EXPERIMENTAL ELEMENTARY PARTICLE PHYSICS

FACULTY

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The experimental program in elementary particle physics is composed of one large, active experiment (BABAR) and two research and development programs addressing future initiatives in e^+e^- physics (the Linear Collider Detector), and in neutrino physics (EXO). In addition there are occasionally research opportunities in smaller experiments such as the Fractional Charge Search.

BABAR EXPERIMENT

The BABAR Experiment operating at the PEP-II B-Factory is currently the principal ongoing activity in experimental elementary particle physics research at SLAC. This accelerator and detector facility is unique in the United States. Three research groups at SLAC participate in the BABAR Program. The BABAR experiment is exploiting the enormous sample of B-mesons that are being recorded each year. The three main goals of the experimental program are:

to perform a comprehensive set of measurements of CP-violating asymmetries in B-meson decays;

to systematically map out rare decay processes of heavy quark decays; and

to perform detailed studies to elucidate the interplay between the electroweak and strong interactions in heavy-quark decay processes.

These studies focus on testing the Standard Model, measuring its parameters, and searching for effects that are absent in this model.

There are several reasons to believe that phenomena beyond the Standard Model, or New Physics, may be observed in B-mesons decays. The source of CP-violation in the Standard Model is a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. This CKM phase cannot account for the baryon asymmetry of the universe, so some new source of CP-violation must exist. In addition, based on general arguments concerning Electroweak Symmetry Breaking, new particle states having masses from 100 GeV to 1 TeV may exist. The B-meson system is uniquely sensitive to complex phases, as a consequence of the quantum-mechanical coherence of the B^0, and is sensitive to new states, through virtual particle exchange in higher-order processes.

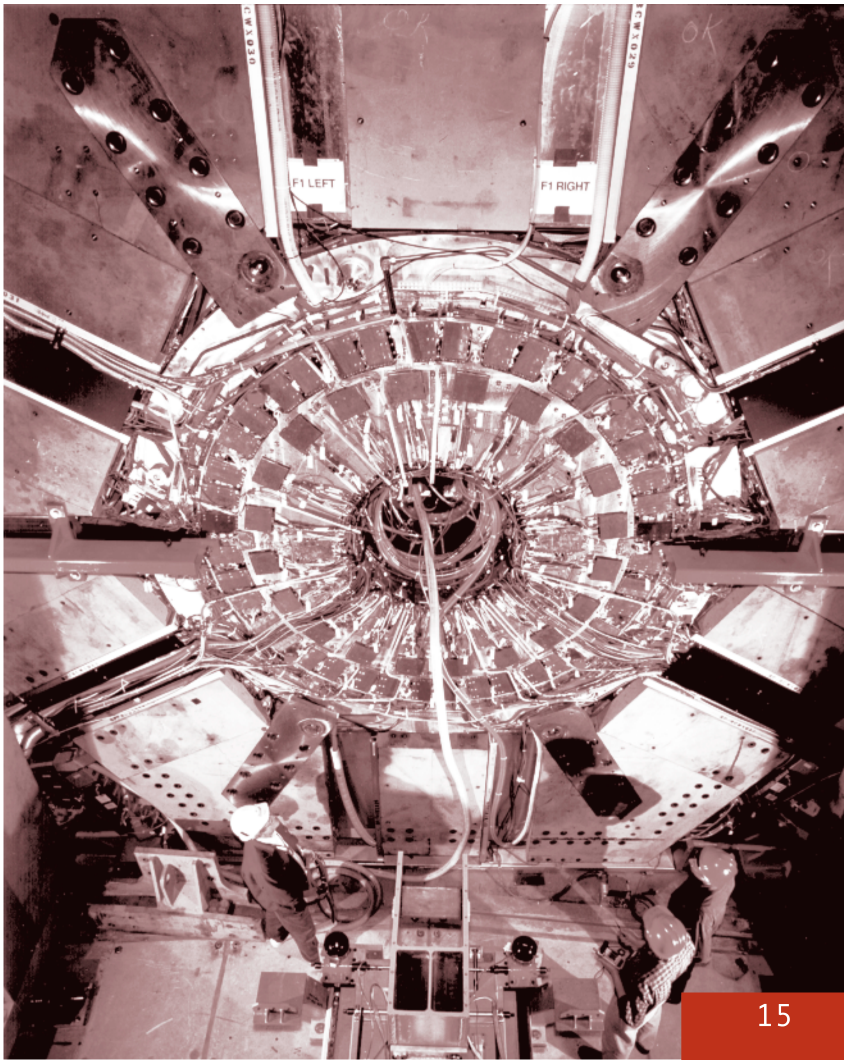
Three internal angles α, β, and γ of the CKM matrix's unitarity triangle characterize the CP-asymmetries in different decay processes. Standard Model predictions for B-decay transitions depend on the values of these three angles

