SLAC–PUB–5910
September 1992
(T/E)

WEAK-ELECTROMAGNETIC INTERFERENCE IN POLARIZED eD SCATTERING*

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ABSTRACT

Observation of parity non-conservation in deep-inelastic scattering of polarized electrons from deuterium was reported in an experiment at SLAC in 1978. The events at SLAC and elsewhere leading to the successful search for parity non-conservation in the electromagnetic processes are described.

Introduction

In 1978, a team of twenty physicists performed an experiment at SLAC which demonstrated convincingly that the weak and electromagnetic forces were acting together in a fundamental process, the inelastic scattering of polarized electrons. This result showed that the electron was a normal partner in the model of electroweak interactions as spelled out by Weinberg in 1967.

The work I am about to describe is the summary of work done mostly by other persons as part of the team effort. In this summary I have tried to give credit to the many excellent contributions from this group. I had hoped to point out all of the important individual efforts that were so critical to the overall success. However, looking at what I said and what is written, I feel that this summary falls short of that goal. It is very difficult to be comprehensive and at the same time concise. Furthermore my perspective on this

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* Work supported by Department of Energy contract DE–AC03–76SF00515.

Invited talk presented at the Third International Symposium on the History of Particle Physics, Stanford, California, June 24–27, 1992 effort is biased toward parts of the work in which I was involved or which I saw going on around me. I surely have missed some of the activities by others on this team, and I apologize for those shortcomings. This talk should be taken as a personal perspective on the work that occurred over a period of eight years at SLAC, Yale University, and other places.

As a part of this talk, the organizers asked that I summarize the work in atomic physics to seek out parity violating effects in atomic levels. I reluctantly agreed to attempt this, even though I had no involvement in those experiments and do not feel qualified to discuss historical notes in that field. In the short time allocated to me, summarizing a major piece of experimental work that lies outside my primary topic is not possible.

What I give here is a brief history of the search for optical rotation by a bismuth vapor, as reported in the literature. I have not attempted to extend this summary to cover the work on the other atoms, thallium, lead, and cesium, which came somewhat later. A proper history talk on the subject of parity violation in atomic physics would include those contributions as well. The work with bismuth atoms began in the mid-1970s, so events were occurring during the time work was underway at SLAC. Some of those events had significant impact for our work. With these thoughts, let me begin.

Physicists love symmetries. Among the important symmetries, parity (the symmetry of mirror reflection) was assumed to be valid for nature's forces and fundamental processes until the mid-1950s when the weak force was shown to violate maximally the parity symmetry in β-decay processes.[1] This unexpected result came as a shock and a surprise. The experimental observations were made in charged-current processes (mediated by the $W^{\pm}$, as we now know). In those days it was conjectured that weak neutral-current processes should exist, but no experiments had access to such processes, and advances in the state of knowledge were slow. In the 1960s, however, progress on the theoretical side was beginning to occur.

Central issues through the 1960s and early 1970s which related to the weak neutral currents were: (i) Do they exist? (ii) If so, what are the characteristics? and (iii) If so, are they maximally parity violating, like the charged currents? Underlying the theoretical speculation was the desire for a common theory that would unify the weak and electromagnetic forces. It was the growing interest and debate in the theoretical community over the connections between the weak and electromagnetic forces that stimulated a number of ventures in the experimental community to look for neutral current effects in electromagnetic processes.

The Early (precursor) Experiments at SLAC

The interest in searching for parity violation at SLAC began in 1970. I was at that time working at the University of California at Santa Cruz, and often visited SLAC. Richard Taylor's Group A at SLAC was heavily involved in the inelastic scattering program. I knew that the Taylor group had recently performed a T-reversal measurement in electron scattering,[2] so I discussed with Taylor and members of his group my interest in looking at the recoiling protons for $\overrightarrow{\sigma_p} \cdot \overrightarrow{p_p}$ terms in electron scattering (specifically elastic scattering) as an experimental approach to parity violation. Although Taylor's group showed considerable interest, the experimental underpinnings of the ideas being considered were too weak to permit a sensitive measurement, so the interest died. Taylor's group was performing a series of experiments in deep inelastic scattering, so I joined that effort as a collaborator from Santa Cruz. A year later(1971), I moved from Santa Cruz to SLAC. Among the experiments to come in the near future was an important one, an experiment E61 which studied 4° scattering from hydrogen and deuterium. It was this 4° experiment that provided the basic information later used for the parity violation work. Cross sections, counting rates, and backgrounds were measured, and E61 was the beginning of a learning curve for me; the facility, the equipment, the beams and monitoring, and the people who inhabited the lab (what they do and what they know).

In late 1970, Professor Vernon Hughes from Yale visited SLAC and presented a proposal to build a polarized electron source for the linac and to accelerate the electrons to high energies. The proposed source was based on a Yale prototype which stripped electrons from a polarized atomic beam of ^{6}Li using an ultraviolet flash lamp.[3] The physics motivation for this proposal was to study the spin of constituents inside polarized protons. That proposal was soon presented to SLAC and was formally accepted and designated E80. The E80 proposal was the beginning of a long and successful program on spin structure which continues to be active today.

I attended Prof. Hughes' seminar in 1970. In my mind there still was the interest in searching for parity violation, and perhaps this source could be used to look for $\vec{\sigma_e} \cdot \vec{p_e}$ terms using the incoming polarized electron beam. I took this idea seriously and began to study the feasibility of a parity violation measurement in the End Station A facility. I remember taking my idea to Richard Taylor looking for support and encouragement and later to Sid Drell (which I got from them). Early in 1971, I arranged a visit to Yale to talk to Vernon Hughes and his group. I wished to form an experimental collaboration and felt I needed the involvement of the Yale group. We discussed the physics possibilities and various strategies. We identified three possible approaches: (i) to utilize the planned E80 experiment and to study parity violation by averaging over the E80 target polarization; (ii) to extend the E80 running to provide dedicated time for a parity violation search; (iii) to propose an independent dedicated experiment for parity violation. We agreed to collaborate and to pursue (i) and (iii).

The E80 experiment was already planned and item (i) required no action on my part. I focussed my attention on a new proposal, E95, whose objective was solely the search for parity violation. Unlike E80, the E95 target was chosen to be unpolarized hydrogen, eliminating a potentially serious systematic error in E80 from polarized protons. The E95 target was optimized for the parity violation test.

