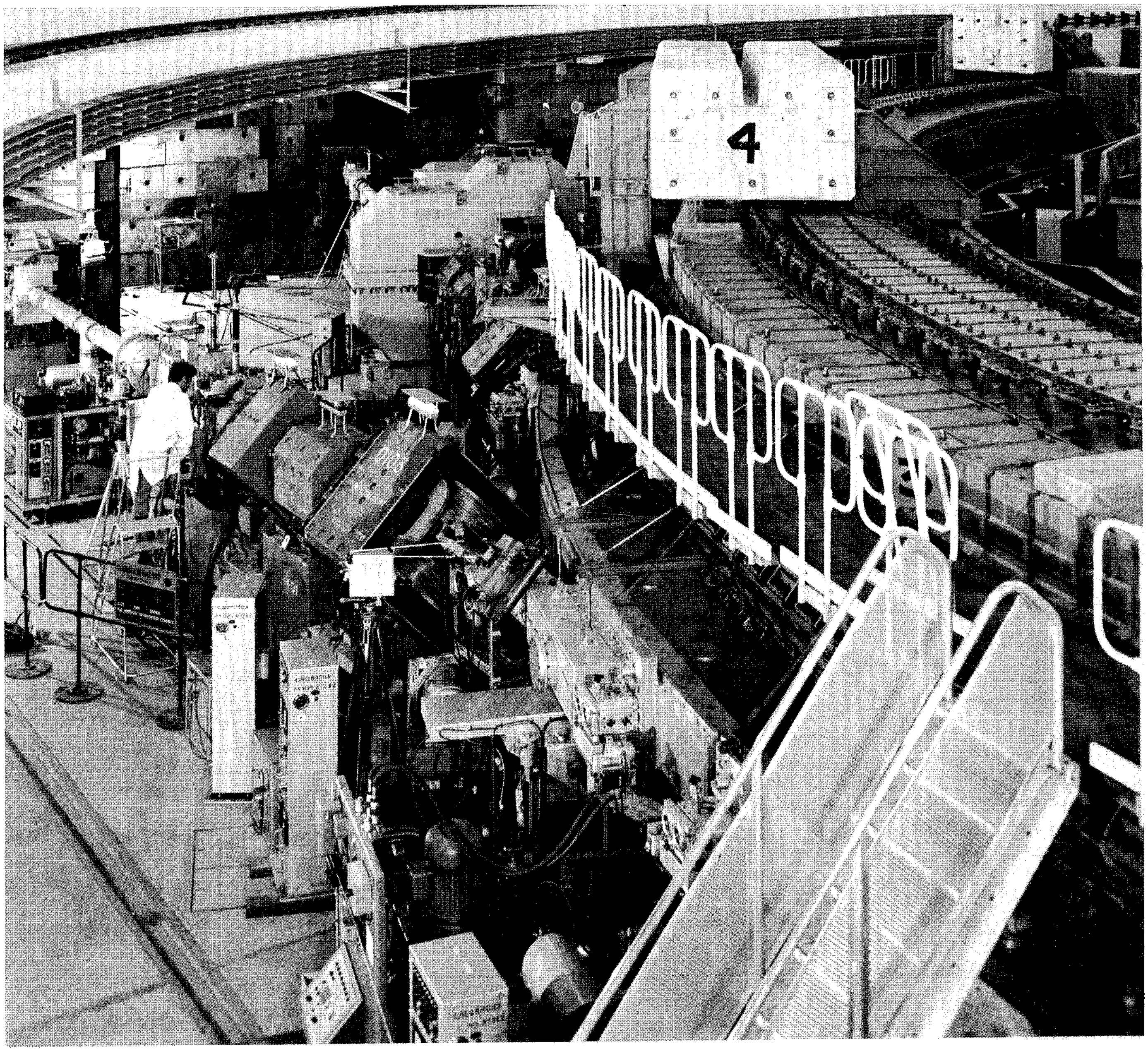
SLAC BEAM LINE

"All composite things decay. Strive diligently."
--Buddha (his last words)

Volume 9, Number 10 October 1978



The photograph above shows the 7 GeV proton synchrotron NIMROD at the Rutherford Laboratory in England. NIMROD (the "mighty hunter" in the Book of Genesis) was recently closed down after 15 years of important contributions to the field of high-energy physics research. During this time, research teams from about 20 different universities carried out a total of about 80 experiments. (Photo: Rutherford Lab.)

In This Issue

Note: The article on "Parity Violation In Polarized Electron Scattering" will be distributed separately in about 2 weeks.

SLAC WOMEN'S ASSOCIATION

Last August 21, the Women's Association presented a slide show by artist Gertrude Reagan called "Science: A Source Of Aesthetic Pleasure." Ms. Reagan displayed a series of strikingly beautiful slides produced by recent techniques of photography. The subjects included sunspots, mountains, living cells, and the human body. Ms. Reagan is married to SLAC physicist Daryl Reagan, and her father was also a physicist. With such a life-long exposure to science, it was natural for her to turn her artistic talent toward scientific subjects, and the results were indeed a source of aesthetic pleasure to those who attended her show.

On September, the noon program of the Women's Association was "An Introduction To SPIRES," originated and presented by Louis Addis of the SLAC Library. The demonstration was presented on a number of computer terminals that were "slaved" together so that each member of the audience could have a clear view of a terminal display screen. The program consisted of a pre-recorded audio tape synchronized with the visual displays which explained the workings of SPIRES and how it is used at SLAC. ("SPIRES" is an acronym for "Stanford Public Information REtrieval System.") Practical hints were given on how to use the SLAC computation facilities, from remote terminals, to identify SLAC publications in various ways, compile bibliographies, search the physics literature, etc. After the recorded part of the presentation, Ms. Addis answered more detailed questions from the audience. This was a most interesting and informative program.

On October 11, the SLAC Women's Association combined their varied talents with hard work to stage a fund-raising barbeque lunch and membership drive. Over 60 SLAC employees attended the barbeque, which was held in the Sector 6 picnic area. We dined on chicken soup, delicious barbequed chicken, assorted salads and side dishes, and a variety of desserts. This affair seemed to be well-received by everyone who came, and many said they would eagerly await the next barbeque.

Please keep an eye on the bulletin boards at SLAC for announcements of future programs and events sponsored by the Women's Association.

If you would like to join the Association, please contact either Shirley Livengood (ext. 2338, Bin 82) or Diana Gregory (ext. 2353, Bin 11). Although we would certainly like everyone to join the Association, any person at SLAC, member or not, is invited to attend any of our future noon-hour programs or events.

--Shirley Livengood

STANFORD WORD PROCESSING TRADE SHOW

A first-time event, the STANFORD WORD PROCESSING TRADE SHOW, will be held on November 17 and 20 for Stanford faculty and staff. Fifteen of the leading manufacturers have been asked to display their equipment in operation and to introduce new products and systems to the Stanford audience. A partial list of suppliers who are planning exhibits includes Addressograph-Multigraph, Xerox, IBM, Wang Laboratories, Lexitron, NBI, Vydec, Digital Equipment Corporation, and 3M Company.

Two on-campus alternatives to these commercial suppliers will also be represented: SCIP, which provides timeshared word processing on the Campus Facility 370/168 computer; and the Encina Word Processing Center, which has video-display text editors and a "Thought Tank" dictation system that can be dialed from any campus extension phone. Documents created on the Center's word-processors can be transmitted to the 370/168, and vice-versa.

The second floor of Tresidder Union has been reserved for the Show on Friday, November 17, from 1:00 to 5:00 PM, and again on Monday, November 20, from 9:00 AM to 1:00 PM.

To help answer questions and to get the most out of the equipment show, a pre-show WORD PROCESSING SEMINAR is slated for November 9, from 9:30 to 11:30 AM, in Room 282 at Tresidder. The Seminar will be of interest to anyone involved in word processing or concerned about office productivity.

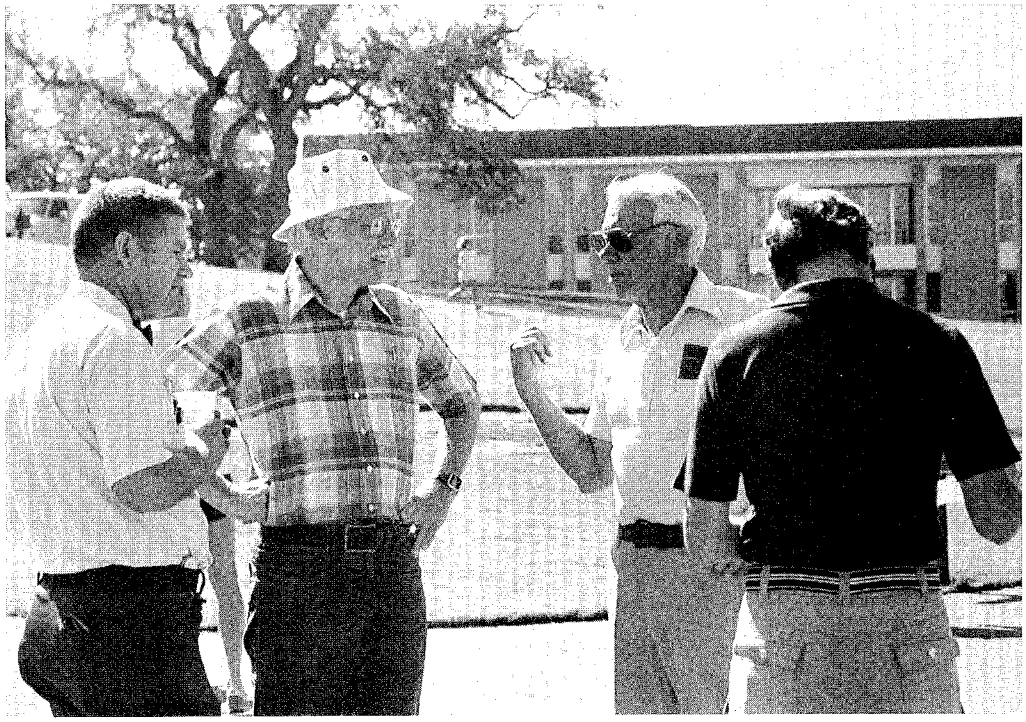
The Seminar and Show are being sponsored by COST, the Committee on Office Systems and Technology, which is comprised of members from various University departments. During the past year, members of this Committee have interviewed Stanford offices using word processors, worked with Procurement Services to provide information to those considering new equipment, helped test equipment compatibility, and begun investigation of the potential for shared campus-wide services, such as electronic mail. The Committee is chaired by Jon Sandelin, Assistant Director of SCIP.

Questions concerning the Seminar or Show should be directed to Harvey Silverman of Procurement Services, at 497-1751.

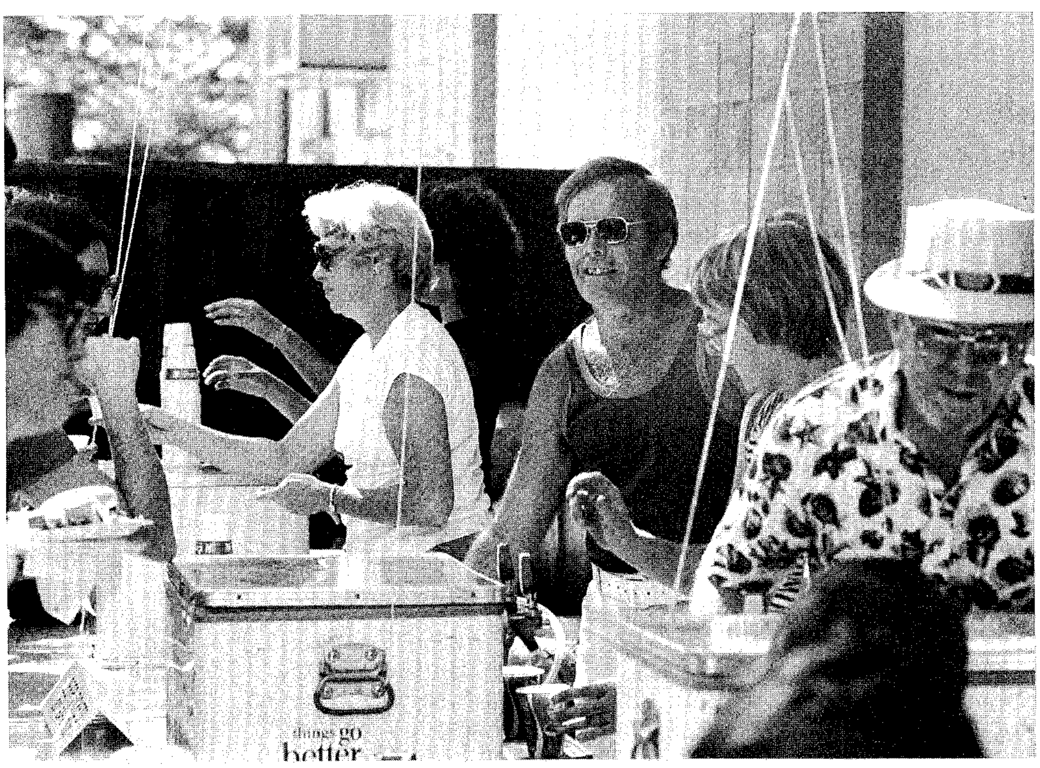
MILITARY TARGET: Any person, thing, idea, entity, or location selected for destruction, inactivation, or rendering non-usable with weapons which will reduce or destroy the will or the ability of the enemy to resist.