SLAC Research Associate Tests New Muon Detector Planes Being Installed in August 2004.

and the lengths of the sides of the unitarity triangle. At present, β is the most precisely measured angle of the triangle. Since the first data taking run in 1999, BABAR has moved the study of CP-violation from the first observation of this phenomenon in the B-meson system, to a precision measurement of it. Our most recent result: $\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$, is derived from a study of B decays of the form $B \to J/\psi K^0_S$ or $B \to J/\psi K^0_L$, and similar decay processes involving other charmonium ($c\bar{c}$ meson) channels.

The BABAR data already permit stringent tests of the Standard Model and probe for New Physics beyond the Standard Model. As the data sample increases, studies of $B \to \phi K$, $\pi\pi$, $\rho\pi$, $K^*\gamma$, $D\pi$, and DK, for example, will extend our CP-violation measurements and thereby allow for even more demanding tests of the Standard Model. In addition, the precise measurements of the lengths of the sides of the unitarity triangle will be made with semileptonic decays such as $B \to D\ell\nu$ and $B^0 \to \pi\ell\nu$. BABAR has also observed or set limits on many new decay modes, including $B^0 \to \rho^+\rho^-$ and $B^0 \to \pi^0\pi^0$ (both channels will contribute to the measurement of the second angle α), $B^+ \to \tau^+\nu_\tau$ and $B^0 \to K^*\ell^+\ell^-$ and many related channels (leptonic decays, rare decays, and flavor-changing neutral current processes) that are sensitive to New Physics beyond the Standard Model.

BABAR is a typical e^+e^- storage ring detector having nested subsystems that each make a specialized measurement of the properties of the longer lived decay products of the particles produced in each e^+e^- annihilation. Charged particle track momenta are measured in a tracking system consisting of a five-layer, double-sided, silicon vertex detector and a 40 layer drift chamber which operate within a 1.5 Tesla solenoidal magnetic field. Particles are identified as pions, kaons or protons based on the Cerenkov angle measured with a detector of internally reflected Cerenkov light within an array of quartz bars. The direction and energy of photons are measured in a highly segmented CsI crystal electromagnetic calorimeter which also serves to identify and separate electrons and pions. Outside the calorimeter, the iron flux return of the solenoid is segmented into 19 layers – each instrumented to measure the position and range of particles, thereby providing separation and identification of hadrons and muons, as well as detection of K^0_L. The data acquisition and trigger are accomplished with custom designed fast digital electronics, and subsequently processed on very large computing farms to manage the +high-event rates.


The BABAR Detector.

The BABAR experiment is presently in its fourth data taking run. Since its turn-on in 1999, PEP-II (the SLAC B Factory) has delivered over 250 inverse femtobarns of colliding beam, corresponding to 250 million produced B-meson pairs. Our goal is to record at least 500 inverse femtobarns of data by the end of 2006. By 2006, PEP-II improvements will be in place giving an increase in the instantaneous luminosity (proportional to the event rate recorded by BABAR) by one order of magnitude over the original storage ring design. Close collaboration between accelerator physicists and BABAR physicists has been a major component of the success of the luminosity improvement program. The most recent example is the development of the capability for continuous (“trickle”) injection into the both the electron and positron rings while simultaneously accumulating data in BABAR.

To better take advantage of the higher luminosity, the BABAR detector hardware and software is continuously being improved. The trigger system electronics underwent an upgrade in 2004 to address higher anticipated background rates associated with future machine improvements. Between the data-taking runs in 2004 and 2005, the detector planes of the muon system and its front-end electronics will undergo a complete replacement to significantly improve the efficiency and performance for separating muons and hadrons. Improvements to the drift chamber electronics and other BABAR hardware and software improvements are under consideration as well. SLAC along with the international BABAR collaboration have also begun to explore the physics case for investment in an even larger upgrade in luminosity. Studies of a “Super B-Factory” with design luminosity 100 times higher still are presently under way.

