SLAC-PUB-7283
August 1996

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

KENNETH G. BAIRD
Rutgers University
Department of Physics and Astronomy
New Brunswick, New Jersey

Representing

The SLD Collaboration*
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

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 SLD 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.

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, 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.

For polarized Z^0 decays to three hadronic jets one can define the triple product $\vec{S_Z}\cdot(\vec{k_1}\times\vec{k_2})$, 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

* Work supported in part by Department of Energy contract DE-AC03-'76SF00515 (SL.AC) and National Science Foundation contract NSF-PHY95-10439 (Rutgers).

Presented at the annual Divisional Meeting (DPF 96) of the Division of Particles and Fields of the American Physical society, 10-15 August 1996, Minneapolis, MN.

the highest- and the second-highest energy jets, respectively. Here we report the first experimental study of this quantity.

The triple product $\vec{S_Z} \cdot (\vec{k_1} \times \vec{k_2})$ 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 non-zero value does not signal CPT violation and is possible in a theory that respects CPT invariance [3].

The differential cross section for $e^+e^- \rightarrow q\bar{q}g$ for massless quarks may be written [4,5]

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

where ω is the polar angle of the vector normal to the event plane with respect to the electron-beam direction, and A_Z is the polarization of the Z^0 bozon along this same direction $(A_Z = (P_{e^-} - A_e)/(1 - P_{e^-} \cdot A_e)$, 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). With $|\beta A_Z|$ representing the magnitude[6], the second term is proportional to the T_N-odd triple product, 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 felicities.

Recently Brandenburg, Dixon, and Shadmi have investigated Standard Model T_N-odd contributions of the form $\vec{S_Z} \cdot (\vec{k_1} \times \vec{k_2})$ at the Z^0 resonance[5]. The triple product vanishes identically at tree level [3], but non-zero contributions arise from higher-order processes; these contributions are found to be very small at the Z^0 resonance and yield values of the correlation parameter $|\beta| \lesssim 10^{-5}$. Because of this background-free situation, measurement of the cross section (1) is sensitive to physics processes beyond the Standard Model that give $\beta \neq 0$.

The measurement was performed with the SLC Large Detector (SLD) [7] using approximately 50,000 Z^0 decays into multi-hadrons 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. In the present analysis [8] the hadronic event selection and three-jet reconstruction were based on the topology of energy depositions in the liquid argon calorimeter, taking advantage of its large solid-angle coverage. 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 $Z^0 \rightarrow \tau^+\tau^-$ and $Z^0 \rightarrow e^+e^-$ events.

To measure the triple-product correlation for $e^+e^- \rightarrow q\bar{q}g$, three-jet events were selected and the three momentum vectors of the jets were reconstructed using the "Durham" jet algorithm [9]. 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. The jet energies were calculated by using the measured jet directions and solving the three-body kinematics assuming massless jets, and were then used to label the jets such that $E_1 > E_2 > E_3$.

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.

The $\cos\omega$ distribution is described by

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

where P_{mis} is the probability of incorrectly ordering the energy of the three jets such that the sign of the $\cos\omega$ term is incorrect.

We performed a maximum-likelihood fit of Eq. 2 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 $\beta = 0.008 \pm 0.015$, where the error is statistical only. The T_N-odd contribution is consistent with zero within the statistical error and we calculate limits of [8]

$$-0.022 < \beta < 0.039 \quad @ \quad 95\% \quad C.L. \qquad (3)$$

A number of systematic checks were performed. The analysis was performed on two Monte Carlo samples with simulated T_N-odd values; in both cases β was measured to be consistent with the input value within the statistical error. The dependence of the β value on the jet-finding algorithm and the jet-resolution parameter was examined. The analysis was also performed using only charged tracks measured in the central drift chamber. In each case the T_N-odd contribution was found to be consistent with zero within the statistical error.

1. E. M. Henley, in *Proceedings of the International Symposium on Weak and Electromagnetic Interactions in Nuclei, Montréal, Canada 1989,* edited by P. Depommier (Éditions Frontièes, Gif-sur-Yvette, 1989), p. 181.