--*Fundamentals Of Aerospace Weapons Systems*
US Air Force ROTC Manual

SLAC FAMILY DAY

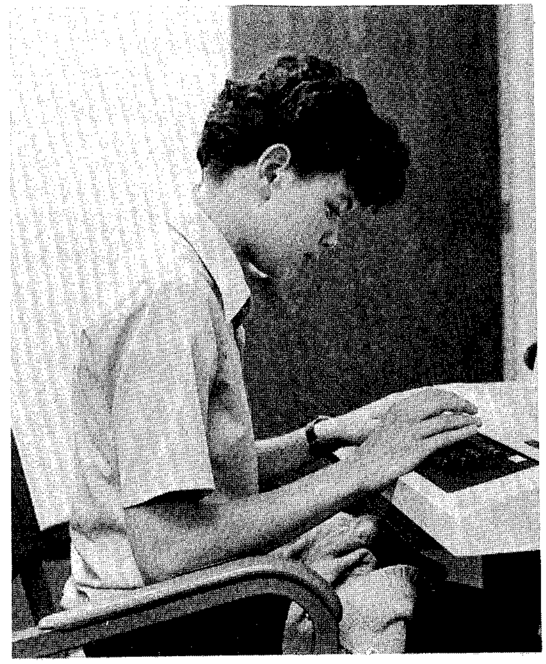


Photos by Joe Faust

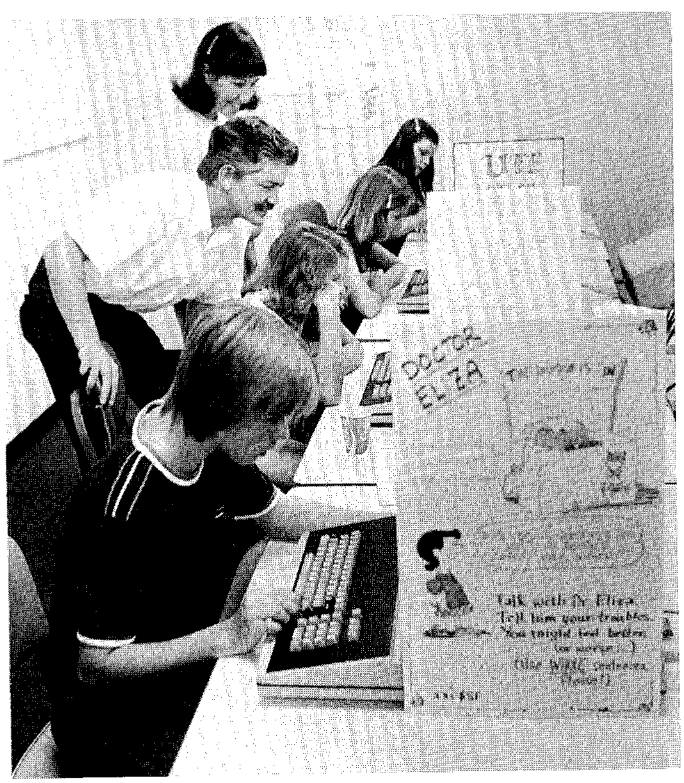


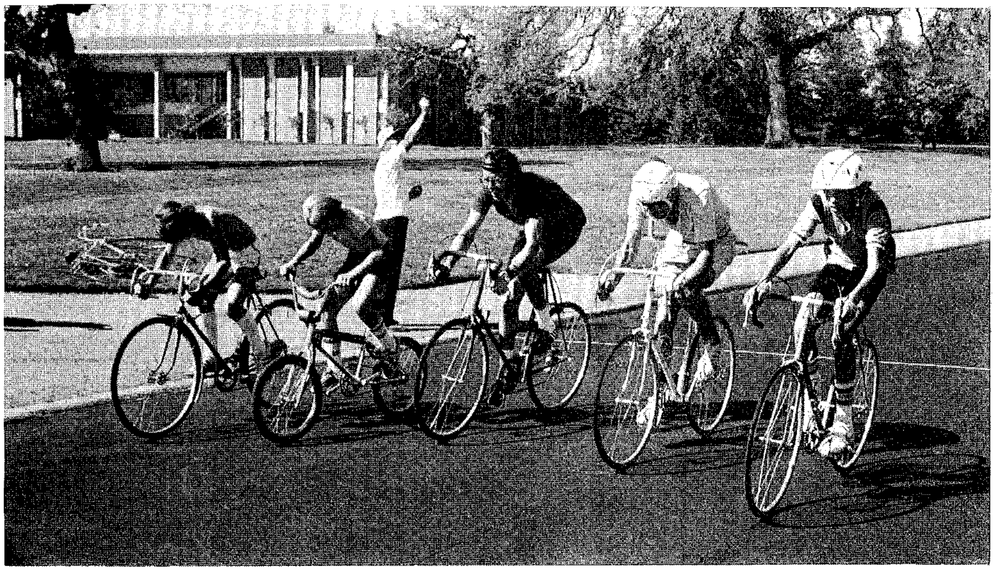
SEPT. 23 1978

Family Day Balloons

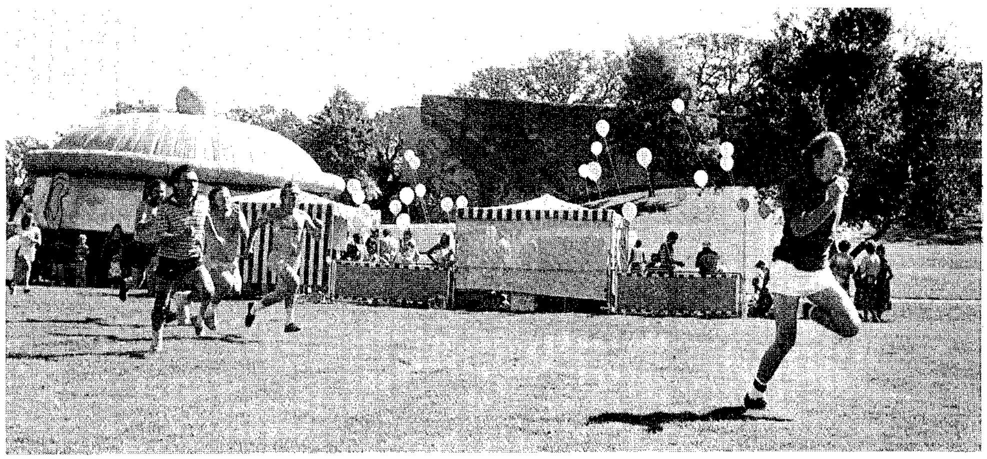


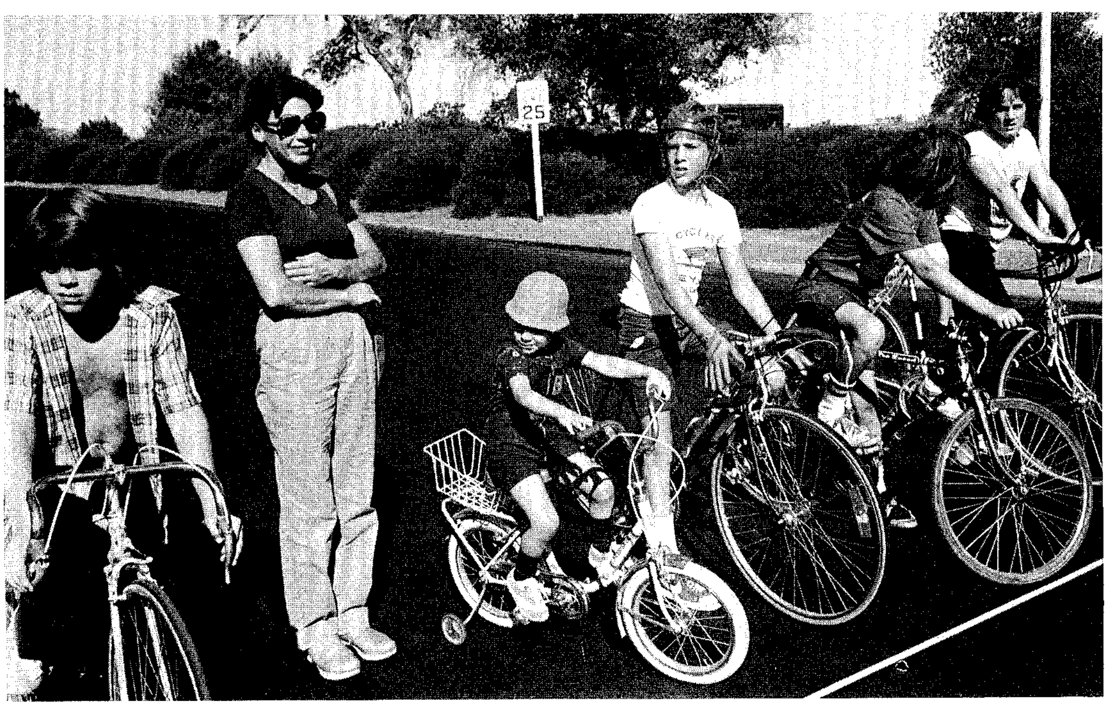
Computer Games

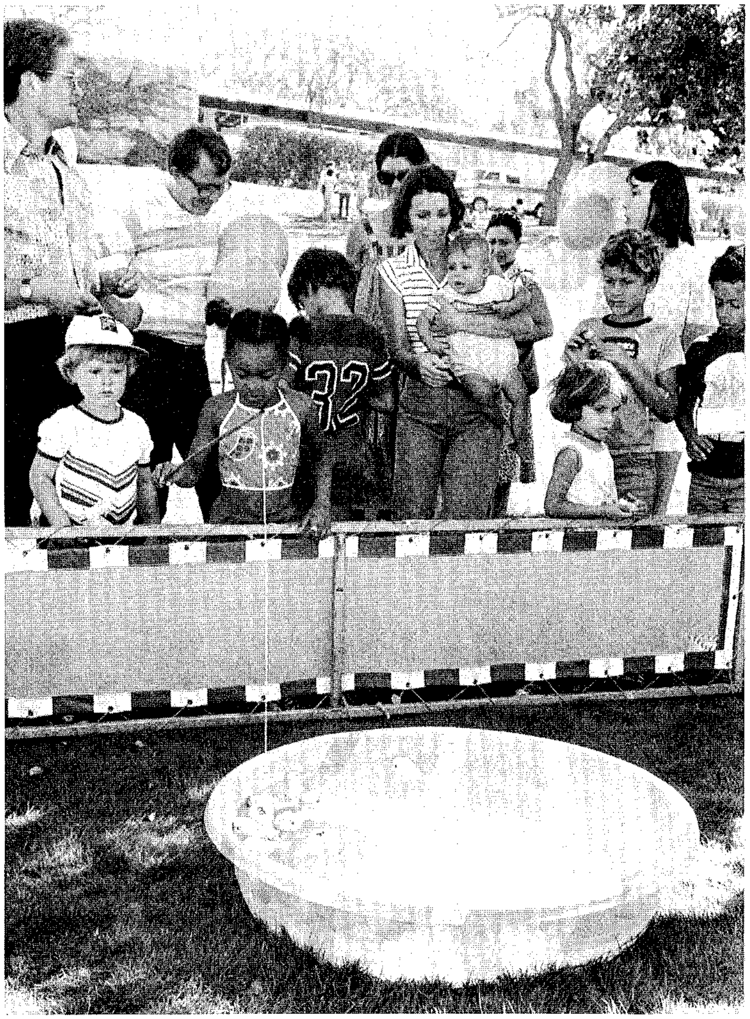


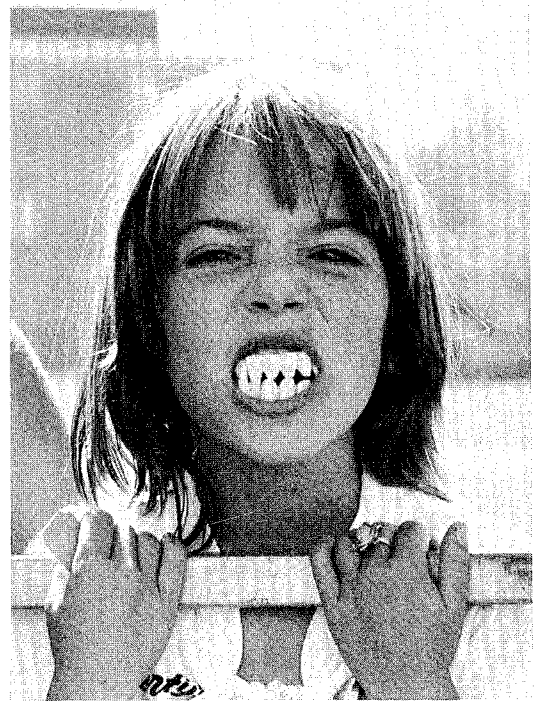


Races

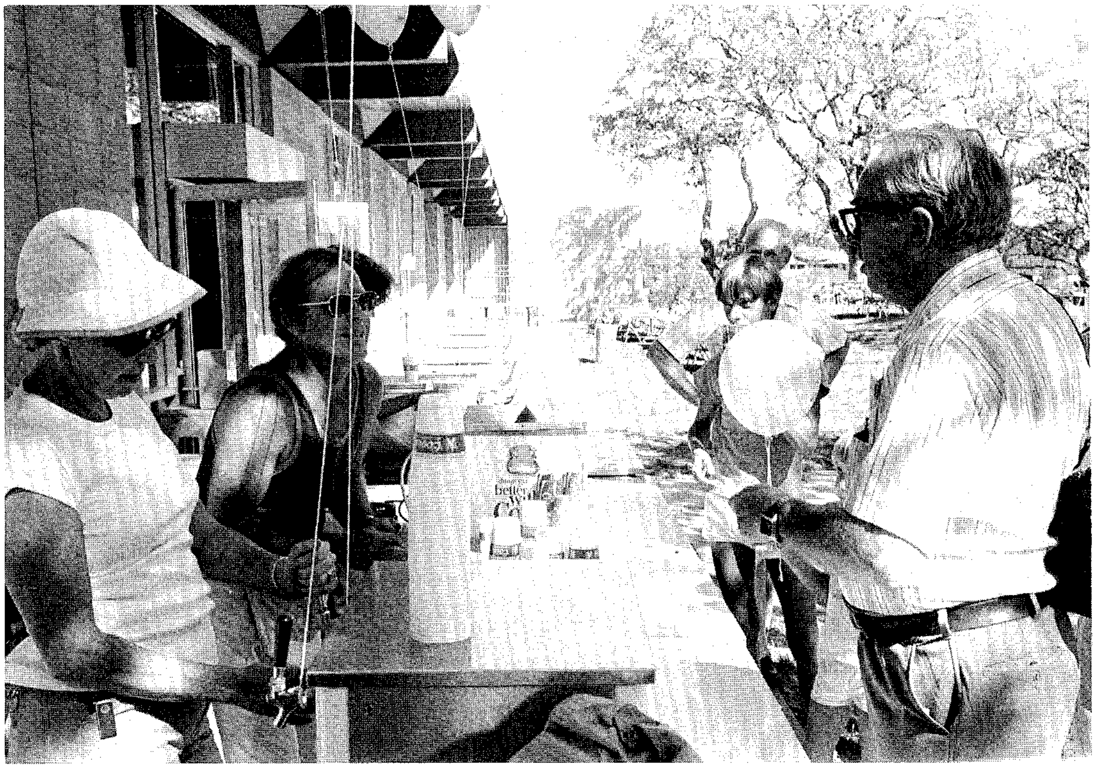




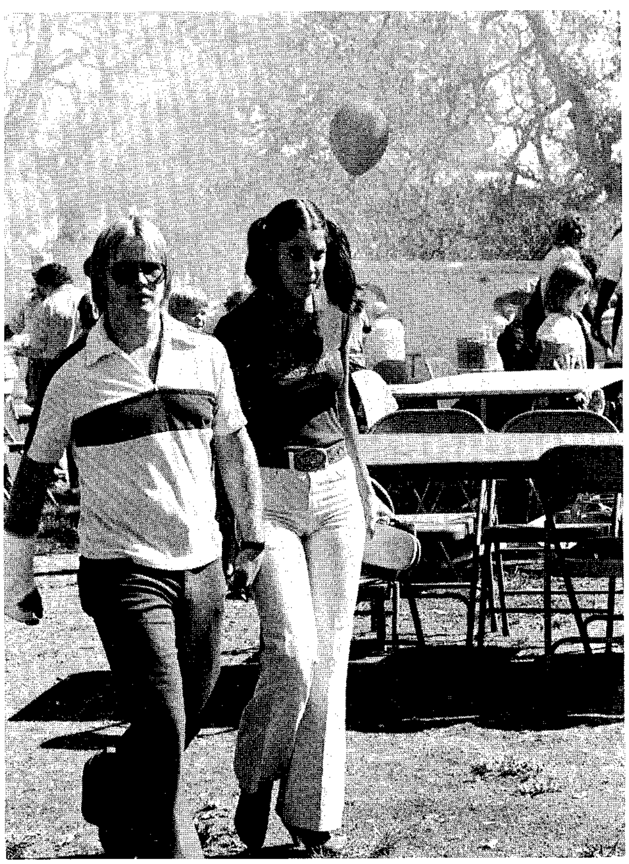




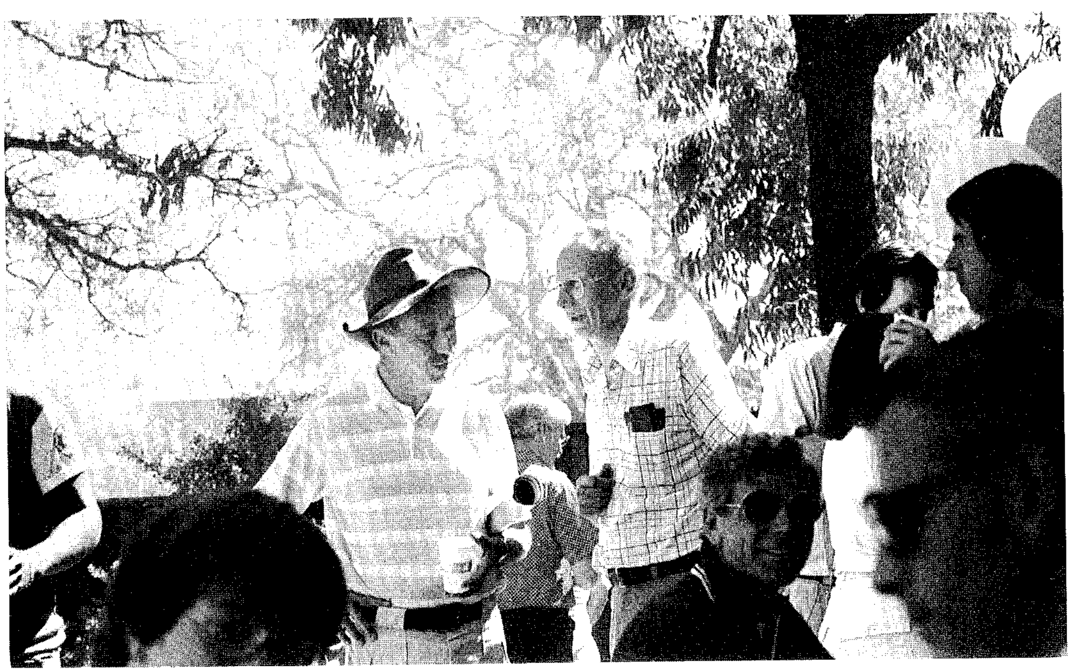
Kids

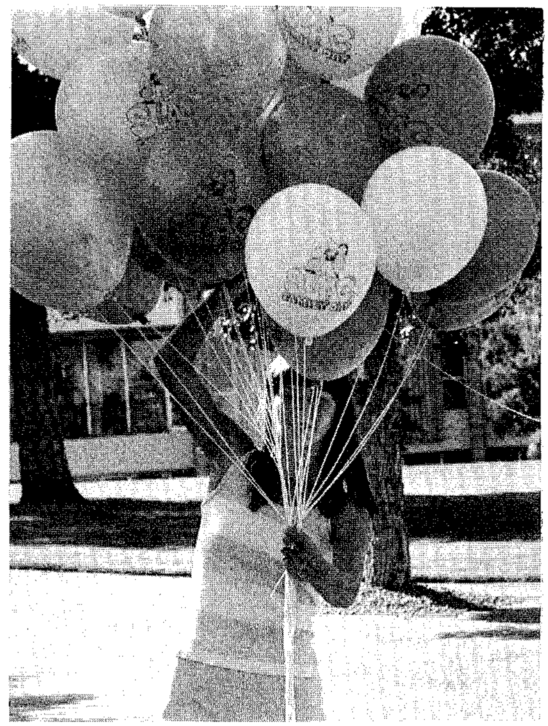


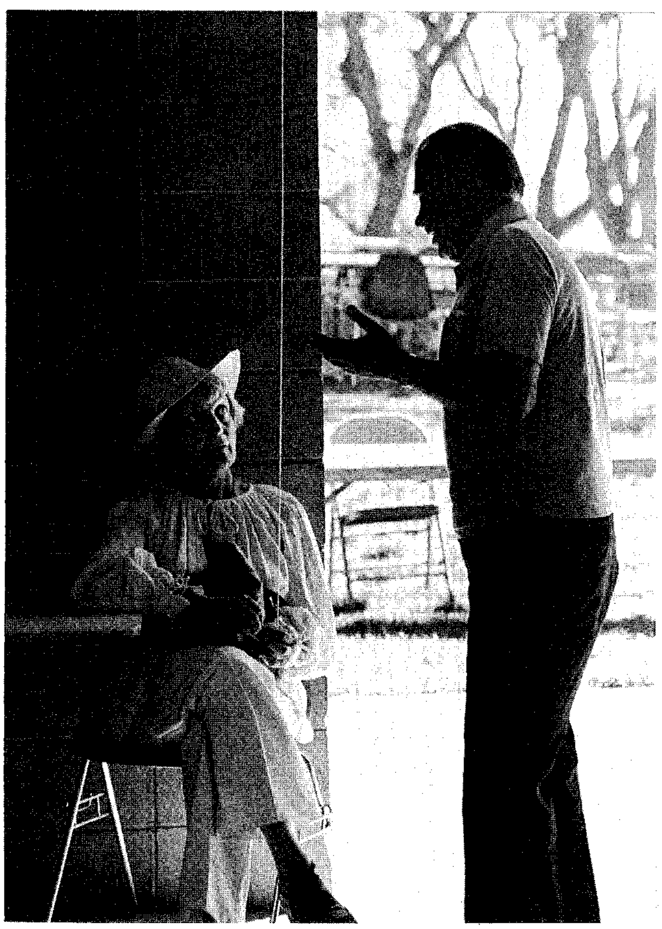
Scarf City



Still Cookin'







Shade

EXPANDING YOUR HORIZONS IN SCIENCE AND MATHEMATICS

A conference for 7th to 12th grade young women and interested adults in San Mateo County

Saturday, November 18, Canada College

SLAC parents of young women in Junior or Senior High School in San Mateo County may be interested in this special Conference. The goals of the Conference as described in the brochure we received are as follows:

--To increase young women's interest in mathematics and science

--To foster awareness of career opportunities for women in math- and science-related fields

--To provide students an opportunity to meet and form personal contacts with women working in traditionally male occupations

--To alleviate the isolation of young women who are interested in science and math

Conference Schedule

9:00 AM Pick up registration packets, Main Theater, Canada College

9:30 AM Welcome And Panel Discussion

Moderator: Jane Day, mathematician, College of Notre Dame

Cancer Researcher: Yolanda Scott George, Lawrence Livermore Laboratory

Mechanical Engineer: Zella Jackson, IBM

Manager: Carolyn Morris, Hewlett-Packard

Doctor: Judith Urrea, O'Connor Hospital

10:30 AM Refreshments

10:45 AM Question Period

11:30 AM Lunch

12:30-1:45 PM First workshop session

2:00-3:15 PM Second workshop session

3:30-4:00 PM Closing and evaluation

Workshop Sessions

The afternoon workshop sessions will be divided into three parts: (1) those for students in the 7th to 9th grades; (2) those for students in the 10th to 12th grades; (3) those for adults. Within each of the two workshop sessions, there is a wide choice of specific sessions to be chosen from either the category of "hands-on workshops" or that of "career discussions."

Within each of the two workshop sessions for the students, there is a wide selection of specific topics to be chosen from either the category of "hands-on workshops" or "career discussions." The adults also have a wide choice of topics available for their worshop sessions.

Registration

Registration ends on November 10. The first 500 applicants will be accepted. There will be no registration at the Conference.

A copy of the brochure describing the Conference will be posted on the bulletin board outside the SLAC Library (second floor of the Central Lab). This brochure contains a registration form that can be Xeroxed. The brochure also describes how to obtain additional information about the Conference, details of the workshop sessions, etc.

John Conduitt, a personal friend of Newton, tells the following: Mr. Molyneux related to us that after he and Mr. Graham and Dr. Bradley had put up a perpendicular telescope at Kew, to find out the parallax of the fixed stars, they found a certain nutation of the Earth which they could not account for, and which Molyneux told me he thought destroyed entirely the Newtonian system; and therefore he was under the greatest difficulty how to break it to Sir Isaac. And when he did break it by degrees, in the softest manner, all Sir Isaac said in answer was, when he had told him his opinion, "It may be so, there is no arguing against facts and experiments," so cold was he to all sense of fame at a time when a man has formed his last understanding.

--D. Bentley
Memoirs of Sir Isaac Newton

FAMILY DAY RACE & RAFFLE WINNERS

4-Mile Foot Race:	Alan Homna	23:41
8-Mile Bike Race:	Dave Coward	24:31
100-Yard Dash:	Larry Abbott	untimed
1.6-Mile Bike Race: (12 years & under)	Andrew Coward	5:37

Raffle Winners

Alice McLerran	Merrill Card
Vern Smith	Robert Smith
Esther Wojcicki	Celeste Gresenti
Anna Laura Berg	Rhonda Roberts
Bill Neill	Kim Young
Al Hillegass	Roy Miller
Herman Winick	Ronald J. Johnson
W. J. Tsiack	Rich Pera
Tom Hostetler	Terry & Marilyn Ehinger

The earth-moving necessary to form the tunnel for the PEP storage ring is now essentially complete. Next month's *Beam Line* will contain a description of this work, along with more of Joe Faust's photographs of the subject.

SLAC Beam Line
Stanford Linear Accelerator Center
Stanford University
Stanford, CA 94305

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Herb Weidner, Bin 20, x2521 *Associate Editor*
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Beam Line	1-*22*	8-*4*	14-*2*	24-*20*	40-*121*	53-*43*	62-*42*	68-*8*	74-*7*	82-*9*	88-*20*	95-*40*
Distribution	2-*6*	9-*3*	15-*4*	25-*2*	45-*12*	55-*39*	63-*18*	69-*44*	75-*3*	83-*6*	89-*13*	96-*22*
at SLAC	3-*7*	10-*2*	20-*65*	26-*24*	48-*8*	56-*10*	64-*14*	70-*2*	78-*34*	84-*8*	90-*4*	97-*85*
Total: 1592	4-*17*	11-*18*	21-*4*	30-*47*	50-*21*	57-*11*	65-*30*	71-*25*	79-*83*	85-*23*	91-*3*	98-*29*
	6-*19*	12-*113*	22-*17*	33-*23*	51-*54*	60-*20*	66-*11*	72-*3*	80-*9*	86-*6*	92-*2*	

SLAC Beam Line Report No. 8 October 1978
Stanford Linear Accelerator Center, P.O.Box 4349, Stanford, Calif. 94305

PARITY VIOLATION IN POLARIZED ELECTRON SCATTERING

I. A Brief Summary

In recent months, a group of physicists from five different institutions has carried out a very difficult and important experiment at SLAC. In this experiment (E-122), polarized electrons from the accelerator were directed against a target of liquid deuterium (heavy hydrogen) or of liquid hydrogen, and those electrons that were deflected or "scattered" through an angle of 4^{o} were recorded in a particle-detection system. The electron beam was polarized in either of two ways: "left-handed" or "right-handed." One of chief motivations for the experiment was to test a theoretical prediction that the scattering of left-handed electrons would occur with a slightly greater probability than the scattering of right-handed electrons.

The predicted asymmetry between left and right was very small, about 1 part in 10,000, and to achieve a clear-cut measurement of so small a difference required both the accumulation of a large sample of scattering events (more than 10^{11}) and exceptional control of the experimental conditions. The main factors contributing to the success of the experiment were these:

1. A new polarized electron source, PEGGY II, which produced beam intensities comparable to those from a conventional SLAC electron gun.

2. The use of a detection system that measured the "flux" of scattered electrons, rather than counting individual events.

3. A beam-monitoring and feedback system that provided precise measurement and control of the beam energy, position at the target, and scattering angle.

4. The use of several independent methods for reversing the beam polarization.

The physics results obtained in Experiment E-122 can be summarized in the following way:

(a) The scattering of left-handed electrons did in fact occur with a greater probability than that of right-handed electrons. Since this asymmetry between left and right is inconsistent with the physics principle known as the "conservation of parity," the most direct statement of the experimental result is this: *Parity is not conserved in the scattering of polarized electrons from deuterium or hydrogen.*

(b) More generally, all previous examples of parity-violation have involved the so-called "charged-current" interactions, in which a unit of electric charge is transferred between the two interacting particles. No charge is transferred in the scattering processes observed in E-122, which thus provided *the first example of parity-violation in a "neutral-current" interaction.*