Motivation for E95 was not easy. E95 was (quoting from the proposal) "... not sensitive to weak neutral currents... ." We knew that the statistical error on A_{pv} would be too large. Weak-electromagnetic interference required an error $\Delta A_{pv} < 10^{-4}Q^2/M_p^2$, and our calculated statistical error was an order-of-magnitude larger. Weak neutral currents were simply not reachable by the techniques we had at hand. (The Yale-SLAC source, called PEGGY, was too low in intensity, 2×10^9/pulse at 80% polarization.) Furthermore helicity reversals required reversal of a magnetic field to flip the electron spin. The action of spin reversal affected the beam parameters and introduced worrisome systematic errors as well. In spite of these limitations and concerns, we proceeded with the E95 proposal.

The formalism for inelastic scattering of polarized electrons was not available in the literature. We knew that polarized electron inelastic scattering and ν inelastic scattering were kinematically very similar. With the aid of a paper by Stephen Adler[4] we showed that relaxing parity invariance introduced a third structure function $W_3(\nu, Q^2)$ in addition to the usual W_1 and W_2. Furthermore, requiring that current conservation be valid led to $W_3(\nu, Q^2) \to 0$ as $Q^2 \to 0$. We argued in the E95 proposal that such parity violating terms *may* exist and could have escaped detection in former experiments at low energies, for example, in nuclear physics studies which were the most sensitive. We could find no experimental work which ruled out such terms at the level of sensitivity achievable in E95.

Speculation on the existence of parity-violating effects in electromagnetic processes could be found in the literature. In a 1957 paper titled "Electromagnetic Interaction with Parity Violation,"[5] Zel'dovich speculated on such terms with a particular model. One year later he wrote a remarkable paper anticipating future experiments with high-energy longitudinally polarized electrons and with optical rotation of linearly polarized light in atoms.[6] Steven Weinberg's paper "A Model of Leptons"[7] appeared in 1967, and t'Hooft's demonstration of renormalizability appeared in 1971.[8] It was in the context of these ideas that E95 was proposed and defended before the SLAC Experimental Program Advisory Committee. E95 was approved in June 1972.

In the years 1972 to 1975, work on E80 and E95 went along with many other activities at SLAC. Deep inelastic scattering in the End Station A facility continued actively. The SPEAR program came into full swing during this period, leading to the discoveries of the $J/\Psi, \Psi'$, the τ lepton, and the charm and charmonium states. The PEP program was starting up. During this very busy time, E80 ran (in 1975) and shortly thereafter E95 ran (in 1976). Neither E80 nor E95 saw any parity-violating signals. E80 published a limit $A_{pv} \leq 5 \times 10^{-3}$ at $Q^2 \approx 1.4$ and 2.7 $(\mathrm{GeV/c})^2$ (1976).[9] A limit $A_{pv} \leq 0.8 \times 10^{-3} Q^2$ at $Q^2 \approx 4$ $(\mathrm{GeV/c})^2$ was published by E95 (1978).[10] These null results were not surprising. Neutral currents had been seen (in 1974)[11] including those for the electron (in 1976).[12]

The lessons of E80 and E95 were many. They taught us a lot about techniques on how to do this kind of experiment. Equally important, they taught us a lot about how *not* to do this kind of experiment.

In 1974, long before E80 and E95 took data, plans were begun to develop a new kind of source, one that would enable us to reach the statistical level needed for the weak effects. Charles Sinclair and I wrote a letter-of-intent to Wolfgang Panofsky concerning a future experiment to look for weak neutral currents at the level of the Weinberg-Salam model in inelastic electron scattering. We proposed to replace the PEGGY source with a new polarized-electron source that would be laser-driven. We sought his support. We had discussed more than one type of device, and were considering photoionization of cesium as one possibility. We were also interested in solid materials for a cathode, and had discussed our needs with Ed Garwin (SLAC). During that year (1974), Garwin went to ETH Zürich for a visit, and while there proposed with H. C. Siegmann and Dan Pierce the use of negative-electron-affinity gallium arsenide for a suitable cathode material for a high-intensity polarized-electron source.[13] It was their proposal which turned out to be a crucial step for success. The combination of a laser (at moderately high powers) and a solid-state cathode material (having high-electron densities) promised to provide the large-electron currents we needed to reach the elusive weak-electromagnetic interference effects. Polarization of the photoemitted electrons resulted from circular polarization of the laser exciting valence-band electrons to the conduction-band. Electrons near the surface could escape. Polarization values near 50% were expected as a consequence of the angular-momentum selection rules. Polarization reversal was accomplished optically by reversing the circular polarization.

Thus in 1974, a new experiment E122 emerged, proposing to test the Weinberg-Salam model via parity violation with a sensitivity $\Delta A_{pv} \leq 1 \times 10^{-5}$ near $Q^2 \approx 1$ $(\mathrm{GeV/c})^2$. The E122 proposal was developed from the experiences E95. Enhancements over the E95 rates would be large:(i) the beam current was up by a factor of 250; (ii) a new spectrometer using magnets from the 8 and 20 GeV/c spectrometers was designed for a large acceptance, an improvement by a factor of 5; and (iii) a 30-cm-long deuterium target was planned, for an additional factor of 3. The overall gain over E95 was the product of these factors (approximately 3750) which would allow us to reach 1-σ sensitivity to Weinberg-Salam neutral currents in as little as 15 minutes of beam time.

The proposed E122 experiment was approved in June 1975. During the next two-and-a-half years, work on the PEGGY-II source was underway. In December of 1977, the new source was ready and was tested in a brief run on the SLAC linac.

Before describing the E122 experiment, however, I now want to turn to developments in the field of atomic physics which were progressing rapidly at the time.

Parity Violation in Atomic Physics

Zel'dovich in 1960[6] was perhaps the first to suggest looking for optical rotation of the plane of linear polarization of light passing through a gas vapor. He concluded that optical rotation by hydrogen would be too small to detect. The subject of optical rotation was revitalized by work of the Bouchiats in Paris in 1974[14] and by Kriplovich at Novosibirsk.[15] They pointed out that in high-Z atoms, the optical rotation is enhanced by an approximately Z^3 factor and that the sought-after parity-violation effects could become measurable in atomic systems using reasonable laboratory techniques. With this stimulation, several groups at widely separated institutions proposed experiments in 1974. Bismuth (Z=83) was identified as a particularly promising atomic system. Four groups, at Oxford, Seattle (University of Washington), Novosibirsk, and Moscow, proposed generally similar measurements based on optical rotation of the plane of linear polarization in bismuth. The specific details of the four proposed experiments differed considerably. At Berkeley, a thallium (Z=81) experiment was proposed to measure circular dichroism of a light beam. (Circular dichroism, the unequal absorption of opposite-circular polarization, is closely related to optical rotation of linear polarization). The Paris group proposed studying circular dichroism in cesium (Z=55).