2. B. K. Arbic et al., Phys. Rev. **B37,** 3189 (1988), M. Skalsey and J. Van House, Phys. Rev. Lett. **67,** 1993 (1991).
3. A. De Rújula et al., Nucl. Phys. **B35,** 365 (1971).
4. K. Fabricius et al., Phys. Rev. Lett. **45,** 867 (1980), and J. G. Körner et al., Phys. Lett. **94B,** 207 (1980).
5. A. Brandenburg, L. Dixon, and Y. Shadmi, Phys. Rev. **D53,** 1264 (1996),
6. The value of β depends on the parameter that determines the jet multiplicity of events, and is not a universal constant.
7. SLD Design Report, SLAC Report 273 (1984).
8. K. Abe et al., Phys. Rev. Lett. **75,** 4173 (1996).
9. S. Catani et al., Phys. Lett. **B263,** 491 (1991).

The SLD Collaboration*

K. Abe,[19] K. Abe,[29] I. Abt,[13] T. Akagi,[27] N.J. Allen,[4] W.W. Ash,[27]†
D. Aston,[27] K.G. Baird,[24] C. Baltay,[33] H.R. Band,[32] M.B. Barakat,[33]
G. Baranko,[9] O. Bardon,[15] T. Barklow,[27] A.O. Bazarko,[10]
R. Ben-David,[33] A.C. Benvenuti,[2] G.M. Bilei,[22] D. Bisello,[21]
G. Blaylock,[6] J.R. Bogart,[27] B. Bolen,[17] T. Bolton,[10] G.R. Bower,[27]
J.E. Brau,[20] M. Breidenbach,[27] W.M. Bugg,[28] D. Burke,[27]
T.H. Burnett,[31] P.N. Burrows,[15] W. Busza,[15] A. Calcaterra,[12]
D.O. Caldwell,[5] D. Calloway,[27] B. Camanzi,[11] M. Carpinelli,[23]
R. Cassell,[27] R. Castaldi,[23][a] A. Castro,[21] M. Cavalli-Sforza,[6]
A. Chou,[27] E. Church,[31] H.O. Cohn,[28] J.A. Coller,[3] V. Cook,[31]
R. Cotton,[4] R.F. Cowan,[15] D.G. Coyne,[6] G. Crawford,[27]
A. D'Oliveira,[7] C.J.S. Damerell,[25] M. Daoudi,[27] R. De Sangro,[12]
R. Dell'Orso,[23] P.J. Dervan,[4] M. Dima,[8] D.N. Dong,[15] P.Y.C. Du,[28]
R. Dubois,[27] B.I. Eisenstein,[13] R. Elia,[27] E. Etzion,[4] D. Falciai,[22]
C. Fan,[9] M.J. Fero,[15] R. Frey,[20] K. Furuno,[20] T. Gillman,[25]
G. Gladding,[13] S. Gonzalez,[15] G.D. Hallewell,[27] E.L. Hart,[28]
J.L. Harton,[8] A. Hasan,[4] Y. Hasegawa,[29] K. Hasuko,[29] S. J. Hedges,[3]
S.S. Hertzbach,[16] M.D. Hildreth,[27] J. Huber,[20] M.E. Huffer,[27]
E.W. Hughes,[27] H. Hwang,[20] Y. Iwasaki,[29] D.J. Jackson,[25]
P. Jacques,[24] J. A. Jaros,[27] A.S. Johnson,[3] J.R. Johnson,[32]
R.A. Johnson,[7] T. Junk,[27] R. Kajikawa,[19] M. Kalelkar,[24]
H. J. Kang,[26] I. Karliner,[13] H. Kawahara,[27] H.W. Kendall,[15]
Y. D. Kim,[26] M.E. King,[27] R. King,[27] R.R. Kofler,[16] N.M. Krishna,[9]
R.S. Kroeger,[17] J.F. Labs,[27] M. Langston,[20] A. Lath,[15] J.A. Lauber,[9]
D.W.G.S. Leith,[27] V. Lia,[15] M.X. Liu,[33] X. Liu,[6] M. Loreti,[21]
A. Lu,[5] H.L. Lynch,[27] J. Ma,[31] G. Mancinelli,[22] S. Manly,[33]
G. Mantovani,[22] T.W. Markiewicz,[27] T. Maruyama,[27] H. Masuda,[27]
E. Mazzucato,[11] A.K. McKemey,[4] B.T. Meadows,[7] R. Messner,[27]
P.M. Mockett,[31] K.C. Moffeit,[27] T.B. Moore,[33] D. Muller,[27]
T. Nagamine,[27] S. Narita,[29] U. Nauenberg,[9] H. Neal,[27]
M. Nussbaum,[7] Y. Ohnishi,[19] L.S. Osborne,[15] R.S. Panvini,[30]
H. Park,[20] T.J. Pavel,[27] I. Peruzzi,[12][b] M. Piccolo,[12] L. Piemontese,[11]
E. Pieroni,[23] K.T. Pitts,[20] R.J. Plano,[24] R. Prepost,[32]
C.Y. Prescott,[27] G.D. Punkar,[27] J. Quigley,[15] B.N. Ratcliff,[27]
T.W. Reeves,[30] J. Reidy,[17] P.E. Rensing,[27] L.S. Rochester,[27]
P.C. Rowson,[10] J.J. Russell,[27] O.H. Saxton,[27] T. Schalk,[6]
R.H. Schindler,[27] B.A. Schumm,[14] S. Sen,[33] V.V. Serbo,[32]
M.H. Shaevitz,[10] J.T. Shank,[3] G. Shapiro,[14] D.J. Sherden,[27]