(c) The measured asymmetry is very close to the level of 1 part in 10,000 predicted by the earliest and simplest of the theories (the "Weinberg-Salam model") which postulate that two of the basic forces in nature, electromagnetism and the weak force, are actually just different manifestations of a single "unified" force. E-122's results support this model, but contradict many of the alternative models recently proposed.

Contents

II. Background Information

In the next 3 pages we review some physics information that may be helpful in trying to understand the recent experiment at SLAC. The topics are these:

A. Particles and forces
B. A picture of particle interactions
C. Electron polarization
D. The violation of parity

Those who already have some familiarity with these matters may find it profitable to skip directly ahead to Section III on page 5.

A. PARTICLES AND FORCES

We begin by dividing up the world into two families of particles and four kinds of forces:

Particles

Hadrons	*Leptons*
proton + many others	electron + a few others

Forces

Gravity
Electromagnetism
Strong Force
Weak Force

In what follows, we try to deal with the particles more briefly than usual, giving most of our attention to the forces.

1. The Hadrons

The hadron family consists of all those particles that are affected by the *strong* or nuclear force, while the lepton family consists of the particles that are *not* so affected. The hadron family includes the familiar proton and neutron, which together form the nuclei of atoms, and it also includes several hundred other members in various classes (mesons, baryons) and subclasses. During the last 10 or so years, a great deal of circumstantial but persuasive evidence has seemed to show that the hadrons are not in themselves "elementary" particles, but are rather composite structures built up from simpler objects called *quarks*. Although the idea of quarks will not concern us until we near the end of this article, we note here that present evidence appears to require 6 kinds of (oddly named) quarks as the "building blocks" of the hadron family:

6 QUARKS

up	*strange*	*top*
down	*charmed*	*bottom*

(*+ 6 anti-quarks*)

2. The Leptons

In contrast to the hadrons, the leptons appear to be as simple as particles can get, and thus to be truly elementary particles. The leptons form a very exclusive club, whose three electrically charged members are the electron (discovered in 1897), the muon (1936), and the tau (1975-77 at SPEAR). The electron and muon each has associated with it its own distinctive neutral partner, a neutrino, and the tau probably does also. So the leptons presently form a sextet similar to that of the quarks:

6 LEPTONS

electron	muon	tau
electron neutrino	muon neutrino	tau neutrino

(+ 6 anti-leptons)

Thus a half-dozen each of quarks and leptons is the present elementary Cast of Characters in particle physics. In the following discussion of forces, however, we'll temporarily set aside the idea of quarks (which have never been seen) and return to the observed hadrons.

3. The Fundamental Forces

The chart at the bottom of this column summarizes the more important characteristics of the four known basic forces in nature. We want to expand upon this chart by adding a little more information about each of the forces.

Gravity. Although the behavior of matter in large-sized lumps (planets, Frisbees) is dominated by the gravitational force, its intrinsic strength is so much less than that of the other three forces that its effects in the small-scale world of the particles are totally ignored. Some theorists speculate about an eventual unification of gravity with the other forces, but for the moment at least, such a prospect seems remote.

Electromagnetism. The electromagnetic force acts between particles that are electrically charged, whether they are leptons or hadrons. As an example of electromagnetism, the size and structure of atoms (and thus of almost everything) is determined by the force of attraction between the positively charged central nuclei

FORCE →	*GRAVITY*	*ELECTRO-MAGNETISM*	*STRONG*	*WEAK*
Range	Infinite	Infinite	$\simeq 10^{-13}$ cm	$<10^{-15}$ cm
Relative Strength	10^{-37}	1	100	$\simeq 10^{-4}$
Particles acted upon	All	All charged	Hadrons	Hadrons Leptons
"Carrier" of force	Gravitons	Photons	Hadrons	Vector Bosons?
Example	Planetary orbits	Atomic forces	Nuclear forces	Radio-activity

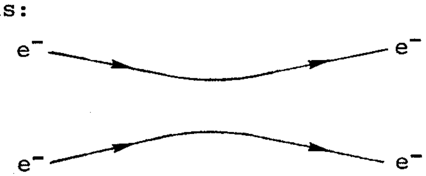
and the surrounding clouds of negatively charged electrons. The theory of electromagnetism as it applies to the elementary particles has been given the jaw-breaking name *quantum electrodynamics*, or QED for short. This theory is by any criterion the most successful in all of physics. The validity of QED has been verified over a range of distance extending from several earth radii down to about 10^{-15} cm. Because of its success (the agreement between theory and experiment often extends out to 6 or 8 decimal places), QED has often been used as a model in attempts to understand the other fundamental forces.

The Strong Force. As we've already noted, the particles upon which the strong force acts are defined as the hadrons ("hadr-" is a Greek form for "strong"). The range over which the strong force is effective is only about 10^{-13} cm, which is roughly the size of a single hadron. But within this range its intrinsic strength is about 100 times greater than that of electromagnetism. Until quite recently, the strong force was commonly described as "poorly understood," even after some 40 years of intensive study. However, during the last several years experiment and theory have conspired to create a certain optimism that a start has finally been made toward understanding this force.

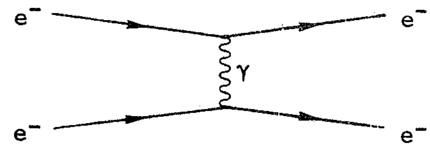
The Weak Force. Unlike the others, the weak force does not seem to hold anything together. Instead, its effects are most evident in the "fall apart" processes of radioactive decay. The weak force acts upon *all* hadrons and *all* leptons and it is thus a more universal force than either electromagnetism or the strong force. (Gravity acts upon everything, even light.) The most peculiar aspect of the weak force is its "range" of less than 10^{-15} cm, less than 1/100 the size of a proton. If the weak force is "carried" through this incredibly small distance by the hypothetical particles that have been named *intermediate vector bosons*, then the range dictates that these bosons must be much more massive than any particle yet discovered. Although these properties of the weak force appear to be as different as can be imagined from the infinite range and massless carrier (the photon) of electromagnetism, there is nevertheless a growing body of evidence that supports the idea of a deep connection between the weak and electromagnetic interactions.

B. A PICTURE OF PARTICLE INTERACTIONS

A classical picture of the interaction between two electrons (e^-) would look something like this:



This process might be described as "mutual repulsion caused by the electric fields of the two negatively charged particles." In the modern, quantum description, the role of the field in the interaction is made explicit:



In this picture, the repulsive force between the two particles is carried or "mediated" by a quantum of the electromagnetic field, a photon (γ), which is said to be "exchanged" between the particles. The experimental evidence makes it reasonably clear that this is what actually happens in electromagnetic interactions. But then the question arises: Do *all* particle interactions happen in this way? That is, are the weak, strong and gravitational interactions also mediated by field quanta (force-carrying particles)?