In the bismuth experiments, the basic idea starts with crossed-linear polarizers. In a hypothetical-ideal experiment with perfect-optical elements, a light beam is not transmitted. Introducing a cell of bismuth vapor between the crossed polarizers would lead to a rotation and a net transmission of light. In the real world, however, one has to deal with imperfect optics, so the experiments become somewhat more elaborate.

The bismuth atom has three p-wave electrons outside fully closed shells. Two suitable optical-absorption lines can be excited from the ground state by magnetic-dipole excitation, one at $\lambda = 648$ nm and one at $\lambda = 876$ nm. Through the weak interactions between the electrons and the nucleus, parity admixtures of these states are expected to exist, leading to a small electric-dipole amplitude in these transitions. This leads to an optical rotation proportional to the imaginary part of the ratio of amplitudes, Im(E1/M1). The optical rotation ϕ is expected to be $\approx 10^{-7}$ radians. This extremely small rotation can be seen by scanning the light frequency across the line. The absorption by a line is symmetric about the line center. Faraday rotation (which can be induced by a longitudinal magnetic field) is symmetric about the line center, and could be used to calibrate the equipment. In contrast, the parity-violating signal is anti-symmetric about the line center, and the experiments were designed to look for an antisymmetric piece in the absorption. The experiments approached the problem with different techniques. Oxford, Moscow, and Novosibirsk chose to work on the $\lambda = 648$ nm line, while Seattle studied the $\lambda = 876$ nm line. Oxford, Seattle, and Moscow chose to modulate ϕ by using Faraday rotators in the light beam, while Novosibirsk modulated λ. Seattle initially did not resolve the hyperfine splittings, while the others did. Each experiment had to deal with a set of systematic effects and these effects were somewhat different from the other groups. The experiments also had to deal with statistical errors. Fluctuations in photon-counting statistics required averaging over long runs.

Tests of systematic errors required careful studies and null tests. Problems common to these early measurements included: (i) difficulties in obtaining suitable lasers;

(ii) molecular species in the bismuth vapor that masked the desired spectral lines; (iii) Faraday rotations induced by stray residual fields; (iv) extra undesired materials in the optical path, such as cell windows; (v) thermal drifts; (vi) scattering and reflections leading to laser-beam interferences; and (vii) undesirable influence on the laser beam due to the scanning or modulation techniques used.

On the theoretical side, considerable work was underway to understand the proper approach needed to deal with the complicated electronic structure of bismuth. The uncertainties were exacerbated by the lack of a good value of $\sin^2\theta_W$ at the time.

In 1977 Seattle and Oxford completed their first measurements and published adjacent articles in *Physical Review Letters.*[16] Both experiments reported null results on optical rotation with experimental precision substantially better than needed for the Weinberg-Salam model predictions. These groups announced that the Weinberg-Salam predictions for the electron neutral current interaction was wrong. In hindsight we know that these experiments were wrong. However the simultaneous publication of two separate groups at that time created considerable turmoil and controversy in the physics community.

During this period when the atomic physics experiments were active and being discussed at conferences and meetings, the work at SLAC had been proceeding steadily. It was at this time, shortly following the publication of null results by the Seattle and Oxford groups, that the SLAC experiment was ready. A polarized source, suitable for testing the Weinberg-Salam effects in deep-inelastic scattering, was completed. The source was tested on the SLAC linac in December 1977. The E122 experiment was scheduled to begin in February 1978.

Before turning to the SLAC experiment, however, I would like to continue the story of atomic bismuth-parity violation.

In March 1978, the Novosibirsk group reported seeing evidence for parity violation on the 648 nm line in bismuth.[17] The initial reports were accompanied by somewhat large systematic errors, which were subsequently reduced in 1979 without affecting the reported value. In 1980, the Moscow group reported a null result on the same 648 nm line in bismuth in their experiment, in agreement with the earlier Oxford and Seattle null results. By 1981 Seattle had improved and repeated their experiment and reported new results. The Seattle group now reported seeing evidence for parity violation, but somewhat smaller in magnitude than the Novosibirsk result. In 1984 Moscow and Oxford reported results of their improved experiments, which agreed with the 1981 results of Seattle. The Novosibirsk group apparently did not report any new measurements in the years after 1979. This history is summarized in Figure 1 where the bismuth results (but not the thallium, lead, or cesium results) are shown.

The theory of parity violation in atomic bismuth was sufficiently uncertain in the early years that calculations provided only general guidance. The authors of the papers reporting parity violation all reported agreement with the theory. As the experimental results were improved, the results settled down to approximately 1/2 of the value reported by the Novosibirsk group. The theory was refined and remained in agreement with the experiments. The values for theoretical expectations as quoted by the authors is also shown in Figure 1.

In 1987, a group of authors[18] published a global analysis of weak-neutral experiments. In that report regarding the early parity-violating experiments they say:

> "We have omitted the early null experiments, the Novosibirsk bismuth

(648 nm) experiment which is clearly inconsistent with the Moscow and Oxford results, and the original Berkeley thallium result...."

Clearly, unknown-systematic uncertainties dominated the atomic physics parity-violation results in the years before 1981. Today the cesium experiments continue to be refined and offer the prospects of precision measurements of parity violation in atoms.

The SLAC Experiment E122

Preparation for a new experiment sensitive to the weak neutral currents predicted in the Weinberg-Salam model began in earnest in 1975 following approval of E122 by the SLAC Experimental Program Advisory Committee. Development of a new source and design of a new spectrometer quietly occupied the efforts of a number of people during the next several years, a remarkable period at SLAC in which dramatic events were occurring at SPEAR. During this period, the null results of E80 and E95 had been obtained. By mid-1977, the null results from the parity-violation experiments in bismuth from the Seattle and Oxford groups were reported.

The frame of mind in the group preparing E122 was certainly colored by these events. The expectations were that E122 could likely provide a null result. The consequences of that concern was to force a re-doubling of the experimental effort to provide "proof" that even if the experiment were to see no parity-violation signature, the experiment *could* see one if it were there. The experiment had to show it would be sensitive to such effects even if they were not seen. Sensitive beam monitors were developed. Feedback controls on beam position on target, on the beam angle on target, and the beam energy were developed and installed to stabilize the beam which had a natural tendency to drift around. Beam-polarization monitors were installed and backup monitors were added to provide a redundancy. A Mott polarimeter at the source and a Møller polarimeter at the experiment were installed.

The spectrometer was instrumented with two detectors which operated independently to measure asymmetries. Two independent computer codes were developed to check the analysis (ultimately the data were processed in two computers).