K.D. Shmakov,[28] C. Simopoulos,[27] N.B. Sinev,[20] S.R. Smith,[27]
M.B. Smy,[8] J.A. Snyder,[33] P. Stamer,[24] H. Steiner,[14] R. Steiner,[1]
M.G. Strauss,[16] D. Su,[27] F. Suekane,[29] A. Sugiyama,[19] S. Suzuki,[19]
M. Swartz,[27] A. Szumilo,[31] T. Takahashi,[27] F.E. Taylor,[15]
E. Torrence,[15] A.I. Trandafir,[16] J.D. Turk,[33] T. Usher,[27] J. Va'vra,[27]
C. Vannini,[23] E. Vella,[27] J.P. Venuti,[30] R. Verdier,[15] P.G. Verdini,[23]
S.R. Wagner,[27] A.P. Waite,[27] S.J. Watts,[4] A.W. Weidemann,[28]
E.R. Weiss,[31] J.S. Whitaker,[3] S.L. White,[28] F.J. Wickens,[25]
D.A. Williams,[6] D.C. Williams,[15] S.H. Williams,[27] S. Willocq,[33]
R.J. Wilson,[8] W.J. Wisniewski,[27] M. Woods,[27] G.B. Word,[24]
J. Wyss,[21] R.K. Yamamoto,[15] J.M. Yamartino,[15] X. Yang,[20]
S.J. Yellin,[5] C.C. Young,[27] H. Yuta,[29] G. Zapalac,[32] R.W. Zdarko,[27]
C. Zeitlin,[20] and J. Zhou,[20]

[1] *Adelphi University, Garden City, New York 11530*
[2] *INFN Sezione di Bologna, I-40126 Bologna, Italy*
[3] *Boston University, Boston, Massachusetts 02215*
[4] *Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[5] *University of California at Santa Barbara, Santa Barbara, California 93106*
[6] *University of California at Santa Cruz, Santa Cruz, California 95064*
[7] *University of Cincinnati, Cincinnati, Ohio 45221*
[8] *Colorado State University, Fort Collins, Colorado 80523*
[9] *University of Colorado, Boulder, Colorado 80309*
[10] *Columbia University, New York, New York 10027*
[11] *INFN Sezione di Ferrara and Università di Ferrara, I-44100 Ferrara, Italy*
[12] *INFN Lab. Nazionali di Frascati, I-00044 Frascati, Italy*
[13] *University of Illinois, Urbana, Illinois 61801*
[14] *Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*
[15] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[16] *University of Massachusetts, Amherst, Massachusetts 01003*
[17] *University of Mississippi, University, Mississippi 38677*
[19] *Nagoya University, Chikusa-ku, Nagoya 464 Japan*
[20] *University of Oregon, Eugene, Oregon 97403*
[21] *INFN Sezione di Padova and Università di Padova, I-35100 Padova, Italy*
[22] *INFN Sezione di Perugia and Università di Perugia, I-06100 Perugia,*

Italy
[23]*INFN Sezione di Pisa and Università di Pisa, I-56100 Pisa, Italy*
[24]*Rutgers University, Piscataway, New Jersey 08855*
[25]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX United Kingdom*
[26]*Sogang University, Seoul, Korea*
[27]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[28]*University of Tennessee, Knoxville, Tennessee 37996*
[29]*Tohoku University, Sendai 980 Japan*
[30]*Vanderbilt University, Nashville, Tennessee 37235*
[31]*University of Washington, Seattle, Washington 98195*
[32]*University of Wisconsin, Madison, Wisconsin 53706*
[33]*Yale University, New Haven, Connecticut 06511*
†*Deceased*
[a]*Also at the Università di Genova*
[b]*Also at the Università di Perugia*