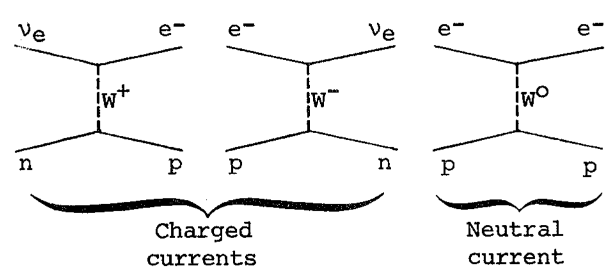
Physicists generally assume that the answer to this question is "Yes," although each of the other three forces presents some difficulties that we won't describe here. In the case of the weak interactions, it will turn out to be useful for us simply to adopt the force-carrier picture as though it were correct (it may be), and then to see where that leads us. We assume that the quanta of the weak force are the intermediate vector bosons mentioned earlier, and that there are three such particles:

$$W^+ \qquad W^o \qquad W^-$$

(The neutral boson is usually called Z^o rather than W^o, but we use the latter here for simplicity.) Now we remind ourselves of the symbols that are used for four familiar particles:

electron = e^-	proton = p
electron neutrino = ν_e	neutron = n

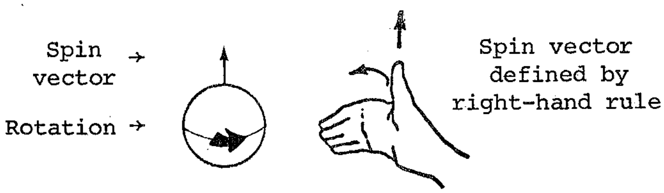
Then the following sketch shows three possible weak interactions in which the W bosons carry the force between pairs of interacting particles:



Events in which either a W^+ or a W^- boson is exchanged are called "charged-current" interactions, because in both cases one unit of electrical charge passes between the two interacting particles. In contrast, the exchange of a W^0 boson is an example of a "neutral-current" interaction.

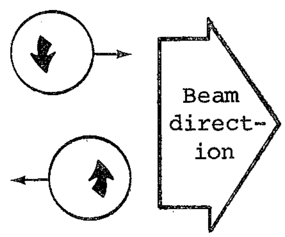
C. ELECTRON POLARIZATION

Electrons share with many other kinds of particles the intrinsic property called "spin," which we can think of as the rotation of the particle about some axis. This spin (or angular momentum) is a "vector" quantity, which means that it is characterized by both a magnitude and a direction. The magnitude need not concern us here, but the direction is important. According to the *arbitrary* convention that has been adopted, the particle's "spin vector" or "spin direction" is taken to be along its axis of rotation and is determined by the so-called "right-hand rule" shown in the next sketch:

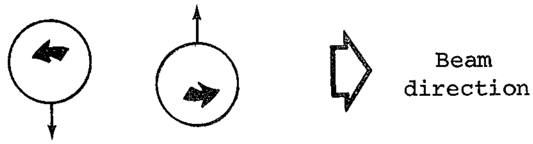


Now we suppose that we have a beam of electrons traveling in a certain direction, and that the electrons in this beam are oriented in either of two different ways:

1. Spin vector same as beam direction: *RIGHT-HANDED LONGITUDINAL POLARIZATION*
2. Spin vector opposite to beam direction: *LEFT-HANDED LONGITUDINAL POLARIZATION*



Our main interest here will be in these two states of longitudinal polarization, right- and left-handed, because it is the scattering of these two states from a target that was studied in Experiment E-122. However, there is also a certain probability that the beam electrons will have their spin vectors oriented at 90° with respect to the beam direction:



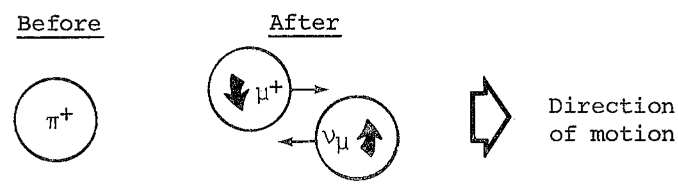
This is called *transverse polarization*, and we shall come later to an important test that was made during the running of E-122 in which the electron beam was transversely polarized.

Finally, when an electron beam consists of a mixture of equal numbers of electrons in each of the various polarization states, then the polarization effects cancel out, and the beam is said simply to be *unpolarized*. Unpolarized beams also have a role to play in E-122.

D. THE VIOLATION OF PARITY

In the preceding section we saw that the distinction between RH and LH polarization was based on the use of an arbitrary convention, the "right-hand rule," which connects the direction of a particle's spin vector with the actual physical rotation of the particle. It seems evident that nature will be indifferent to such ideas of right- and left-handedness, and this presumed indifference is one aspect of the important physical principle called the "conservation of parity."

But this presumed indifference turns out to wrong. In the case of the weak interactions (but not the electromagnetic or strong), nature makes an absolute distinction between right- and left-handedness. One simple example of this "violation of parity" is the weak-interaction process by which a positive pion (π^+) decays into a positive muon (μ^+) and a muon neutrino (ν_μ). We imagine the pion, whose spin is zero, to be moving at high speed from left to right, so that after the decay the muon and neutrino will also be moving in approximately the same direction:



Since the total spin of the muon and neutrino must add up to zero, these two particles must have opposite polarizations. In the sketch the muon's polarization is right-handed, while that of the neutrino is left-handed. There is nothing in the laws of quantum physics that prevents the polarizations from being reversed: LH muon and RH neutrino, *but this is never observed*. Muons can appear with either LH or RH polarization in various circumstances, *but neutrinos are always polarized left-handed*. Stated differently, there is no such thing as a right-handed neutrino, and thus processes in which neutrinos appear always violate parity.

Parity-violation has also been observed in weak-force processes that do not involve neutrinos, but only in the charged-current weak interactions that we described on the previous page. In view of the identification of parity-violation with the weak interactions, it is not surprising that the neutral-current weak interactions also violate parity, but Experiment E-122 has provided the first clear evidence to substantiate this.

III. The Experiment

Experiment E-122 was carried out at SLAC during several months in the spring of this year. The experimental group consisted of 20 physicists from five different institutions; these are shown in the box below. The experiment was technically complex, and in this section we try to describe the apparatus and the design of the experiment in enough detail to get a sense of the complexity.

A. GENERAL REQUIREMENTS

Experiment E-122 at SLAC set out to look for an asymmetry in the scattering of longitudinally polarized electrons from a deuterium (or hydrogen) target. More specifically, the quantities to be measured in the experiment were these:

P_{RH} = the probability (or "cross section") of scattering for electrons with right-handed polarization.

P_{LH} = the probability of scattering for electrons with left-handed polarization.

The comparison between these two measured probabilities was to be expressed in terms of an asymmetry, A, which was defined as

$$A = \frac{P_{RH} - P_{LH}}{P_{RH} + P_{LH}}$$

For a number of years it has been quite evident that a measurement of this possible asymmetry would have a great deal of physics interest, and in fact several earlier experiments, at SLAC and elsewhere, had made an effort to measure it. But this earlier work had yielded the result that $A = 0$ (no asymmetry), as far as could be determined. The key phrase here is "as far as could be determined." A somewhat less formal rephrasing might be something like, "Man, this is a hard way to make a living. We'll *never* find the damn thing." But the experimenters in E-122 finally *did* find it, and to do so they had to solve some hairy problems that we now want to look at briefly.

1. Statistics

In earlier electron-scattering experiments at SLAC, the maximum rate at which scattering events could be recorded was one event during each 1.5-microsecond-long beam pulse from the accelerator. If the accelerator produced 120 pulses/second and ran 24 hours/day, then the daily event accumulation was about

$$120 \times 60 \times 60 \times 24 \simeq 10^7 \text{ events/day}$$

But before we decide than 10 million is a big number, let's see how many events E-122 needed to collect.

The experimental design of E-122 was based partly of the theoretical prediction that an asymmetry might show up at a level of about $A = 10^{-4}$, or one part in 10,000. This means that any errors or statistical uncertainties in the data would have to be held down to about 10^{-5} or less to produce a convincing result. To reduce the statistical uncertainty to that level requires that the total sample of scattering events be more than 10^{10}. As a practical matter, various tests have to be made, and not all the data is sufficiently clean to be useful, so the actual total in E-122 was more than 10^{11}.

Rounding off at 10^{11} events, the time required to run E-122 with conventional experimental techniques would have been:

$$\frac{10^{11}}{10^7} = 10^4 \text{ days} \simeq 27 \text{ years}$$

of flat-out accelerator running. This is a great leap forward toward job security, but difficult to sell as a piece of physics.

The solution to this 27-year problem is the obvious one of doing things faster. That is, instead of collecting 1 scattering event during each accelerator beam pulse, figure out a way to collect about 1000 events/pulse. To achieve such a speed-up, the E-122 experimenters had to develop two important new techniques:

1. A source that could produce polarized electrons some hundreds of times more copiously than had been previously achieved.

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING*

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ABSTRACT

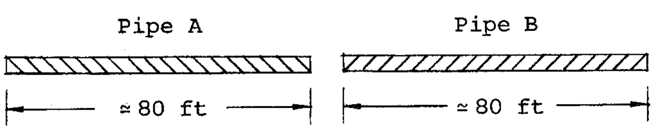
We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6$ (GeV/c)^2 the asymmetry is $(-9.5 \times 10^{-5})\ Q^2$ with statistical and systematic uncertainties each about 10%.

(Submitted to Phys. Lett.)

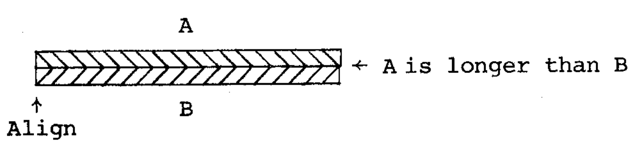
2. A particle-detection system that could handle about 1000 events/pulse not by the standard technique of counting each one individually, but rather by measuring the integrated *flux* of scattered electrons during each beam pulse.

2. Experimental Errors

Both of these new techniques added to the already formidible problem of holding down the possible measurement errors to a very small level. We'll describe the monitoring and control of possible error sources in some detail later in this section. For the moment we want to make only the following remarks. E-122 would have faced an impossible task if it had set out to measure the *absolute* cross sections or probabilities for the scattering of RH and LH polarized electrons. To use an analogy, suppose that we have two pieces of steel pipe, Pipe A and Pipe B. Each of the pipes is approximately 80 feet long, but one of them is 1/8 of an inch longer than the other. The problem is to decide which pipe is the longer:



It is probably obvious that measuring each pipe separately with two different yardsticks, or even one very accurate yardstick, is not likely to provide a convincing answer. The two-measurement approach might work out with some sort of very fancy laser-ranging system, but there is an easier way, namely, to lay the two pipes side-by-side on a flat surface, align them at one end, and then look at the other end to see which pipe sticks out:



In an analagous way, the goal in Experiment E-122 was not to measure the absolute sizes of anything (scattering probabilities) but rather the *difference* between two things of almost equal size. So to the extent possible, the experiment was designed to "lay the two pipes side-by-side" in order to make an immediate and direct comparison.

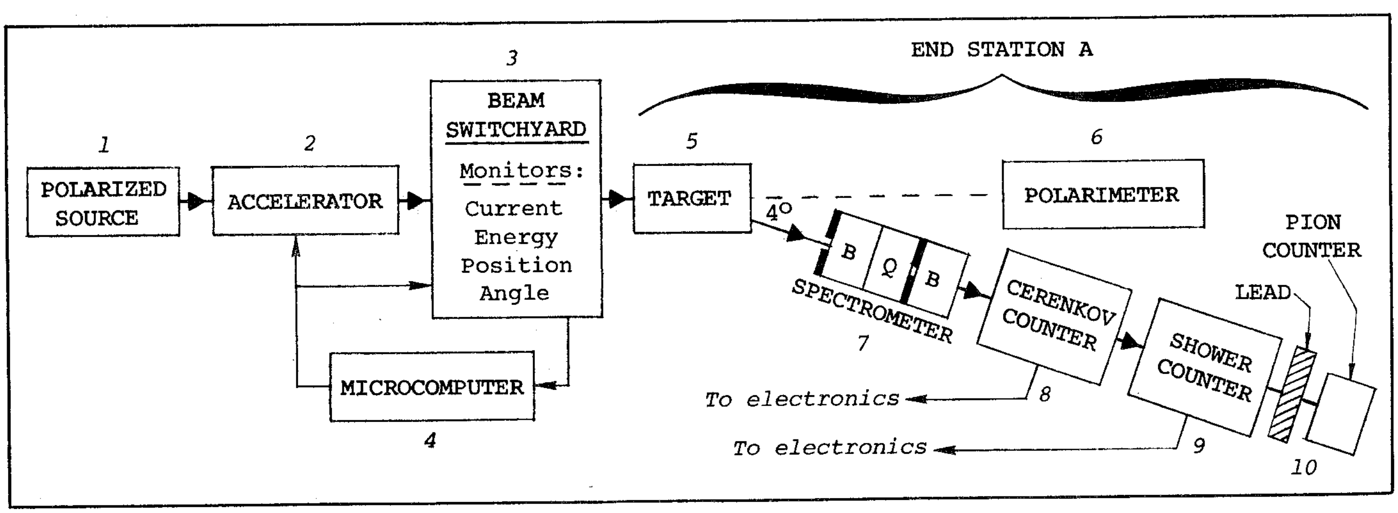
B. LAYOUT OF THE EXPERIMENT

The drawing at the bottom of this page is a schematic layout of E-122. Each of the main elements in the experiment is identified by an italic number *(1-10)*, and we want to begin here by describing each of these elements briefly. After that we'll look in a little more detail at the polarized electron source *(1)*, the particle-detection system *(7-10)*, and the beam-monitoring and control system *(2-4)*.

1. The *polarized source* is designed to inject into the accelerator a beam of electrons that is polarized in either a RH or LH sense. The source is pulsed at the same rate as the accelerator, 120 pps, and the choice between RH and LH polarization is determined randomly for each pulse. The source can also be adjusted to provide unpolarized electrons for certain cross-checking tests.

2. After injection into the SLAC *accelerator*, the beams are accelerated to one of several different energies between 16.2 and 22.2 GeV. Earlier tests had established the fact that the acceleration process has a negligible effect on the initial polarization of the beam electrons.

3-4. In the *beam switchyard,* the high-energy beam is deflected through an angle of $24\frac{1}{2}^{\circ}$ (not shown in the figure). Beam monitors of several kinds measure the energy, current, position and angle of the beam and feed this information into a *microcomputer*. This computer then sends out control signals to beam-steering coils and to the accelerator klystrons in order to make small corrections in beam energy, position and angle.



5. The beam passes from the switchyard into End Station A, where it strikes a 30-cm-long *target* which contains liquid deuterium. (Some data were also taken with liquid hydrogen.) The nucleus of the deuterium atom consists of one proton combined with one neutron in a composite particle called the "deuteron" (d). When a beam electron collides with a deuteron in the target, either of two general kinds of interactions can occur: (1) elastic scattering, in which the deuteron simply recoils from the collision like a billiard ball; or (2) inelastic scattering, in which the deuteron is broken up, or new particles are created, or both:

$$\text{elastic:}\quad e^- + d \rightarrow e^- + d$$

$$\text{inelastic:}\quad \begin{cases} e^- + d \rightarrow e^- + p + n \\ e^- + d \rightarrow e^- + d + \pi^+ + \pi^- \\ e^- + d \rightarrow e^- + p + n + \pi^0 \\ e^- + d \rightarrow e^- + (\text{anything else}) \end{cases}$$

The experimental conditions chosen for E-122 were such that the great majority of the detected electrons came from inelastic scattering processes. Since none of the other kinds of particles was detected by the apparatus, the general reaction that was studied was the sum of the 3 inelastic interactions listed above plus those implied by the "anything else" of the 4th such interaction.

6. From time to time during the experiment the sign and magnitude of the beam's polarization are measured in a device called a *polarimeter*. This is accomplished by observing the elastic scattering of beam electrons from the atomic electrons in a magnetized iron foil (a process called Møller scattering). The polarization varied somewhat but averaged about 37% during the course of the experiment.

7. The first element in the particle-detection system is the *spectrometer*, which consists of two bending (B) or dipole magnets and one quadrupole (Q) magnet. The spectrometer is positioned with its axis at an angle of 4° with respect to the primary beam direction, and it is designed to "accept" (pass through) scattered electrons whose momentum is between about 65% and 95% of that of the primary electron beam. On the average, each beam pulse from the accelerator brings to the target somewhat more than 10^{11} electrons, and of these the spectrometer will typically accept, momentum-analyze and pass through about 1000 electrons that have scattered from the target deuterons.