This rather elaborate preparation before the experiment reflected our internal concerns that the experiment would be a very difficult one to prove, first to ourselves, but then ultimately to the physics community outside the experiment.

By February 1978, the E122 experiment was scheduled to run, and checkout of the beam and the spectrometers began using unpolarized electrons from the thermionic gun. The checkout procedures were rather lengthy, involving looking at each component and carefully testing the performance. These tests typically utilized low pulse rates while beams to other experiments were in use. By late March, the tests were mostly complete. Richard Taylor had arranged, through earlier negotiations within the laboratory, to run E122 without any beams to other experiments. This dedicated mode, that is sole use of the linac for the E122 experiment, was exceptional but proved to be very important to the experiment. It contributed to the stability of the beams. It also contributed to an improved confidence in the crew of experimenters, and to the undivided attention of the accelerator operators devoted to E122. E122 began dedicated-beam operation in April 1978 with polarized beams.

The polarized-electron source delivered longitudinally polarized electrons to the linac at the rate of 120 pulses per second. The source was driven by circularly polarized light from a dye laser at 710 nm wavelength. Circular polarization was achieved by a calcite prism linear polarizer followed by a Pockels cell, as seen in Figure 2. Reversal of the biasing voltage on the cell would reverse the circular polarization. The linac accelerated the beams with little depolarization. The experiment could be operated with e_L or e_R beams, at the choice of the experimenters. Throughout most of the running, e_L and e_R pulses were mixed with a randomized pattern.

The spectrometer looked at forward scattering at 4° from the 30-cm-long deuterium target. Scattered electrons which entered the spectrometer aperture and fell within the momentum acceptance were detected in the two independent counters, a gas Cerenkov counter and a lead-glass calorimeter. Up to 1000 electrons per linac pulse were detected in the spectrometer. To analyze the high counting rate, signals were integrated and digitized for the Cerenkov counter and the lead-glass counter. Signals from each of the beam monitors were also digitized for each beam pulse. The data-acquisition computer stored the normalized signals (the digitized counters divided by the digitized beam charge) for each pulse, sorted by the beam polarization, one for e_L and one for e_R. After a period of running (typically 1 to 3 hours) the run was ended and summarized.

Periodically the incoming linear polarization of the laser light was rotated by mechanically rotating the axis of the calcite prism by 90°. This rotation had the effect of reversing the circular polarization and hence interchanging e_L and e_R. However, the data-acquisition computer was not informed of these prism reversals, but continued summarizing the data referenced to the sign of the voltage on the Pockels cell. Thus the on-line asymmetries were expected to reverse sign. Figure 3 shows the series of 44 runs taken during the April running. The combined data show a clear pattern of asymmetries following the prism rotation. Figure 4 shows the combined data for the prism at 0°, 45°, and 90°. For each angle the asymmetries measured independently by the Cerenkov and the lead-glass counter are shown, in excellent agreement.

Systematic errors were studied at considerable length. The most serious of systematic errors arose from beam parameters which changed with helicity reversals. Such effects could induce false asymmetries indistinguishable from the real ones. The experiment was set up to monitor six beam parameters, x and y at the target, θ_x and θ_y at the target, Q (charge per pulse) and E_{beam}. Each parameter was read and logged for each beam pulse. Asymmetries, or differences, generated by the helicity reversals were an important part of the monitoring and analysis. The most important contribution to the systematic errors arose from ΔE_{beam} due to the helicity reversals. This effect arose due to minor changes in Q generated at the source by the Pockels-cell modulation. Beam loading in the linac coupled changes in Q to changes in E_{beam}. Since the deep-inelastic scattering cross-section is strongly dependent on the energy of the beam, the effect of ΔE_{beam} was the most serious. The combined errors amounted to 4% of the observed asymmetries, and were treated as part of the overall systematic errors.

By the end of April, the experiment was seeing clear evidence for a parity-violating signal. The next step invoked was to lower the beam energy to 16.18 GeV from 19.42 GeV. The spin motion through the beam transport (a 24.5° bend angle) was such that the spin precessed ahead of the momentum vector by π every 3.237 GeV of energy. That is, at 19.42 GeV, the spin precessed 6π before reaching the target, and at 16.18 GeV, only 5π. The on-line asymmetries would be expected to reflect the change in spin orientation.

Data were also taken at 17.80 GeV and 22.20 GeV. Figure 5 shows the measured asymmetries for the two counters, the Cerenkov and the lead-glass devices. The asymmetries clearly followed a g-2 curve which was expected if the asymmetries were not dominated by false effects. The null points, one at 45° in the prism-rotation curve, and one at 17.80 GeV in the g-2 scan of beam energy, were important as evidence that the false effects must have been small. A short run on hydrogen was also taken and showed evidence with parity violation in agreement with the deuterium results.

Evidence for parity violation in deep-inelastic scattering of polarized electrons was announced at a colloquium at SLAC in June 1978 and a week later in Europe at Trieste.[17] The Weinberg-Salam model agreed for a value of $\sin^2\theta_W = 0.20 \pm 0.03$.

In the summer and fall of 1978, plans for further measurements were made. During this period, many talks were given at many places. I would like to tell one story which occurred at CalTech. Richard Feynman was in the audience and listened to the talk I gave on the careful tests and checks that were done. At the end he asked a typically astute question, *"How do you know that the detectors respond equally to* e_L *and* e_R *beams?"* He sought an experimental test we had done to exclude that possibility. I explained the usual arguments, that soft-electromagnetic processes were responsible for light produced in the Cerenkov and lead-glass counters, and these processes were known to be helicity-independent. We had not performed experimental checks because we did not have the facility to do so. He was not satisfied. He preferred to see checks with experimental tests. Upon returning to SLAC I looked into the question of the spin in the detectors. The spectrometers deflected the scattered electrons an additonal 14° bending at a lower energy E'. The spin at the detectors precessed even faster than the g-2 curve (see Figure 5, the dotted curve). I argued in a letter to Feynman that the dotted curve showed there was no evidence for his conjectured systematic effect. In a subsequent conversation he told me he believed our results, even without that argument, but felt we should have made tests to rule out *experimentally* that possible systematic error.

By the fall of 1978 we resumed our running of E122 to extend our data sample. The goals of the spring 1978 running were mostly met. Existence of parity violation in deep-inelastic scattering had been demonstrated. However, questions regarding the Weinberg-Salam model remained open, and we used the extended-fall running to pursue the answers. Let me explain.

