cos\omega = 0$, 0.21 as $|\cos\omega| \to 1$, and averaged $\approx$0.22.

For each event the reconstructed jet vectors were used to determine the vector normal to the jet plane and its polar angle ω, from which the measured distribution of $\cos\omega$ was derived. A bin-by-bin correction factor $\epsilon(|\cos\omega|)$, for detector acceptance and initial-state radiation, was determined from Monte Carlo simulations by taking the ratio of the distribution at the parton level for an event sample generated without initial-state radiation to the distribution at the detector level for an event sample generated with initial-state radiation. Figure 2 shows the corrected $\cos\omega$ distribution separately for (a) left- and (b) right-handed beam events in the 1994–95 data sample. A T_N-odd contribution would appear as a forward-backward asymmetry of opposite sign between (a) and (b); no asymmetry is apparent. The distributions may be described by

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\omega} = \frac{9}{16}\left[\left(1 - \frac{1}{3}\cos^2\omega\right) + \beta A_Z[1 - 2P_{\rm mis}(|\cos\omega|)]\cos\omega\right]. \qquad (6)$$

We performed a maximum-likelihood fit of Eq. (6) simultaneously to the $\cos\omega$ distributions from the 1993 and 1994–1995 left- and right-handed event samples, with the relevant values of A_Z, and allowing the parameter β to vary. We found

$$\beta = 0.008 \pm 0.015, \qquad (7)$$

where the error is statistical only. The result of this fit is shown in Fig. 2; the χ^2 is 26.0 for 20 data points. The T_N-odd contribution is consistent with zero within the statistical error, and we calculate limits of

$$-0.022 < \beta < 0.039 \quad @\ 95\% \quad \text{C.L.} \qquad (8)$$

A number of systematic checks were performed. The analysis was performed on two samples of Monte Carlo events; one sample in which no T_N-odd effect was simulated, yielding β consistent with zero within ± 0.010, and another sample, in which a T_N-odd effect was simulated by weighting events according to the parton-level cross section Eq. (2) with $\beta = 0.1$, yielding a measured β consistent with the input value within the statistical error. The dependence on the jet-resolution parameter was studied by varying y_c between 0.001 and 0.03. The analysis was also performed using the JADE jet algorithm [17] and $y_c = 0.01$. While $P_{\rm mis}$ was somewhat larger than the value for the Durham algorithm, 0.25 averaged over $|\cos\omega|$, the experi-

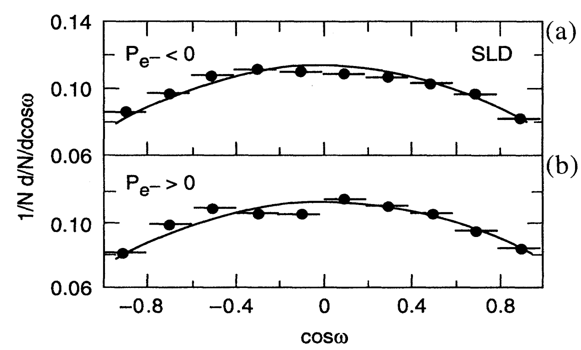

FIG. 2. Polar-angle distribution of the jet-plane normal with respect to the electron-beam direction for the 1994–95 data sample with (a) left-handed and (b) right-handed electron beams. The solid curve is the best fit to the combined 1993 and 1994–95 data samples.

mental sensitivity was comparable as a result of the larger three-jet rate. Finally, the analysis was performed using only charged tracks measured in the central drift chamber (CDC). While the event sample was reduced to about 50% of the calorimetric sample as a result of the smaller solid-angle coverage of the CDC, the charged tracks provided an independent basis for selecting and reconstructing three-jet events. In each case, the T_N-odd contribution was found to be consistent with zero within the statistical error.

In conclusion, we have made the first measurement of the T_N-odd correlation in polarized Z^0 decays to three jets. We find the correlation to be consistent with zero and set 95% C.L. limits on beyond-the-standard-model T_N-odd contributions to Z^0 decays to three jets of $-0.022 < \beta < 0.039$.

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