8-9. The scattered electrons exit from the spectrometer and pass through the *Cerenkov counter*, then enter the *shower counter*. In both of these detection devices, the electrons cause an amount of light to be emitted (by different processes) that is proportional to the number of incident electrons. This light is collected separately in each counter by phototubes, whose output is a flow of electrical current that is also proportional to the amount of light collected. The Cerenkov and shower counters thus provide two separate measurements of the *flux* of scattered electrons which traversed the spectrometer.

10. Some particles other than scattered electrons are expected to pass through the particle-detection system, in particular the pions (π) that are the most easily created of the strongly interacting hadrons. In order to measure how much "contamination" these unwanted particles produce in the flux of scattered electrons, the shower counter is followed by a block of *lead* that is sufficiently thick to stop all of the electrons, and then by a *pion counter* which detects any electrically charged particles that have succeeded in penetrating through the lead (or in creating new particles there). For the two highest beam energies used in the experiment, 19.4 and 22.2 GeV, the total contamination of unwanted particles was about 2% of the scattered electron flux.

C. THE POLARIZED ELECTRON SOURCE

Work on the development of a source of polarized electrons for use with the SLAC accelerator extends back to about 1971. The first such source, called PEGGY I, was developed as a collaborative effort between the Yale University physics group led by Vernon Hughes and several members of the SLAC staff. This source was used in earlier experiments E-80 and E-95.

The new source used in E-122, called PEGGY II, was developed largely through the efforts of Ed Garwin, Roger Miller, Charles Prescott and Charles Sinclair of SLAC. Its chief advantages over the original source are that it can deliver a polarized beam intensity that is several hundred times greater and is in fact comparable to the intensity of a conventional SLAC electron gun; and also that the polarization of the beam can be reversed by purely optical means, rather than through the reversal of a magnetic field. Both of these factors were very important to the success of E-122.

1. PEGGY II

The general structure of the PEGGY II polarized electron source is somewhat similar to that of a conventional electron gun. The main

A Columbus Story

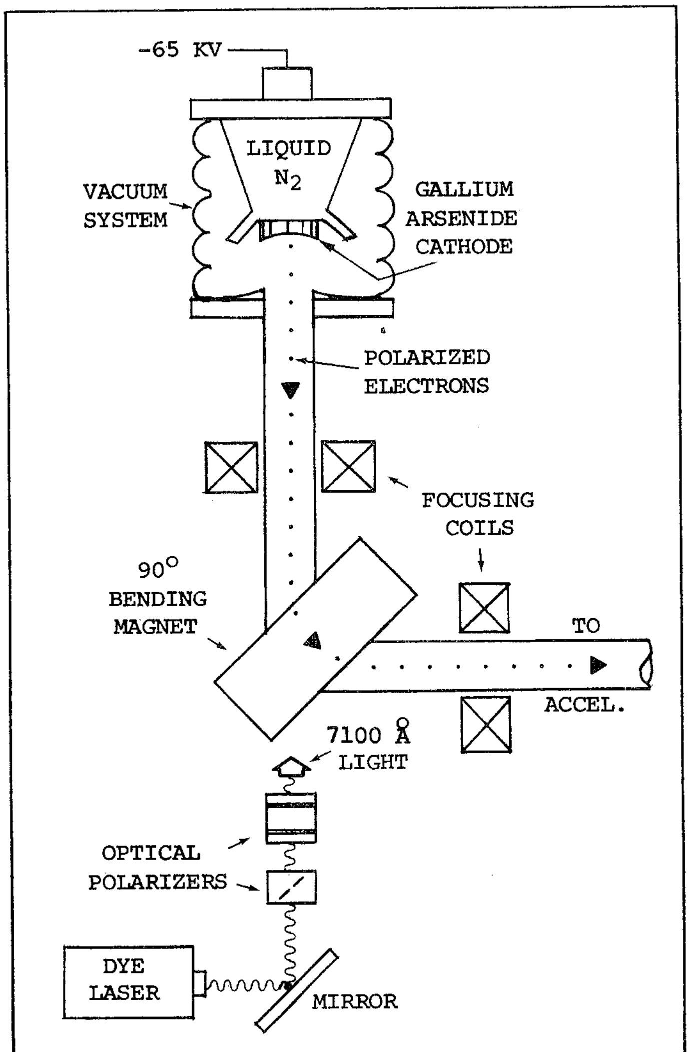
The accelerator physicists and engineers are the ones who built the boat. The experimental physicists are the ones who set sail and discovered America. The theoreticians are the ones who stayed behind in Madrid and predicted the boat would land in India.

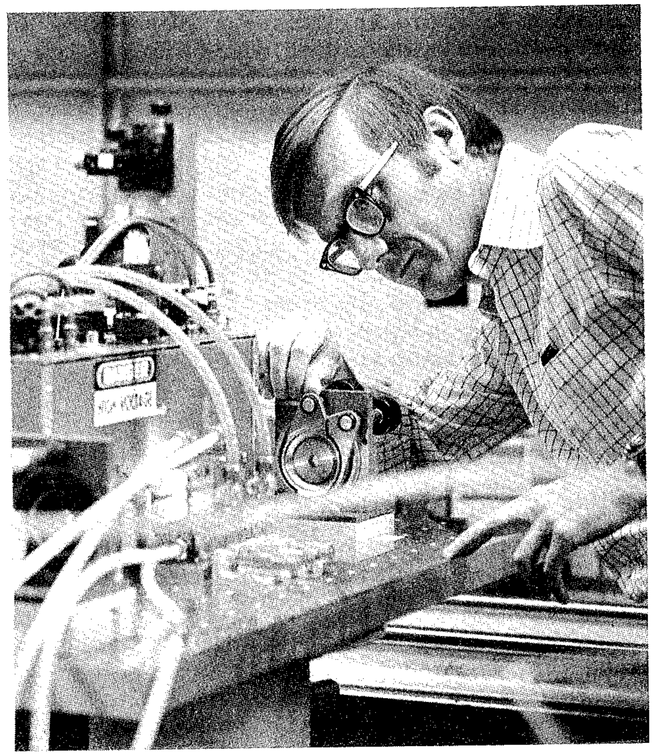
--V. Weisskopf

points of difference are indicated in the schematic drawing of PEGGY II at the bottom of this column and can be described as follows:

1. The usual thermionic cathode (heated emitting surface) is replaced with a crystal of the compound gallium arsenide (GaAs), which is maintained at the temperature of liquid nitrogen within a very good vacuum system. Very thin layers of the elements cesium and oxygen are deposited on the surface of the GaAs to make it easier for electrons to escape ("to produce negative electron affinity," is the jargon).

2. A tuneable dye laser produces intense flashes of light at a wavelength of 7100 angstroms (7100 Å, which is red light like that emitted by light-emitting diodes). The laser is pulsed in a pattern that matches that of the accelerator: 1.5-microsecond pulses repeated 120 times per second. The laser light pulses are reflected by a mirror through two different optical polarizing elements, after which they travel up to strike the GaAs cathode. These light pulses "pump" electrons out of the cathode by the photoelectric process. The photoemitted electrons



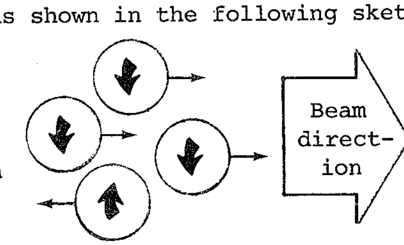


Charles Sinclair is shown here with the high-power laser used with the PEGGY II polarized electron source. (Photo by Joe Faust.)

can be polarized either left- or right-handed, or unpolarized, depending on the polarization of the incident laser light.

The electronic band structure of gallium arsenide is such that right-circularly polarized light will cause the emission of longitudinally polarized electrons in the following ratio: 3/4 RH-polarized, and 1/4 LH-polarized. (And vice-versa for left-circularly polarized light.) This mixture of 3/4 RH- and 1/4 LH-polarization results in a beam that has an overall RH-polarization of 50%, as shown in the following sketch:

3/4 RH + 1/4 LH
= 50% overall
beam polarization



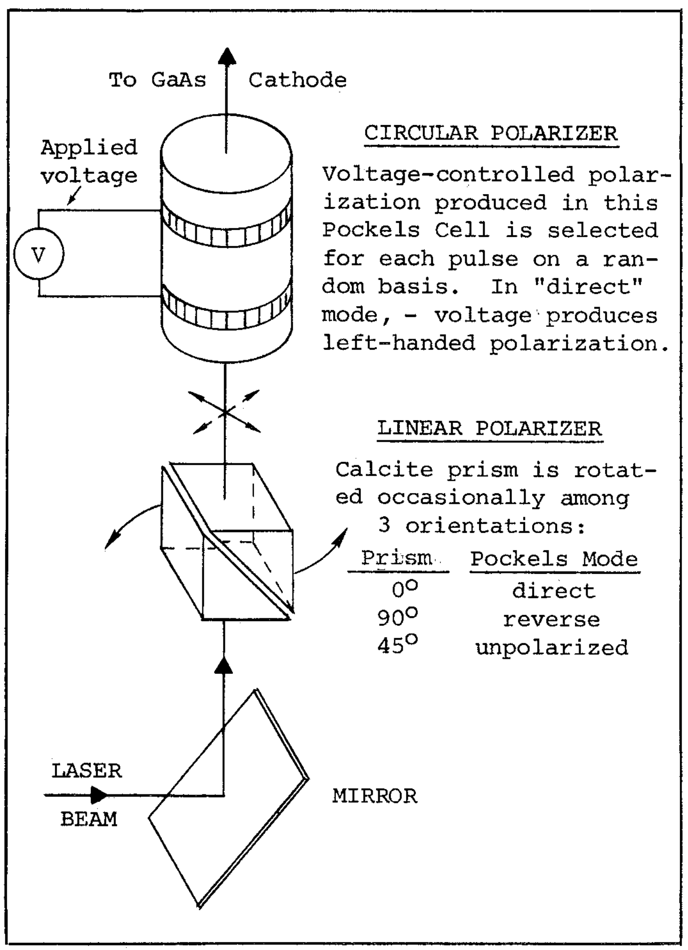
This overall 50% beam polarization is actually the theoretical maximum, and in practice it is not so easy to achieve. As we noted earlier, the average beam polarization, $|P_e|$, during the course of the experiment was 0.37 or 37%. There was enough fluctuation in the measured values of beam polarization, however, to introduce an error attributable to this cause of ±5% in the final asymmetry measurement for the experiment. This was the largest single source of systematic error in the experiment.

3. The electrons emitted from the GaAs cathode are focused by magnetic coils and deflected through a right angle by a bending magnet on their way to the accelerator. These manipulations of the low-energy (65 keV) beam do not affect its polarization in any significant way.

2. *Optical Control Of The Polarization*

As we shall soon see, it was very important in Experiment E-122 to reduce any systematic differences in the beam parameters between left- and right-handed polarized beams to an absolute minimum. With the previous PEGGY I source, polarization reversal was effected by reversing a magnetic field; this was much less satisfactory than the purely optical control of polarization that became available with the PEGGY II source. The new control system in PEGGY II also allowed the beam polarization to be selected randomly for each individual accelerator pulse, which minimized the effects of slow instrumental drifts.

The figure below shows the two optical polarizing elements in the PEGGY II source in more detail, The linearly polarized light flashes from the dye laser are reflected by a mirror through, first, a linear and then a circular polarizer in the path leading to the GaAs cathode.



Briefly, the linear polarizer is a birefringent calcite prism that is used as the "slow switch" in the system. The prism can be set to any of three different rotational positions identified as 0°, 45° and 90°. Changes from one position to another are made only occasionally (about once a day).

The circular polarizer is also a birefringent crystal called a "Pockels cell." This is the system's fast switch. The cell acts to convert linearly to circularly polarized light under the control of an applied DC voltage. Reversing the voltage reverses the polarization of the light, which in turn reverses the polarization of the photoemitted electrons. The Pockels cell is programmed to produce either RH or LH polarization for each individual beam pulse on a random basis. (The decay pattern of a small radioactive source provides the "randomness.")

The manner in which the two optical polarizers select the beam polarization is shown in the next small table:

Prism Setting	Pockels Cell Voltage	Electron Polarization
0°	+	RH
	-	LH
45°	+	0
	-	0
90°	+	LH
	-	RH

We'll postpone a discussion of the significance of these different combinations until the last part of this section.

D. THE PARTICLE-DETECTION SYSTEM

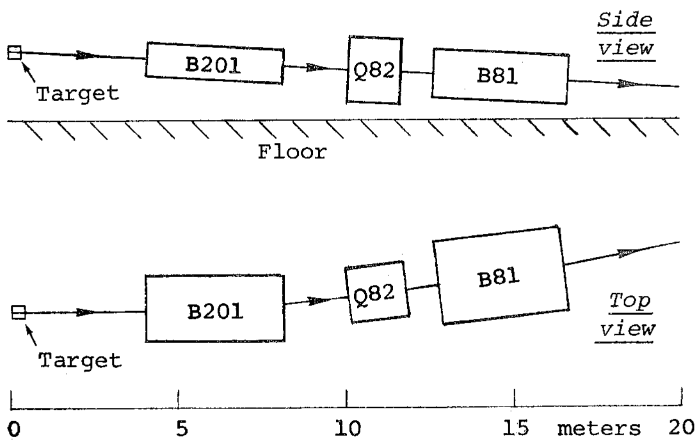
We turn now to a description of the system

Spectrometer → Cerenkov Counter → Shower Counter → Pion Counter

which was used to detect the scattered electrons.

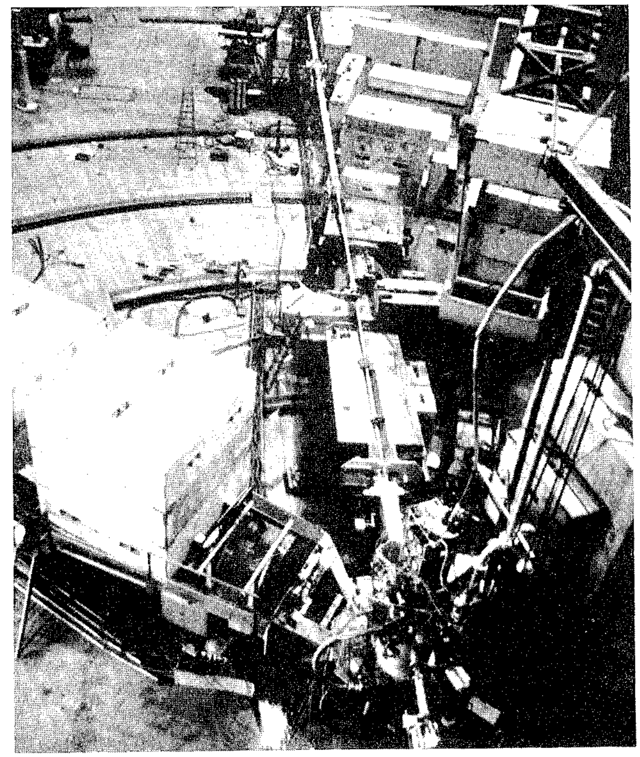
1. *Spectrometer*

Although the existing 8 and 20 GeV/c spectrometers in End Station A had been used in the earlier experiments, E-80 and E-95, the experimenters on E-122 decided to use a different system of momentum analysis for the recent work. The problem with the existing instruments was that they had not been designed to "accept" scattered particles over a broad enough range of momenta and angles to make the desired 1000 scattering events per beam pulse practical. For this reason, E-122 put together a new spectrometer with greater acceptance which consisted of three large magnets that were temporarily borrowed from the existing machines. The final arrangement was bending magnet B201 (from the 20 GeV/c spectrometer), followed by quadrupole Q82 and bending magnet B81 (from the 8 GeV/c), in roughly the following spatial configuration:



The spectrometer "looks" up at the target at an angle of 4° with respect to the primary electron beam (side view). The top view shows that the bending magnets each deflect the beam to the left. The quadrupole magnet focuses the scattered particles in the horizontal plane, but defocuses them in the vertical plane. As noted earlier, the magnet currents are adjusted so that the spectrometer will accept about a 30% spread in the momenta of the scattered electrons, with the acceptance centered at a momentum about 20% below that of the primary beam.

The photograph on this page is an (accidentally reversed) view of the E-122 particle detection system in End Station A.