In a parity-violating process such as deep-inelastic scattering where the interaction is mediated by a vector boson (the Z°), there are two electron couplings, one for e_L and one for e_R. These couplings, g_L and g_R, are necessarily different for parity non-conservation to exist. The vector and axial-vector couplings g_V and g_A are defined to be the sum and difference of g_L and g_R; $g_V = (g_R + g_L)/2$, and $g_A = (g_R - g_L)/2$. It turns out that while deep-inelastic scattering is sensitive to both coupling terms, the atomic-parity violation in bismuth is sensitive only to g_A. Could it be that both the SLAC and the Oxford/Seattle results were valid (at that time the dual results of Oxford/Seattle had not been proved to be wrong)? Perhaps $g_A \approx 0$ and $g_V \neq 0$, thus agreeing with the experiments (but not the Weinberg-Salam model). The purpose of the fall 1978 running was to measure both g_V and g_A in deep-inelastic scattering, to investigate that question.

The fall running extended the kinematic range of the data. Separation of the g_V and g_A terms required measurement at different y values ($y = (E_{beam} - E')/E_{beam}$) which in a simple quark model is related to an angular distribution. Figure 6 shows the results of the fall running. The "model-independent" fit corresponds to a $g_A \neq 0$, ruling out any possible agreement with atomic-physics null measurements. (The "hybrid" curve in Figure 6 was one such model satisfying a null value in atomic-bismuth parity violation; it was excluded by the fall 1978 data). The data were also in excellent agreement with the Weinberg-Salam model.

With the ending of the fall 1978 running, the E122 experiment was concluded. It had been a great success. From the combined running in 1978, the SLAC data were consistent with the Weinberg-Salam model for a value

$$\sin^2(\theta_W) = 0.224 \pm .020 \text{ (stat. and sys. errors combined)}$$

which agreed with existing measurements from ν scattering, and significantly improved on the errors at that time. The observation that the weak neutral-current process interfered with the photon-exchange process demonstrated that the neutral currents were mediated by a spin-1 boson. Within the context of the Weinberg-Salam model, the electron behaved as a normal partner; from the measurements of the couplings, e_R was placed in a weak-isospin singlet assignment while e_L and its ν were in a doublet assignment.

We considered in subsequent months further extension of this work. Several factors argued against further running. They were: (i) We had achieved essentially all the goals for E122; (ii) the experiment had occupied nearly six months of SLAC's beam time and was a heavy hit on other experiments trying to run; (iii) significant improvement over E122 would be hard, requiring new developments in the source and experimental apparatus; and (iv) SLAC was beginning to embark on the SLC program and it seemed best to participate in that project to understand better the physics of the Z°.

Thus ended the eight-year search at SLAC for parity violation in the electromagnetic processes.

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FIGURE CAPTIONS

Fig 1 : This figure summarizes measurements of parity violation in atomic bismuth by measurement of the optical rotation of the plane of linear polarization. The parameter R=Im(E1/M1) is plotted versus the date of publication. Where possible, the value of the theoretical prediction *as quoted by the authors at that time* is also shown. Note that the Seattle group studied the 876 nm line, while the other groups studied the 648 nm line in bismuth.

Fig 2 : Rapid reversals of electron spin were achieved by a voltage-driven Pockels cell which generated ±100% circularly polarized laser light. The pattern of voltages was randomized to avoid synchronization with potential harmonic components in the beam parameters. A calcite prism (linear polarizer) was rotated periodically by 90 degrees and 45 degrees to study systematic effects associated with the rapid reversals. Raw asymmetries were constructed using the sign of the Pockels-cell voltages (see Figures 3 and 4).

Fig 3 : The raw asymmetry divided by the measured-beam polarization, A_{exp}/P_e, is shown for a sequence of 44 runs, each lasting from one to three hours. The solid line represents the expected result (the average), taking into account the prism orientation.

Fig 4 : The raw asymmetry divided by the beam polarization, A_{exp}/P_e, for the three prism settings. Two independent detectors in the spectrometer, a gas Čerenkov counter, and a lead-glass shower counter, are shown and are seen to agree. The null values at 45 degrees indicate no helicity-dependent systematic errors are seen at the level of the statistical errors shown.

Fig 5 : By varying the beam energy, the spin orientation at the target varied due to the "g-2" electron spin precession in the 24.5 degrees of bending by the beam transport system. The quantity A_{exp}/P_eQ^2 is plotted for two independent counters in the spectrometer. The dashed curve is the best fit to the expected curve (to a form $k\ cos(E_{beam}/3.237\text{GeV})$). The dotted curve represents the spin orientation of the electrons as they passed through the detectors, and was used to answer a question posed by Richard Feynman (see text).

Fig 6 : The quantities A_{exp}/P_eQ^2 are plotted versus the kinematic variable $y = (E_{beam} - E')/E_{beam}$. The model-independent fit is in good agreement with the Weinberg-Salam model, but not with the hybrid model (see text). These data established values for the neutral-current couplings g_V^e and g_A^e, and showed that the SLAC results were incompatible with the earlier reports of no parity violation in bismuth.