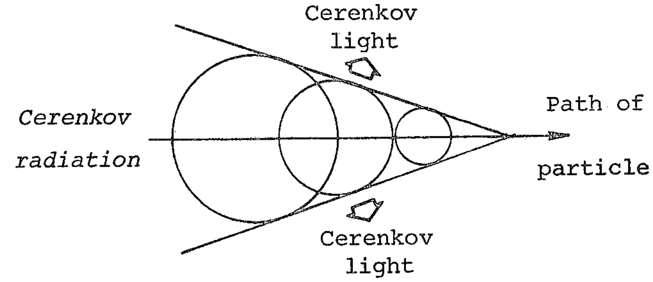
This left-right reversed photo was taken from a point above the target (foreground) in End Station A. The E-122 spectrometer curves off to the right (left) of the straight beam pipe.

2. Cerenkov Counter

This counter makes use of an interesting physical effect that was discovered by the Russian physicist Pavel Cerenkov in 1934. To begin with, one of the well-known consequences of Einstein's Theory of Relativity is the fact that no material object can travel faster than the speed of light. But this principle applies to the speed of light *in vacuum*, which is the ultimate speed limit. When light propagates through other media (say water or glass or the earth's atmosphere), its speed is reduced by an amount that depends on the index of refraction of the particular medium. In the case of water, for example, the index of refraction is about 1.33, which means that the speed of light in water is only about 75% (1 ÷ 1.33) as great as that in vacuum.

The high-energy particles we deal with here at SLAC travel at very high speeds. If we use the symbol c to indicate the speed of light in vacuum, then the speed of a 20 GeV electron is about 0.9999999997 c. If such a particle finds itself is almost any material medium, even a very dilute gas, its speed will be greater than the speed of light in that medium; and the question is, What happens then?

The answer is that the too-fast electron will immediately begin to slow down by radiating away some of its energy in the form of light and other kinds of electromagnetic radiation. The emission of such *Cerenkov radiation* occurs in a way that is somewhat similar to a sonic boom. That is, an airplane traveling faster than the speed of sound produces a cone-shaped shock wave which spreads out behind it as it moves forward. This is also what happens to a too-fast particle as it travels through matter. The following sketch shows the general idea:

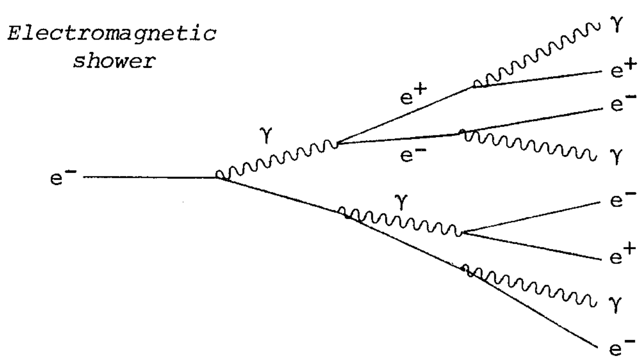


The three circles in the sketch are meant to represent the expanding spheres of radiation emitted by the particle at three different times. These reinforce each other to create the cone-shaped "shock wave" of Cerenkov light that propagates outward from the particle's wake.

The Cerenkov counter used in E-122 is filled with nitrogen at normal atmospheric pressure. Although the index of refraction of this gas is only about 1.0003, this is enough to give rise to Cerenkov radiation from any scattered electron that has passed through the spectrometer before entering the Cerenkov counter.

3. Shower Counter

After the scattered electrons have marked their passage through the gas in the Cerenkov counter by trailing a soft blue glow of light, they then bump into what must seem the stone wall of the shower counter. The active element in this device is glass that has been "loaded" with lead; and as the electrons penetrate into this material, they signal their presence by shedding energy in several different ways. The most important of these energy-loss processes at high energies is called an "electromagnetic shower." The beginning of such a shower is shown schematically in the following sketch:



The incoming electron (e^-) first emits a quantum of radiation, a photon (γ), by interacting with one of the nuclei (not shown) in the lead-glass. Then the photon interacts to create an electron-positron (e^+) pair, the pair radiate more photons, which create more pairs, which . . . and so on. The result of all this is a cascading process, the "shower," which may eventually include thousands of photons, electrons and positrons.

The output signal from a shower counter is often obtained by directly collecting some of the electrically charged particles that are created or are knocked loose from the atoms in the device. In the case of E-122's shower counter, however, the charged particles are ignored; instead, the visible light that is produced during the shower is collected by phototubes, which deliver an output signal that is proportional to the amount of light that was generated within the counter. This is essentially the same technique that is also used with the Cerenkov counter. The output signals from each of these two counters are processed in separate electronics systems. These provide two measurements of the flux of scattered electrons coming from the target. Although the two different measurements are not completely independent of each other, they do provide complementary information because the two counters do not respond in exactly the same way to the background "noise" of stray particles coming through the spectrometer, etc.

The E-122 experimenters had to carry out extensive calibration and testing of the Cerenkov and shower counters in order to assure themselves that the flux of scattered electrons could be measured with the accuracy that the experiment required. We will not describe these instrumental tests here, other than to note that the particle-detection system was able to handle a typical number of about 1000 scattered electrons during each beam pulse, and that the system allowed the measurement of the scattering asymmetry, A, to a level of about 1 part in 10^5.

E. BEAM-MONITORING AND CONTROL

When the SLAC accelerator is running, it is not unusual for it to provide beams of different energies and intensities to as many as 4 or 6 different experiments that are being carried out simultaneously. Well, not *exactly* simultaneously. What happens is that the accelerator is programmed to deliver, say, 60 pulses per second (pps) of 20 GeV electrons to Experiment A, 10 pps at 16 GeV to B, 40 pps at 2.25 GeV to the SPEAR storage ring, and so on. Over the years, a good deal of effort has gone into developing this multiple-beam capability so that any changes that are made in the characteristics of one beam will have as little effect as possible upon the other beams in the programmed sequence.

There were few complaints about the quality of the interlaced multiple beams until E-122 came along. But the beam-monitoring and control system that the E-122 experimenters designed for their work was so sensitive that they began to find little quirks in beam behavior that no one had ever seen, or even thought of, before. Our fantasy is that someone from E-122 would seize the floor at the experimental scheduling meetings to complain bitterly about jitter, or beam-energy fluctuations, or *some*thing, when pulses were being switched back and forth among different experiments. And to any who might question that the Princess's mattress could really be all that uncomfortable, E-122's response was to produce from under the bed, *Presto!* a motley collection of hitherto undetected square rabbits.

Sweetness and light returned when the experimental schedule was finally juggled to let E-122 go it alone for awhile. During that solo running the accelerator operated at the maximum pulsing rate that E-122 could handle, 120 pps, and all attention was focused on delivering to the experiment a beam of the highest possible quality. We can get an idea of the reasons for the group's persnickety standards of beam quality by considering the following potential problems.

If the beams with left-handed polarization were to differ from those with right-handed polarization in a systematic way, then such differences would be a serious source of potential error. This is because even very small changes in the beam energy, current, position at the target, and angle of scattering can all influence the flux of scattered electrons which the detection system actually measures. To achieve the required accuracy for the experiment as a whole, any systematic differences between the RH- and LH-polarized beams were to be held to the limits that are listed in the following table.

Average Systematic Differences Between Beams With Right- And Left-Handed Polarization

Beam Parameter	Desired Limit	Measured Difference	Units
Energy	< .0016	.0018	Percent
Current	< .01	- .005	milliamp
Position (V) At Target (H)	< 0.4 < 0.7	.014 .06	micro-meter
Scattering (V) Angle (H)	< 0.06 < 0.6	.0007 .001	micro-radian

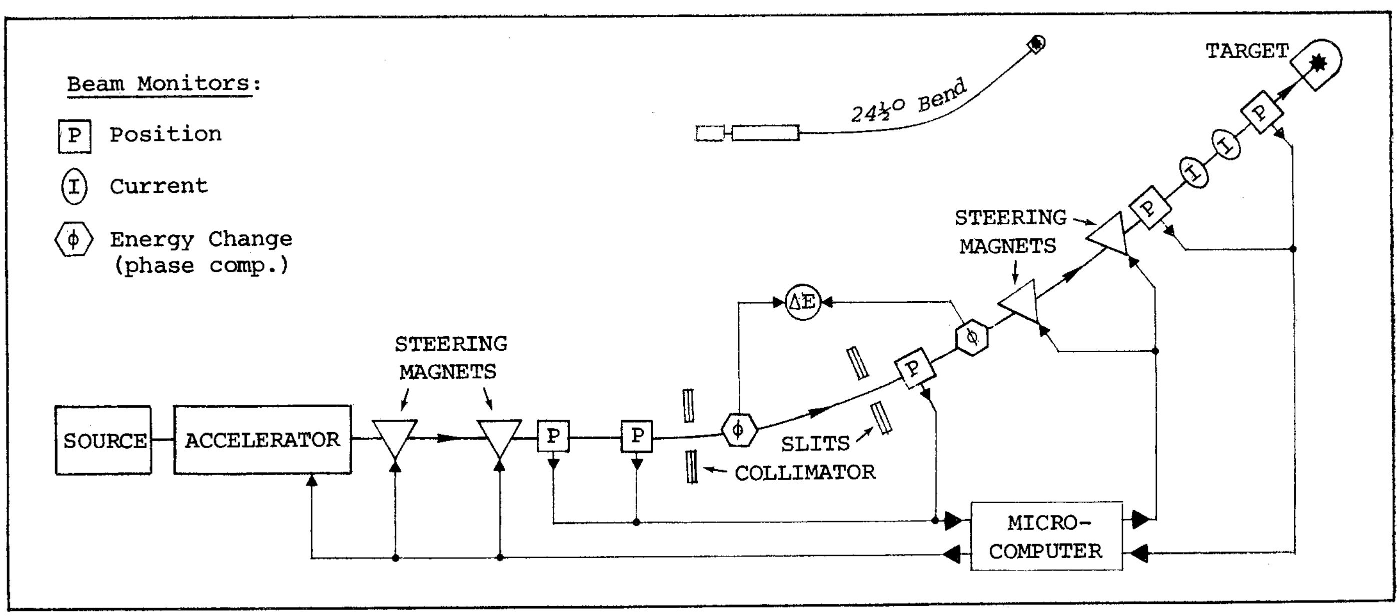
In this table, the minus sign means that the average beam current with LH-polarized electrons exceeded that for RH-polarized electrons. Also, (V) and (H) refer to the vertical and horizontal positions of the beam at the target, and the vertical and horizontal scattering angles.

The data in the table indicate that there were in fact systematic differences in beam parameters between RH- and LH-polarized beams, but that these were quite small. The most important systematic difference was that of beam energy, where the measured difference was not quite held within the desired limit. Taken all together, the measured beam-parameter differences resulted in a correction of 3.3% that was applied to the final asymmetry value measured in the experiment. In addition, ± 3.3% was added to the systematic error in the final answer as the assumed contribution from these beam-parameter differences.

(Incidentally, the small numbers in the table are not a statement about how good the SLAC beams are, but rather how good the experimenters were in averaging out beam jitter. Also, as an example of how small is small: .001 microradian is the angle that a penny would cover if it were looked at from a distance of *10,000 miles.)*

The Beam-Monitoring Hardware

The reduction of systematic errors to the levels shown in the table was made possible by the system of beam monitors and controls that is illustrated schematically in the box below. Most of the monitoring devices shown in this sketch make use of microwave cavities, in which fields are induced by the passage of an electron beam pulse. For each beam pulse during Experiment E-122, the beam position, energy and current were measured, and the angles were determined by cavities located 50 meters apart. A



feedback system controlled by a microcomputer used signals from the monitors to make small pulse-to-pulse corrections of the beam position and angle (through beam-steering coils) and of the beam energy (through the accelerator klystrons).

The two beam monitors labelled $\langle\phi\rangle$ (phi) in the drawing are located at either end of the "bending" region in the beam switchyard, where a sequence of magnets deflects the primary electron beam through an angle of $24\frac{1}{2}^{\circ}$ on its way to the target in End Station A. These monitors take advantage of the fact that the length-of-path, and thus the time-of-flight, of the beam electrons through the switchyard depends upon the beam energy. For a 1% difference in beam energy, the flight-time difference is 17 picoseconds (17×10^{-12} second). The phase of the fields induced in these two monitors accurately reflects the arrival time of the beam pulse in each, and by comparing the signals from these monitors in a phase bridge the beam flight time can be determined to an accuracy of about 0.1 picosecond (equivalent to an energy difference, ΔE, of .006%). This extremely sensitive method for measuring the energy difference between successive beam pulses was developed fairly recently by members of SLAC's Accelerator Physics group in collaboration with some of the E-122 experimenters.

F. RUNNING THE EXPERIMENT

Now that we've gained some familiarity with the apparatus used in Experiment E-122, we turn to a description of the actual execution of the experiment. We plan to proceed in the following sequence:

1. What is measured
2. Tests with unpolarized beams
3. Polarized beams: optical selection
4. Polarized beams: selection by precession
5. The final result

1. *What Is Measured*

Back on page 5 we noted that a comparison of the scattering probabilities for RH- and LH-polarized electrons was the aim of E-122, and that any observed difference between P_{RH} & P_{LH} would be expressed as the asymmetry A:

$$A = \frac{P_{RH} - P_{LH}}{P_{RH} + P_{LH}}$$

Note that an excess of RH- over LH-scattering would yield a positive value of A, while the opposite would yield a negative value.

The experiment proceeds by measuring two quantities for each beam pulse:

(a) The integrated beam charge as measured by the toroid beam monitors labelled (I) in the previous sketch.

(b) The integrated output of the phototubes which "read" the Cerenkov and shower counters.

We'll call (a) the "beam flux" and (b) the "detector flux." The ratio of (b) to (a) is a measure of the scattering probability for each beam pulse, and we'll assign the symbol p to this one-pulse probability measurement:

$$p = \frac{\text{detector flux}}{\text{beam flux}}$$

After we've accumulated a great many values of p, we can draw the following two conclusions:

1. p is independent of the beam flux (accelerator beam current) to within a fraction of a percent ($\pm$ 0.3%). This means that the detectors respond linearly to changes in beam intensity within the desired accuracy.

2. The variations in p are consistent with the statistical fluctuations of about 3% from pulse to pulse that are expected from a detector flux that is typically 1000 electrons per pulse.

So far, so good.

2. *Tests With Unpolarized Beams*

Now we do a series of runs in which we look for an asymmetry where none is expected by using a regular unpolarized beam from the SLAC accel-

> Neutrinos, they are very small.
> They have no charge and have no mass
> And do not interact at all.
> The earth is just a silly ball
> To them, through which they simply pass,
> Like dustmaids down a drafty hall
> Or photons through a sheet of glass.
> They snub the most exquisite gas,
> Ignore the most substantial wall,
> Cold shoulder steel and sounding brass,
> Insult the stallion in his stall,
> And, scorning barriers of class,
> Infiltrate you and me. Like tall
> And painless guillotines, they fall
> Down through our heads into the grass.
> At night, they enter at Nepal
> And pierce the lover and his lass
> From underneath the bed—you call
> It wonderful; I call it crass.
>
> --John Updike

> Now my own suspicion is that the Universe is not only queerer than we suppose, but queerer than we can suppose.
> --J. B. S. Haldane
>
> Don't let me catch anyone talking about the Universe in my department.
> --E. Rutherford

erator. Each beam pulse is fictitiously designated "RH" or "LH" by the same random number generator that is used to determine the sign of the Pockels cell voltage. For these unpolarized-beam runs, the shower counter measurements gave the following result:

$$\frac{A_{\text{unpolarized}}}{\text{Beam polarization}} = (-2.5 \pm 2.2) \times 10^{-5}$$

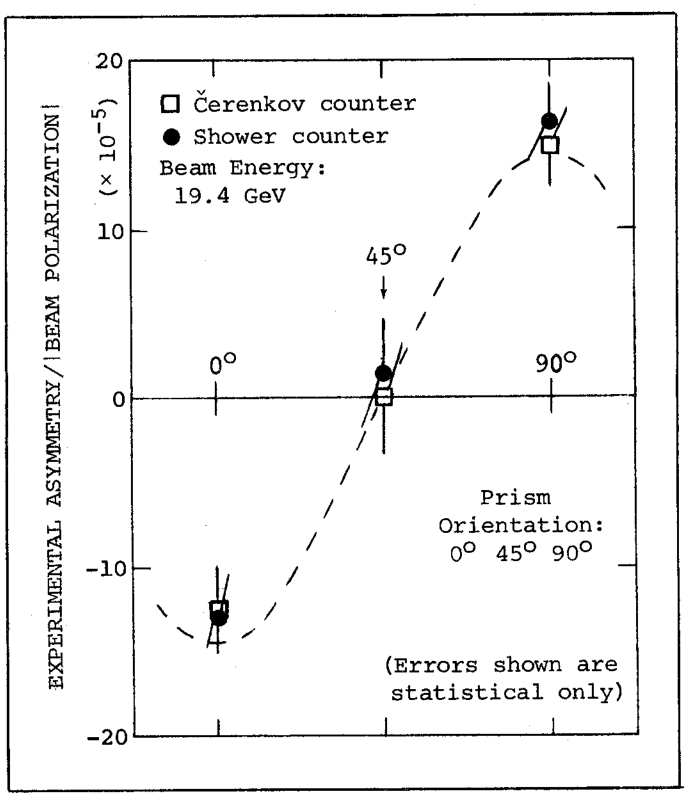
where the average beam polarization $|P_e| = 0.37$, as previously noted. This measured value of a "fake" asymmetry was small enough to lend assurance that the experimental apparatus would be able to measure a possible *real* asymmetry between the scattering of RH- and LH-polarized electrons down to the desired level of about 10^{-5}.