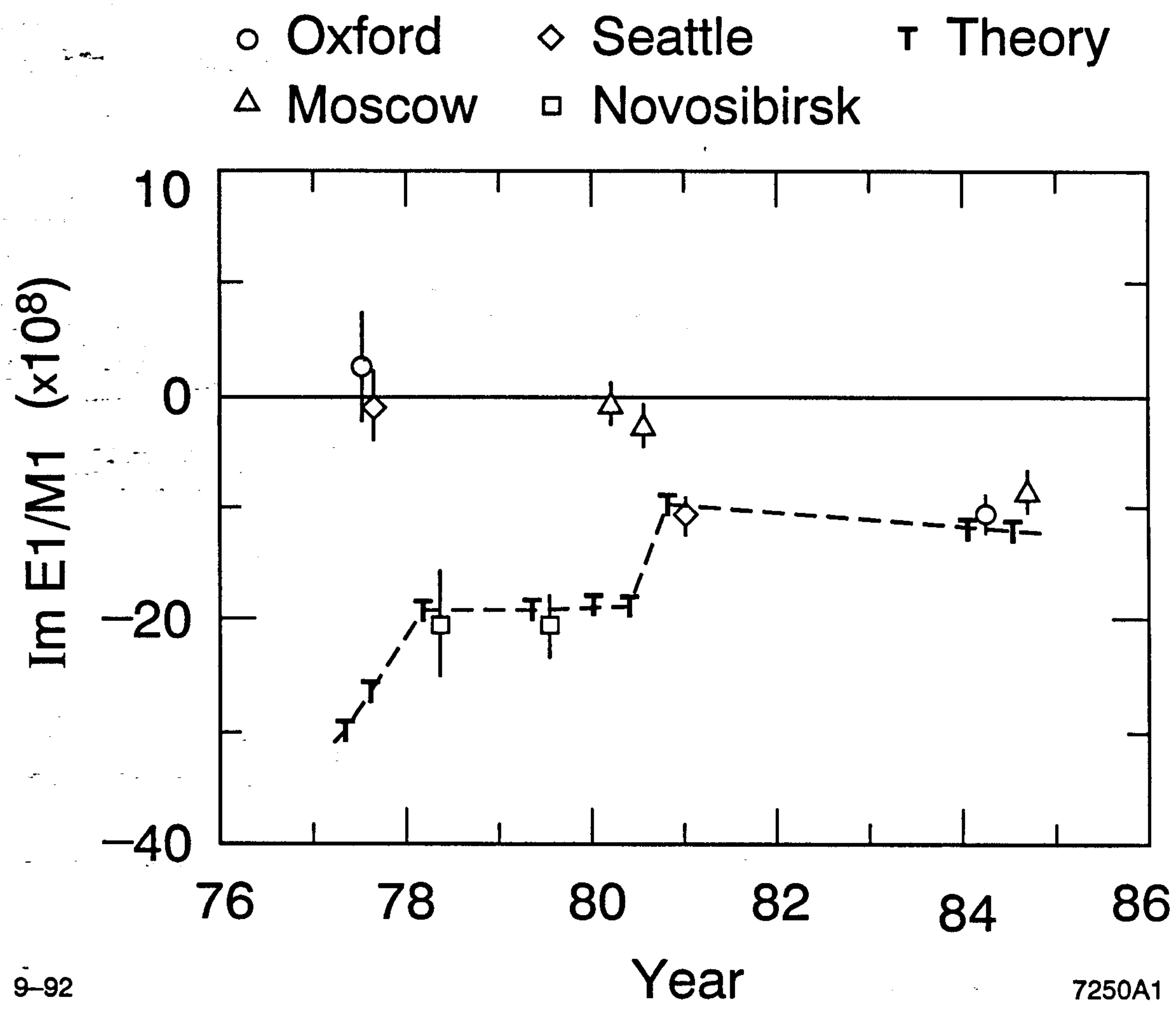
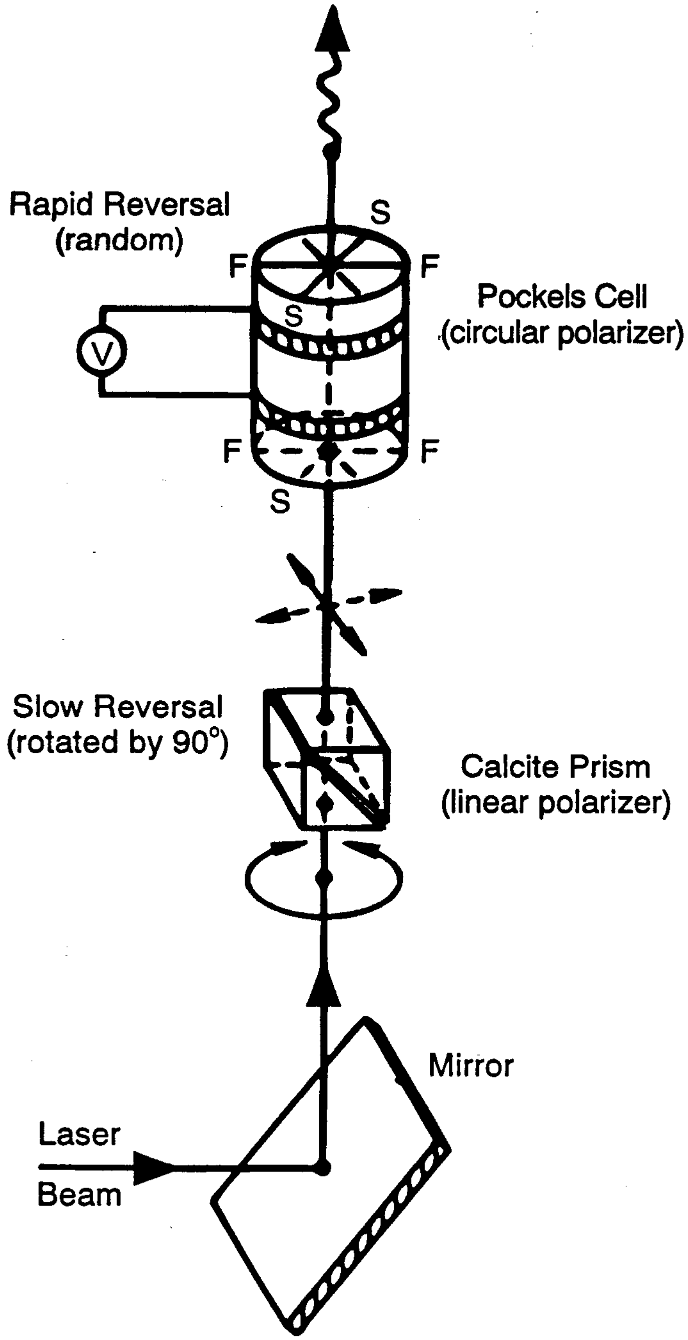

○ Oxford
◇ Seattle
т Theory
△ Moscow
□ Novosibirsk
10
0
−20
−40
Im E1/M1 (x10^8)
76
78
80
82
84
86
Year
9–92
7250A1