3. *Polarized Beams: Optical Selection*

The next step was to apply the same measuring procedures to a series of runs using polarized beams from the PEGGY II source. During these runs, the beam polarization was determined by the combined influence of the two optical polarizing elements that we discussed back on page *9*. As a reminder:

Prism setting:	0°		45°		90°	
Pockels voltage:	+	-	+	-	+	-
Beam polarization:	RH	LH	0	0	LH	RH

Data were taken at each of the three orientations of the calcite prism. The results of these runs for a beam energy of 19.4 GeV are shown in the next figure, which includes both the Cerenkov and shower counter measurements:



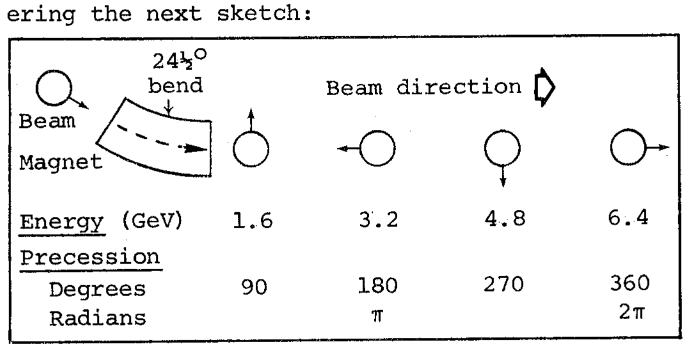
The figure shows clearly that the measured experimental asymmetry reverses, as expected, in going from a prism setting of 0° to 90°. This result serves to separate the effects attributable to the beam polarization itself from any peculiar systematic effects that may be connected with reversal of the Pockels cell voltage. In addition, the fact that the measured asymmetry at a prism setting of 45° is zero (with small errors) is an indication that any other sources of error related to the asymmetry must be quite small. The approximately equal and opposite asymmetry values measured at 0° and 90° also support this conclusion.

The last point to be noted about this figure is the fact that the measurements made by the Cerenkov and shower counters are mutually consistent. As we noted earlier, these two counters have quite different responses to different kinds of background effects, so their very similar responses here serve as a check that background contamination of this data is no more than a minor effect.

4. *Polarized Beams: Selection By Precession*

As we've just seen, with the calcite prism at 0° and positive voltage on the Pockels cell, PEGGY II emits a beam with RH polarization. However, we have not yet mentioned the fact that the beam polarization *at the target* depends upon the final energy to which the beam is accelerated in the SLAC linac.

This energy dependence of the polarization comes about in the following way. Electrons possess a certain magnetic property ("anomalous magnetic moment") which causes their spin direction to *precess* relative to their direction of motion when they are deflected by a magnetic field. One kind of precessional motion is the wobbling of a spinning top, but we can probably get a picture that suits our present purposes better by considering the next sketch:



In this picture, we send a 1.6 GeV electron beam through a bend angle of $24\frac{1}{2}^{\circ}$ and note that the spin direction precesses through 90°. Then, in turn, beams of 3.2, 4.8 and 6.4 GeV pass through the same magnet (adjusting the magnet current to produce the same $24\frac{1}{2}^{\circ}$ deflection each time); and we note spin-precession angles of 180°, 270°, and 360°, respectively. In the last case, a precession of 360° brings the spin direction around full circle and back to its original orientation.

Before applying this information to the situation at SLAC, we want to convert our angular measurements from degrees to the units called *radians:*

Radians	Degrees
1	57.3
π	180
2π	360
4π	720
6π	1080

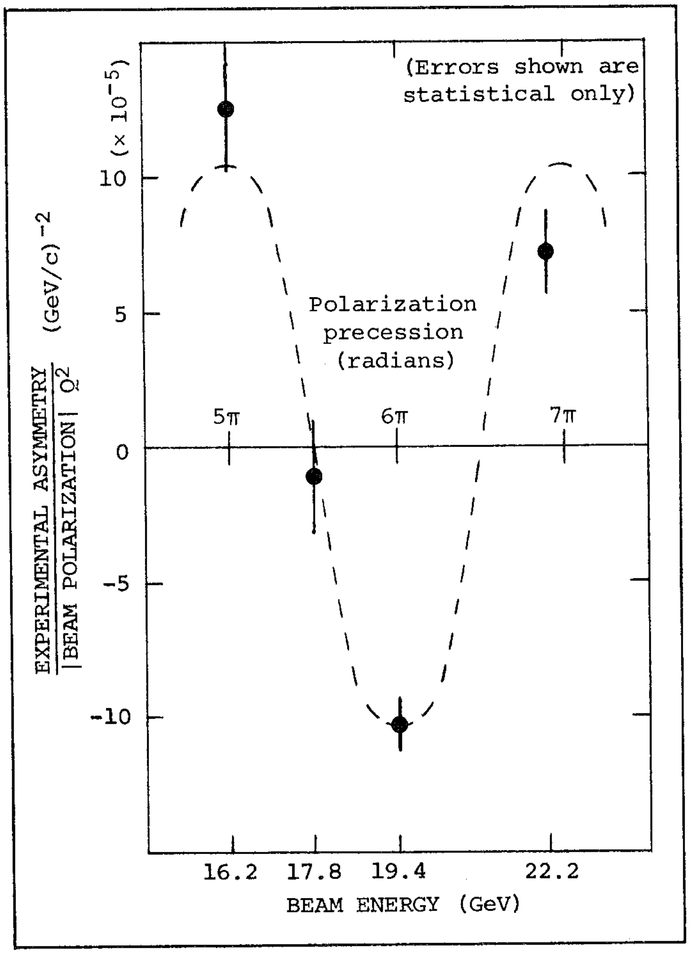
So 2π, 4π, 6π radians are equal to 1, 2, 3 complete cycles of precession that bring the spin direction back to its original orientation.

For the actual experimental conditions at SLAC, the 24½° beam deflection between the accelerator and End Station A results in a spin precession of π radians for each additional 3.2 GeV (actually 3.237 GeV) of beam energy. The next table shows the four values of beam energy that were used in running Experiment E-122 and how these energies affected the beam polarization at the target. The table also includes a column labeled "momentum transfer," which we'll discuss in a moment.

Assume RH-Polarized At Source:			Q^2 Average Momentum Transfer $(\text{GeV/c})^2$
Beam Energy (GeV)	Precession Angle (Radians)	Polarization At Target	
16.2	$5.0\,\pi$	LH	1.05
17.8	$5.5\,\pi$	Transverse	1.25
19.4	$6.0\,\pi$	RH	1.46
22.2	$6.9\,\pi$	≃ LH	1.91

Note that the highest energy beam used in the experiment, 22.2 GeV, was not quite energetic enough to produce a precession angle of 7π radians, so the beam polarization at the target did not quite reach a full reversal of the source polarization for this beam energy.

The quantity symbolized as "Q^2" in the right-hand column above is a measure of the average momentum that is transferred from the incoming beam electrons to the recoiling target deuterons during the collisions of interest. The value of Q^2 is different for each of the four beam-energy settings, and we will have to make allowance for these differences because the experimental asymmetry is expected to be proportional to Q^2. This is done in the following figure, which summarizes the data obtained at the four different beam-energy settings.



The measurements shown here were made with the shower counter. The expected behavior is indicated by the dashed curve, which is normalized to the point at 19.4 GeV. The effects of different values of Q^2 at the different energies are compensated in the figure by dividing the experimental asymmetry by Q^2.

The data shown here clearly demonstrate the effect of the polarization precession on the measured experimental asymmetry. At a beam energy of 17.8 GeV, where the polarization is transverse, the data are consistent with the expection that no asymmetry would be observed.

To summarize, both of the methods used to select the beam polarization at the target--by optical control at the source, and by spin precession through the beam switchyard--yielded results that closely matched the expected behavior. In combination, these two methods provide rather persuasive evidence that the measured experimental asymmetry between the scattering of RH- and LH-polarized electrons is a consequence of the beam polarization itself, and not of any peculiarities in the experimental hardware nor in the handling of the data.

G. THE FINAL RESULT

Now that we've checked, rechecked, cross-checked and in general combed all the fleas out of E-122's experimental procedure, it's time to get down to brass tacks and produce the Final Answer.

1. The Input Data

The data that were used to arrive at the final result were the measurements made by the shower counter (but not the Cerenkov counter) at beam energies of 19.4 and 22.2 GeV (not 16.2 GeV). The reasons for these selections were as follows:

(a) The shower and Cerenkov counters did not function as statistically independent detectors during this experiment, because both counters responded to the same scattered particles. So it was not reasonable simply to add the measurements from the two counters together. The shower counter data was chosen because its level of unwanted background events was about 1½%, whereas it was about 4% in the Cerenkov counter. The shower counter thus provided the "cleaner" data.

(b) At a beam energy of 16.2 GeV, an uncertain but relatively large fraction of the scattered electrons originated from "elastic" collisions in the target (see page 7), and also from collisions in which "resonant states" were produced. Events of both of these kinds serve to muddy up the data. At the two highest energy points, 19.4 and 22.2 GeV, the contribution from these background sources was negligibly small.

The figure below shows the measurements made by the shower counter during a series of 44 individual "runs" at a beam energy of 19.4 GeV. More data were taken at this energy than at any of the other beam-energy points, and the figure includes all of this 19.4 GeV data. The results of the running at 22.2 GeV are very similar to those shown in the figure, so we do not display them here. The individual runs varied but were typically a few hours per run.

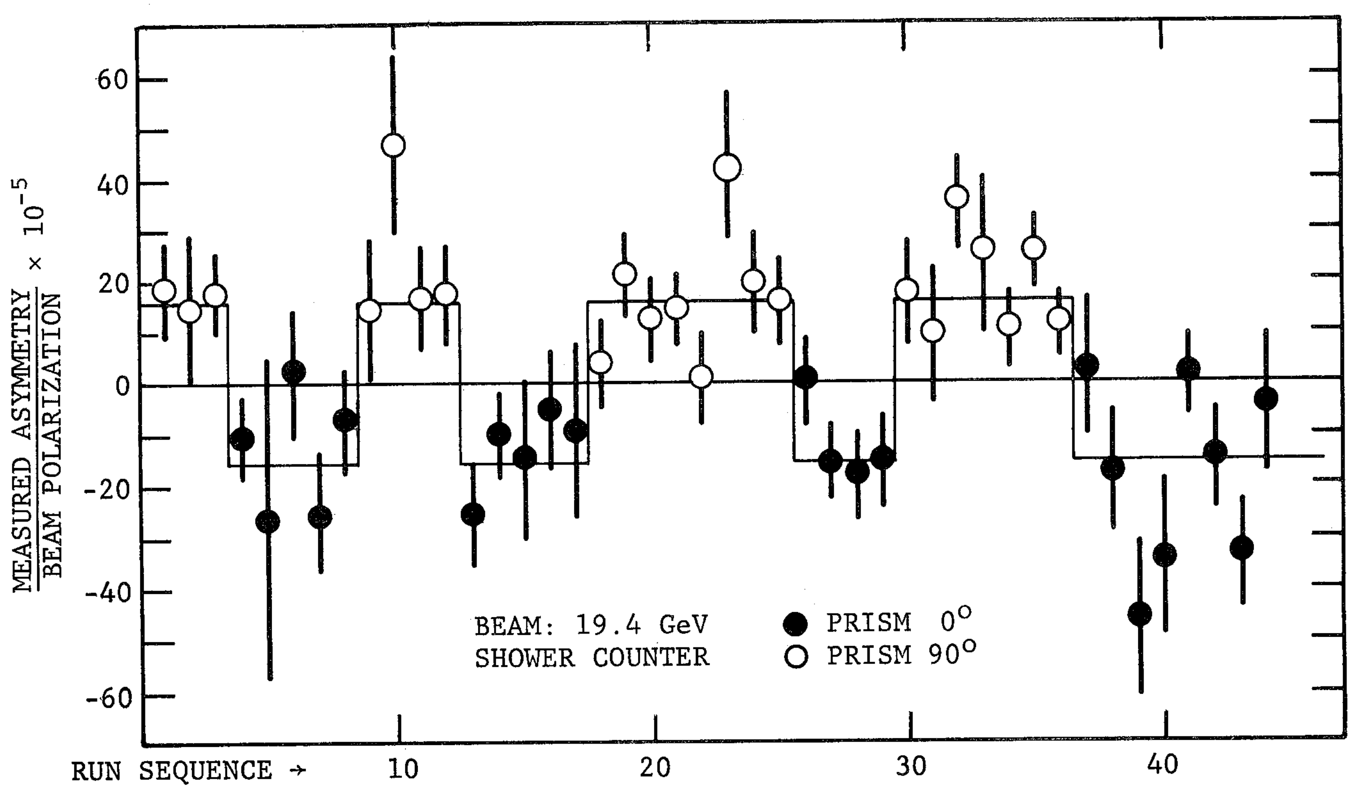
There are two aspects of the data shown in figure that we want to emphasize:

(a) The fractional beam polarization of 0.37 has been taken into account in plotting the figure. That is, the asymmetry measurements have been divided by 0.37 in order to show what asymmetry would have been measured if the beam polarization had been 1.00 (100% polarized).

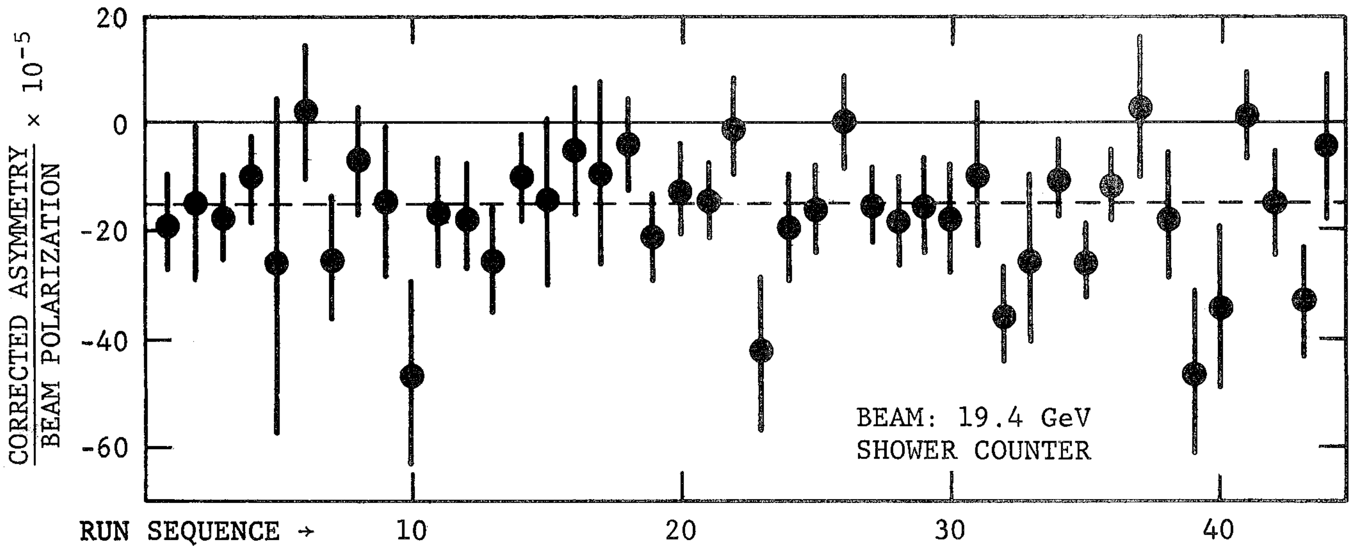
(b) From our definition of the asymmetry,

$$A = \frac{P_{RH} - P_{LH}}{P_{RH} + P_{LH}}$$

we recall that a *positive* value of A will indicate a greater probability for the scattering of RH-polarized electrons than for LH-polarized el-electrons, while a *negative* value will indicate the opposite. In the figure below, the data points are divided about equally between positive and negative values of A as measured. But hold on a minute--we forgot about the prism orientation. A prism setting of 90° *reverses* the 0° polarization, so all of the open-circle (○) data



points should actually show *negative* rather than positive values of A. We straighten out this possible confusion factor by replotting all the 90° data points from the previous figure to form the *corrected* asymmetry measurements in the following new figure:



This corrected figure makes it evident that there really is a net asymmetry in the data, and that electrons polarized left-handed do in fact scatter with a greater probability than those polarized right-handed. The dashed line in the new figure is the mean value of the 44 individual asymmetry measurements that are plotted. Numerically, this value is about

$$-15 \times 10^{-5}$$

and there is only one more step we have to take in order to convert this number into the final experimental result.