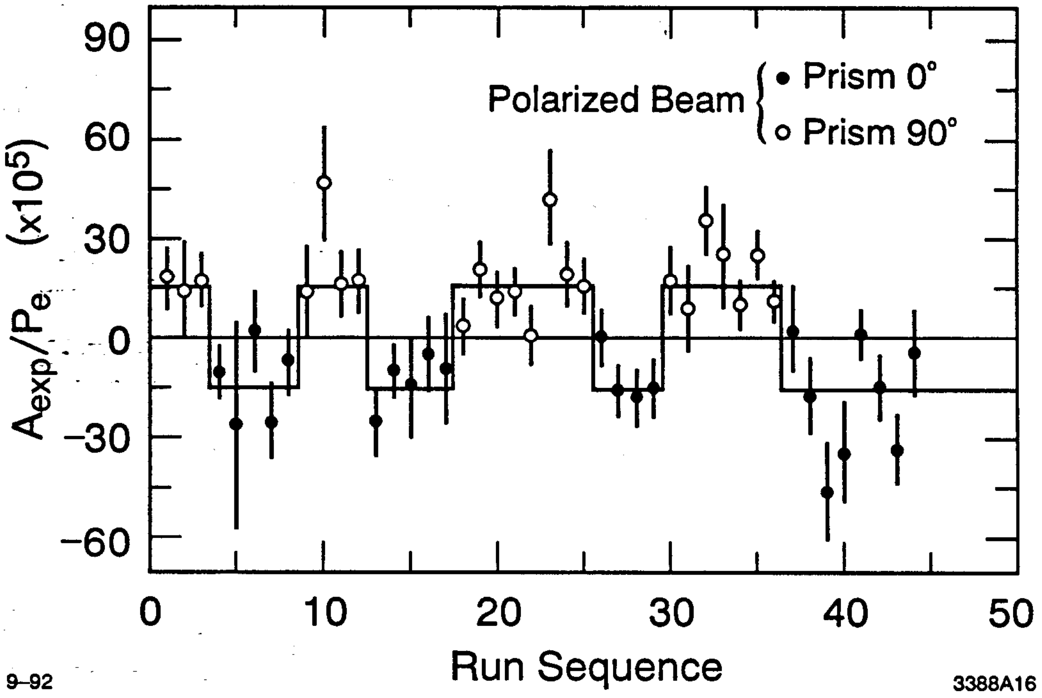
Fig. 1

Polarized Laser Beam to the Ga As Cathode



9–92 Optical Reversal Scheme 3388A3

Fig. 2



90
60
30
0
−30
−60
A_{exp}/P_e (x10^5)
Polarized Beam
● Prism 0°
○ Prism 90°
0
10
20
30
40
50
Run Sequence
9–92
3388A16

Fig. 3

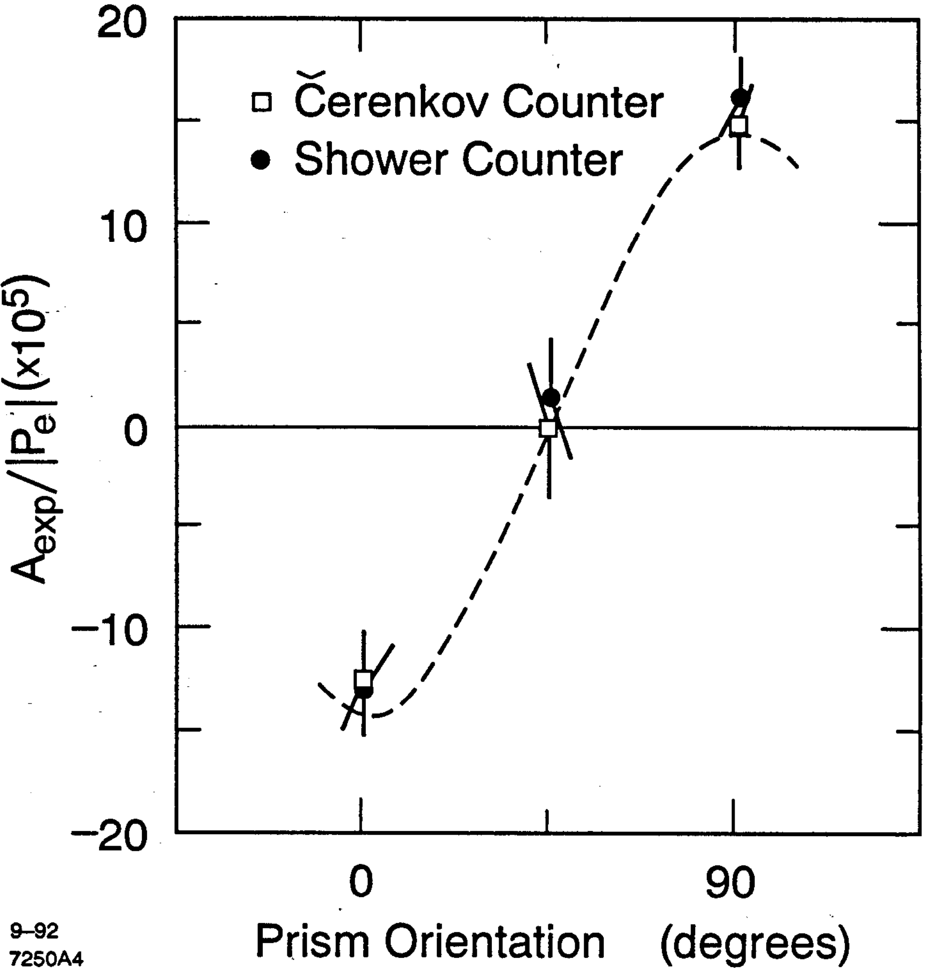

20
10
0
−10
−20
□ Čerenkov Counter
● Shower Counter
$A_{exp}/|P_e|\,(\times 10^5)$
0
90
Prism Orientation (degrees)
9–92
7250A4

Fig. 4

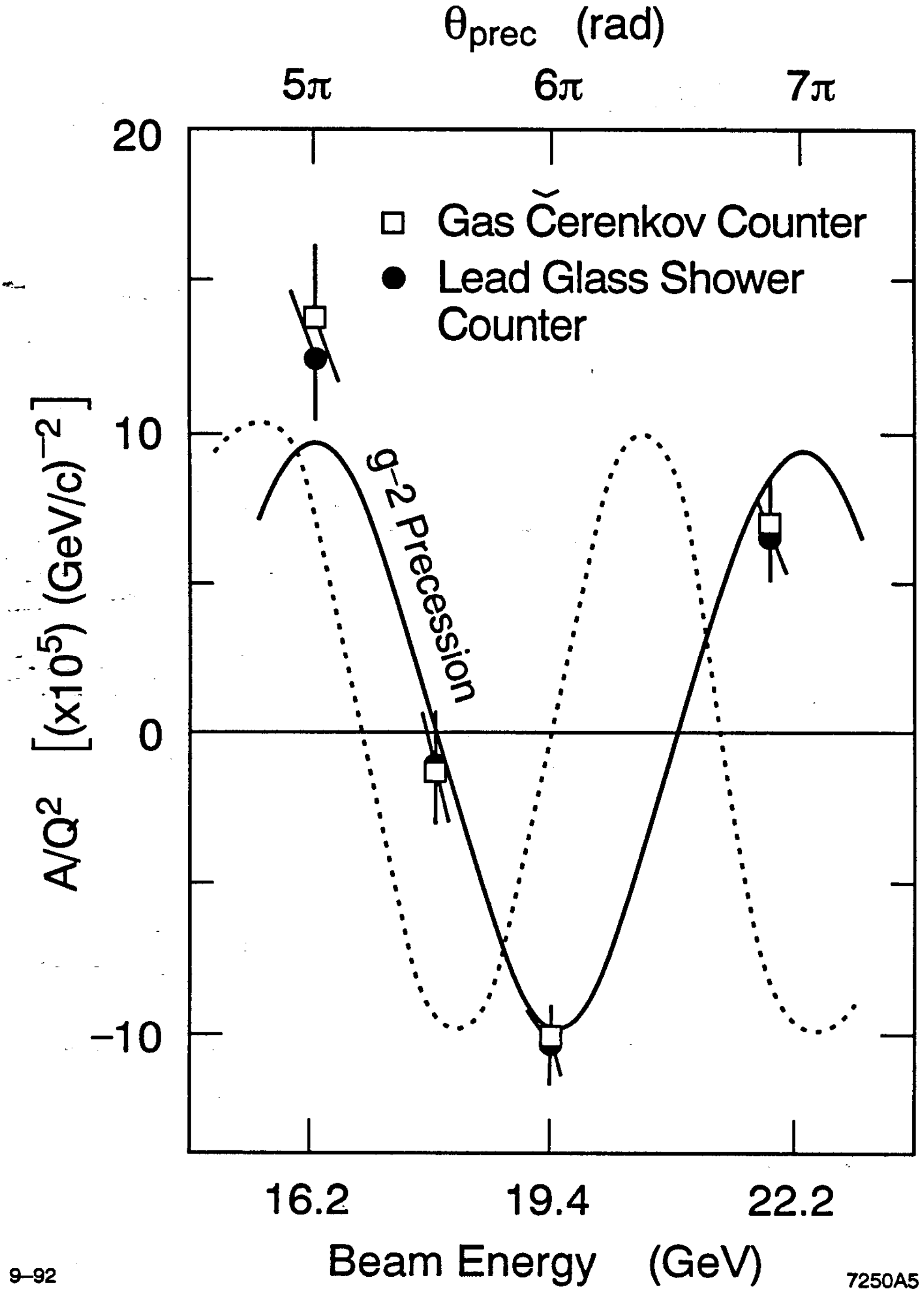
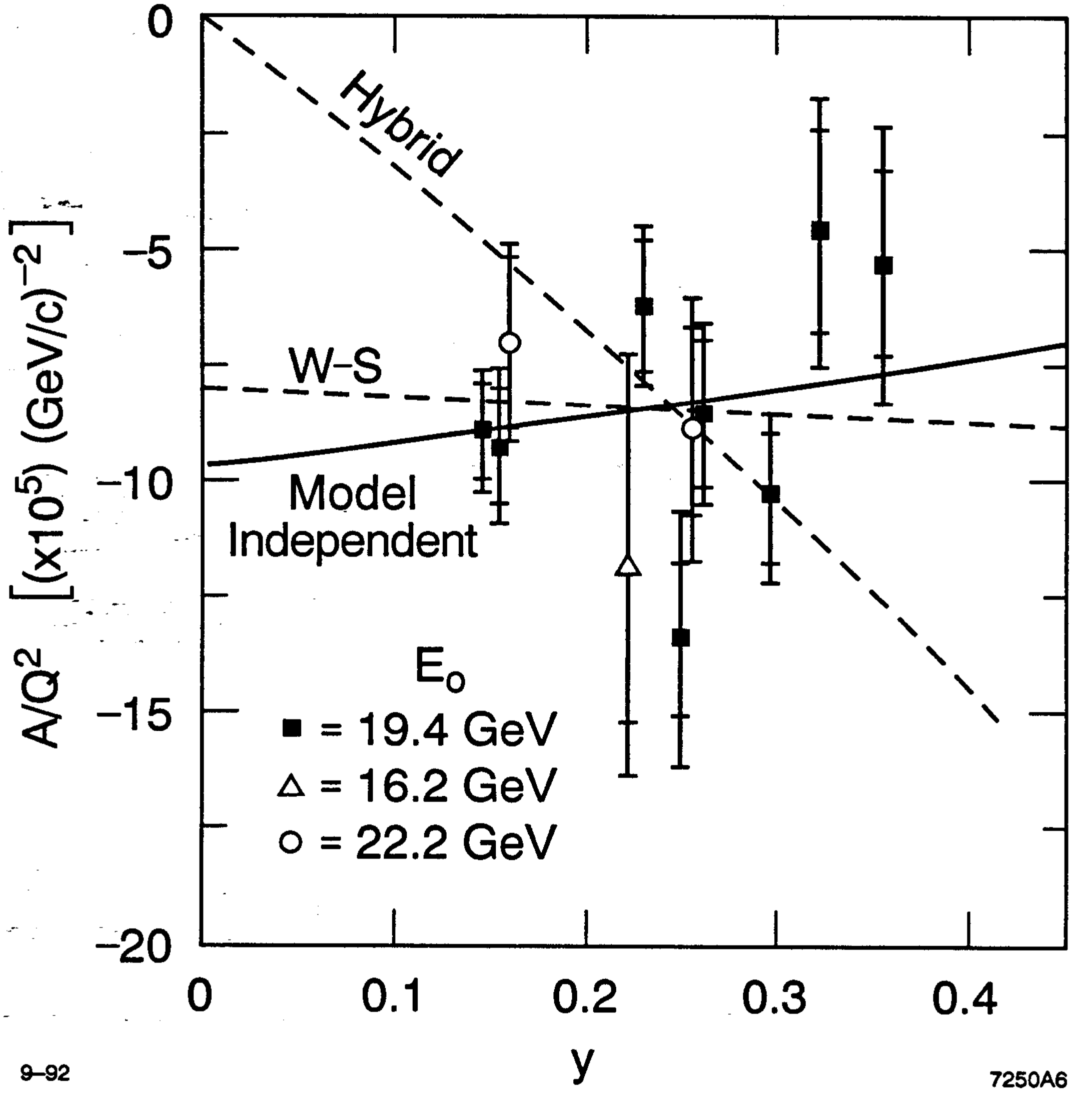

θprec (rad)
5π
6π
7π
20
10
0
−10
A/Q² [(x10⁵) (GeV/c)⁻²]
□ Gas Čerenkov Counter
● Lead Glass Shower Counter
g–2 Precession
16.2
19.4
22.2
Beam Energy (GeV)
9–92
7250A5

Fig. 5



0
−5
−10
−15
−20
0
0.1
0.2
0.3
0.4
y
A/Q² [(x10⁵) (GeV/c)⁻²]
Hybrid
W–S
Model Independent
E₀
■ = 19.4 GeV
△ = 16.2 GeV
○ = 22.2 GeV
9–92
7250A6

Fig. 6