We noted earlier that the asymmetry in scattering between LH and RH polarization would not be a single, constant number, but rather that it would depend upon (be proportional to) the quantity symbolized by "Q^2," which is the amount of momentum that is transferred from beam electron to target deuteron in a scattering collision. In a certain sense, the momentum transfer is related to the forcefulness or "crunch" with which two particles collide. But we don't need to dwell upon this subject here other than to note that a bigger *bang* means a larger Q^2, and that on the average Q^2 increases when higher energy beams are used.

From the table on page *16* we take the average Q^2 values for beams of 19.4 and 22.2 GeV, namely 1.46 and 1.91. (The units don't matter for our present purpose.) For the data samples that were used in Experiment E-122, the weighted mean of these two numbers is about 1.6, and this is the number we'll use to get the final answer, namely,

$$\frac{A}{Q^2} = \frac{-15 \times 10^{-5}}{1.6} = -(9.5 \pm \text{errors}) \times 10^{-5}$$

Since it took us 17 pages of gab to get here, we'll add the errors and then celebrate by writing out the Final Answer so it's plainly visible:

$$\boxed{A/Q^2 = -(9.5 \pm 0.8 \pm 0.8) \times 10^{-5}}$$

Statistical Error — Systematic Error

This is the final result for the runs made with a deuterium target. For the smaller data sample that was collected with a hydrogen target, the final result was

$$A/Q^2 = -(9.7 \pm 2.7) \times 10^{-5}$$

where the statistical and systematic errors have been combined. These two results are self-consistent, but in the following discussion we shall deal only with the larger sample of deuterium data.

2. *Systematic Error*

In most high-energy physics experiments, the

> If your experiment needs statistics, you ought to have done a better experiment.
>
> We haven't the money, so we've got to think.
>
> --Ernest Rutherford
>
> From *The Harvest of a Quiet Eye*, a selection of scientific quotations by Alan L. Mackay.

potential sources of systematic error include such things as slow drifts of the gains of phototubes, of magnet currents, and of the response of various electronic devices. In the case of E-122, all such *gradual* instrumental changes were irrelevant because of the rapid and random reversals of the beam polarization. In addition, the small pulse-to-pulse variations in the beam parameters can be discounted because they were much less than the ≃ 3% statistical fluctuations that occurred in the detectors as a consequence of the average flux of about 1000 particles per pulse.

The two main sources that did contribute to the systematic error in the experiment were the *average* differences in beam parameters between LH- and RH-polarized beams, and the uncertainty in the fractional beam polarization. The estimated errors from these two sources were ±3.3% and ±5%, respectively, which were added to give ±8.3%. The final assigned systematic error was thus ±8.3% × -9.5 = ±0.785, rounded off to ±0.8 $\times 10^{-5}$.

3. *Statistical Error*

It is a tricky business to make a reasonable estimate of the systematic error in an experiment, because there is no way of of knowing that all possible sources have been evaluated. In contrast, the statistical error can be calculated straightforwardly and exactly from the total number of events, n, that were used in the final data sample. The formula is $\Delta A = \pm(1/\sqrt{n})$. For E-122, n was about 1.5×10^{10}, which resulted in a statistical error of $\Delta A = \pm(0.86 \times 10^{-5})$. So the final statistical error was ±0.86 × -9.5 = ±0.817, rounded off to $\pm 0.8 \times 10^{-5}$.

> Now the same kind of suggestion applies for experimenters. Experimenters should finish the experiment; they should also have pride in their work, their result should last more than a year. If the result is given as 1.5 ± 0.2, it should not later turn out that it is 0.8 ± 0.1. It sounds ridiculous, but it is true that data disagree with each other by numbers greater than the errors. The reason is that the stated errors are usually statistical errors only, which is a very lazy way to write down the result of an experiment. Who cares what the statistical error is? You want to know what the *number* is. The sources of systematic errors must be investigated to a point where you are sure what the real number is. When in ten years from now the exact number is found, it has to be close to what you said it was, within one or two standard deviations of what you quoted.
>
> --R. P. Feynman

4. *How Good Is The Final Result?*

In the paper that described the results of E-122, the systematic and statistical errors were added linearly to give a total assigned error of $\pm 1.6 \times 10^{-5}$ in the quoted value of A/Q^2. We want to finish up this section by trying to get an idea, generally, about how firm (or shaky) the final experimental answer is likely to be. To begin with, let's first imagine an entirely different experiment that has somehow managed to have no systematic error at all (that definitely makes it imaginary). The result quoted for this ideal experiment is, say,

$$10 \pm 1$$

where the ±1 is the statistical error. Now we ask the question, What are the odds that the "real" answer is given by Cases A, B or C below?

"Real" Answer Is	Odds Against
A: less than 9 or more than 11	2 to 1
B: less than 8 or more than 12	21 to 1
C: less than 7 or more than 13	370 to 1

So there is a pretty good chance, statistically, that the real answer is closer to 9 or 11 than to 10, but not much chance that it's around 7 or 13. Cases A, B, C correspond to what is called "one-," "two-," and "three-standard deviations," respectively, and the odds listed above are an accurate indication of how likely such deviations are to occur. But the key point here is that such odds can only be reasonably applied to *statistical* errors, because with statistics (cards, coin tosses) you know exactly what it is that you don't know.

With systematic errors, two problems arise: (1) nothing is known about any error sources that you haven't even found yet; (2) not *enough* may be known about the sources that *have* been found to be able to estimate the error accurately (maybe it should be $^{+2}_{-1}$ instead of simply ±1). So the message that emerges is to keep looking hard and to estimate conservatively.

So we can't take the E-122 result, $A/Q^2 = -(9.5 \pm 1.6) \times 10^{-5}$, and do the standard deviation business with it to calculate specific odds. However, we get the impression that the E-122 experimenters would prefer not to have their answer turn out to be way out in left field somewhere when the chickens come home to roost. (Block that metaphor!) So our opinion is that -9.5 might stray away by ±2.0 or ±2.5, but any more than that we'll begin to make book against.

IV. Physics Significance

A. THE NEWS GOES OUT

Experiment E-122 was first described publicly last June 12, when the spokeman for the work, Charles Prescott of SLAC, addressed an overflow crowd of about 350 persons in the SLAC auditorium. Something of the special character of the occasion became evident when an unusual thing happened, and a usual thing did *not* happen, after Prescott had completed his 90-minute talk. First, the applause from the audience was unusually vigorous and unusually sustained. And second, when the floor was thrown open for the usual 5- to 10-minute question-and-answer session, not a single question was asked. (In the typical physics seminar, the speaker begins answering, or waiving off, questions shortly before he says, "May I have the first slide, please.")

The expressive silence that ended Prescott's seminar was a recognition of both the elegance of the experiment *per se* and of the physics significance of the final result. In the preceding sections of this article we're tried to suggest some aspects of the elegance. Now we try to deal briefly with the significance.

B. WHAT WAS LEARNED IN E-122

What was learned *for sure* in Experiment E-122 was the following:

1. Parity is violated in the scattering of polarized electrons from deuterium or hydrogen.

2. More generally, parity is violated in neutral current interactions.

3. The level of the observed parity violation is about 1 part in 10,000.

However, when E-122's results were first described in such publications as *Nature* and *Science News*, the articles had titles such as "A giant step toward unified field theory," "Major boost for unified field theory," "Particle theory: Stanford electron experiment closes options."

So in the minds of many (us too), E-122's significance is based only partly on what was discovered, with the other part coming from what the discovery implied. The class of theories in question is the "unified field (or gauge) theories," and the specific theory that E-122's result supported is the "Weinberg-Salam model."

C. THE WEINBERG-SALAM MODEL

The whole subject of unified field or gauge theories is very difficult; we barely scratch its surface here. We noted earlier that the electromagnetic interactions of the elementary particles are described with remarkable accuracy by the theory known as quantum electrodynamics, or QED. Because of its success, QED has served as a model or as starting point in attempts to devise theories of the weak- and strong-force interactions. QED has a certain property called "gauge invariance," and other theories that have a similar or analagous property are known as "gauge" theories. (Try to ignore the "measurement" or "length" connotation that goes with the word "gauge"; it was mistakenly chosen long ago but now just generates confusion.) The original appeal of gauge theories lay in their formal elegance, but it was not until the mid-1960's that it began to appear that such theories could have a connection with the real world.

In 1967-68, Steven Weinberg and Abdus Salam independently proposed a gauge theory in which the weak and electromagnetic interactions were "unified," but in which the underlying identity of these two forces was masked in their observed interactions. We briefly mention here a couple of the inportant aspects of the Weinberg-Salam (W-S) model:

1. Quarks and leptons. The "building blocks" are the quarks and leptons, which are grouped together in an unfamiliar way that separates their states of left- and right-handed polarization. We use only the "first generation" leptons (e^-, ν_e) and quarks (u, d) to show the groupings:

Left-Handed Doublets	Right-Handed Singlets
$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L \quad \begin{pmatrix}u \\ d\end{pmatrix}_L$	$(e^-)_R \quad (u)_R \quad (d)_R$

The W-S model was expanded to include the "second generation" leptons (μ^-, ν_μ) and quarks (c, s), and can be expanded to include the third generation (τ^-, ν_τ and t, b), all of which would appear in the same pattern of left-handed doublets and right-handed singlets.

2. The "gauge" bosons. The interactions between and among leptons and quarks are carried by four "gauge" particles: the photon and the three W bosons (γ, W^o, W^+, W^-). These force-carrying particles form a single, related group of field quanta that couple to matter with the same *intrinsic* strength. The large observed difference in *effective* coupling strength is attributed to the huge masses of the W particles (the photon has zero mass), which on present evidence are on the order of 75 to 100 GeV.

3. The Weinberg angle. The only "free parameter" in the theory is called the "Weinberg angle," θ_W, which is to be determined from experiment, which plays a central role, and which usually appears as a trigonometric function (sin θ_W

$\cos\theta_W$, $\sin^2\theta_W$, etc.).

Experimental Evidence

We now review briefly the major pieces of experimental evidence concerning the W-S model. Our conclusion will be that this model presently looks very good, while its competitors appear at best sickly and at worst dead.

Neutral currents. The W^o particle should mediate neutral-current interactions, but none had been seen until 1973, when they were discovered at CERN.

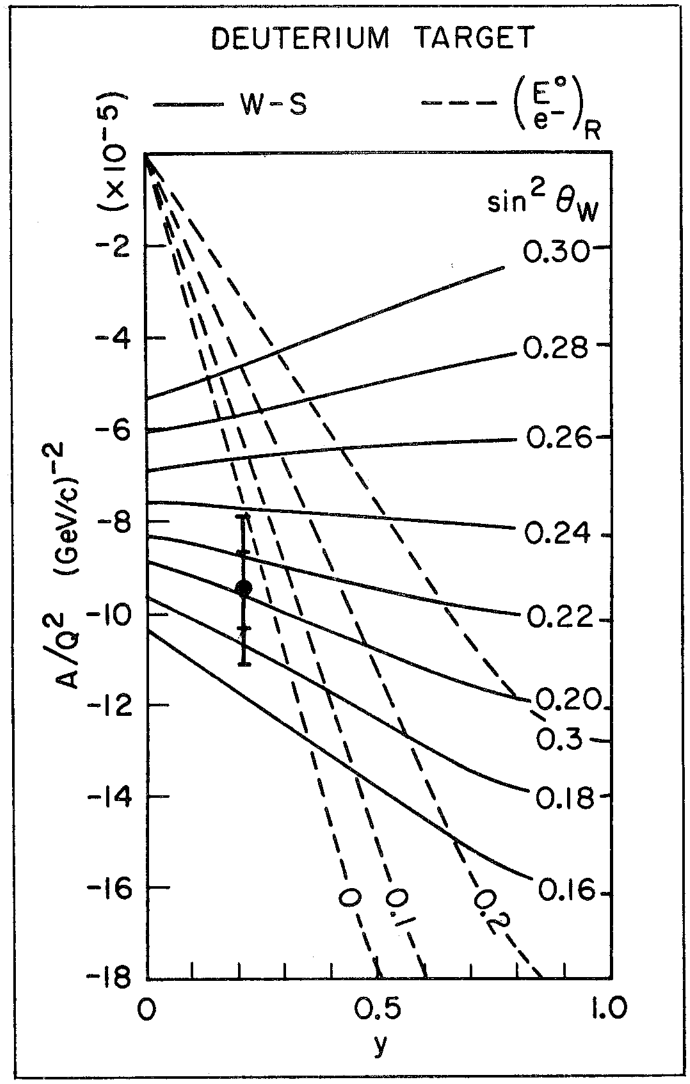
Charm. The discoveries of the ψ/J particles, of other psions, and finally of "nakedly" charmed particles in the period 1974-1976 led, among other things, to the resolution of a certain puzzling problem (the absence of "strangeness-changing" neutral-current interactions). The fourth, charmed quark had been postulated by Glashow, Iliopoulos and Maiani as the solution to this problem (the "GIM mechanism") in 1970.

Neutrino experiments. During the last five years there have been many neutrino experiments, all of which yielded results consistent with the predictions of the W-S model. These experiments narrow down the possible value of the Weinberg angle to $\sin^2\theta_W$ between about 0.20 and 0.30, with ≈ 0.24-0.25 preferred.

Contradictory evidence. We ignore here some unresolved problems with atomic physics experiments for which parity violation was predicted and observed (one case) or not observed (two cases). Wait-and-see is the consensus.

The E-122 result. There are perhaps 8 or 10 alternative theoretical models which unify the weak and electromagnetic interactions in ways slightly or considerably different from the W-S model. SLAC theorist Michael Barnett has recently reviewed the experimental evidence that can discriminate among these alternative theories. Ignoring a couple of W-S "look-alike" models, Barnett concludes that only the W-S model and perhaps the so-called "hybrid" models can survive the testing. (See SLAC-PUB-2183.)

The figure shows the W-S and hybrid model (dashed lines) predictions compared with the E-122 results. E-122 gives $\sin^2\theta_W = 0.20 \pm 0.03$, which fits the neutrino data well. The hybrid model is marginal with only this data. In the figure, "y" is the fractional loss of energy suffered by the scattered electrons (0.21 in figure).



D. A SECOND RUN FOR E-122

Starting next month, E-122 will take data at several different values of y, ranging from about 0.16 up to 0.50. This should help to sharpen the discrimination between the W-S and hybrid models.

A final word. E-122 was a major experimental confirmation of the W-S model. Although there are ways to explain the data we've discussed without using *any* gauge theory, W-S has now given so many right answers that it's premise of weak-EM unification deserves to be taken seriously.

--Bill Kirk

Distribution at SLAC	0-2 1-12 2-3 3-4 4-9 6-9	7-2 8-2 9-2 10-2 11-9 12-59	13-27 14-2 15-2 20-33 21-2 22-10	23-14 24-9 25-2 26-11 30-24 33-12	34-2 40-60 45-5 48-4 50-10 51-30	52-5 53-24 55-21 56-6 57-7 60-10	61-11 62-20 63-8 64-9 65-16 66-5	67-5 68-6 69-25 69-2 70-13 72-2	73-7 74-4 75-2 78-18 79-43 80-4	81-31 82-5 83-3 84-4 85-14 86-6	87-7 88-11 89-7 91-2 92-2 94-10	95-22 96-10 97-48 98-16

Note: This distribution list is about 1/2 the usual distribution of the *Beam Line*. Extra copies can be obtained from Roslind Pennacchi, Bin 80, x2605; or Dorothy Ellison, Bin 20, x2723.