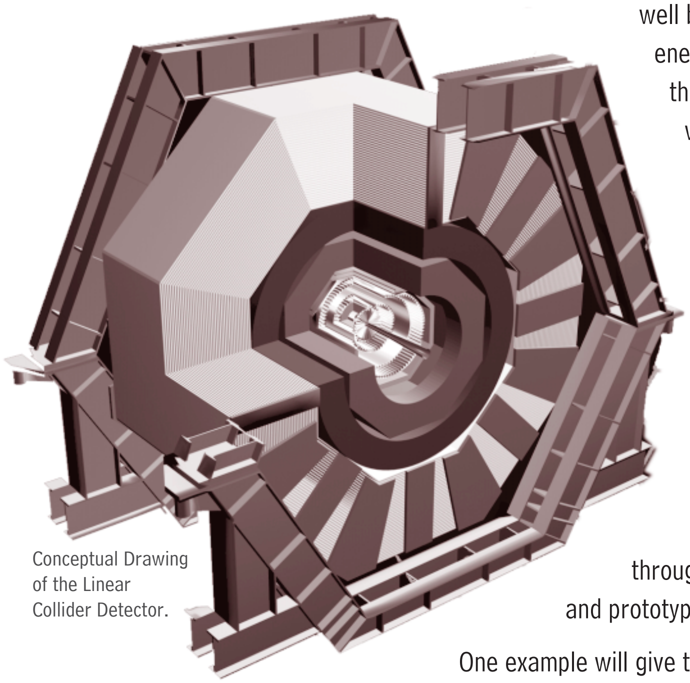
LINEAR COLLIDER DETECTOR RESEARCH AND DEVELOPMENT

Many of the most fundamental questions before particle physics and physics as a whole may be answered by data from the 500 to 1000 GeV e^+e^- International Linear Collider (ILC). Questions such as the nature of dark matter, origin of mass, the existance of supersymmetric particles, and of extra dimensions will all be addressed by data from this machine.

Data from a series of measurements which have probed electroweak interactions with high precision and data from the ongoing revolution in cosmology and astrophysics give sound indications that thresholds for new particles—indeed new types of matter—are just around the energy corner. The Large Hadron Collider (LHC) which is under construction at the European Particle Physics Laboratory (CERN) will provide the first glimpse of that new physics. The ILC, now beginning the formal proposal and design stage, will allow us to understand it.

At the ILC, 250-GeV electrons will collide with 250-GeV positrons by directing beams from two 10-km linacs into head-on collision. Availability of the full collision energy for particle creation, precise knowledge of the initial state’s spin, charge, and energy, and freedom from fierce detector backgrounds and the confusion of multiple and underlying interactions expand the experimental possibilities at the ILC well beyond what’s possible at the LHC. The international high energy physics community has taken note and has endorsed the ILC as the correct next step for particle physics world wide. SLAC, which pioneered the linear collider with its Stanford Linear Collider, and has been playing a dominant role in designing the next machine, will play a major role in designing and constructing the accelerator and the detectors for the ILC.

Detectors at the ILC can take advantage of the cleanliness and precision of the e^+e^- environment to push measurement accuracy well beyond today’s state of the art. In fact, the physics goals of the ILC will require significant advances in detector technology. SLAC research groups, in collaboration with colleagues throughout the US and the world, are in the process of designing and prototyping a Linear Collider Detector.


Conceptual Drawing of the Linear Collider Detector.

One example will give the flavor of the present work. If pions, kaons, protons, and leptons were the quanta measured in previous particle detectors, the gauge bosons (W and Z), the top quark, the Higgs boson, and perhaps the supersymmetric partners of the known particles, are tomorrow’s quarry. To find, identify, and measure these new particles we must measure the jets of “old quanta" particles into which they decay, and combine one jet with others to identify the parents. This is done by measuring the jet's charged particle momenta with unprecedented precision in a silicon barrel tracker then adding the jet's electromagnetic energy (from photons) and hadronic energy (from neutrons and K^0_L long mesons) utilizing the calorimeter. The trick is distinguishing these latter forms of energy from that deposited by the charged particles as they also pass through the calorimeter. To do so, a silicon-tungsten calorimeter is being developed, which detects energy deposition with such small granularity that charged particle paths are separable from neutral energy showers. Simulation studies to understand the fundamental physical limitations of the technique and optimize the parameters of this calorimeter are underway. New readout chips and silicon detectors, are being prepared for prototype evaluation and beam tests. Other detector components are also under study: CCDs and silicon microstrip detectors for the tracker, exotic new devices to measure to high precision the energy flow of the abundant e^+e^- pairs which are produced near the beam energy, to polarimeters that can determine the helicity of the incoming electrons or positrons.

A next generation linear collider will not be in operation for a decade or more. Why should a future particle physics experimentalist get involved in this work on a Linear Collider Detector now? Now is the time that detector concepts are being set and now is the time to participate in the design of the detector. As particle physics experiments have grown in cost and complexity the opportunities to play a key role in experiment design have diminished. The opportunity to develop new detector hardware gives hands-on experimental training, a chance to design and conduct beam tests, and an in-depth look at detector physics. Finally, the opportunity and necessity to understand the physics of the linear collider, which ultimately dictates the detector design, leads one to the central physics issues particle physics faces today.

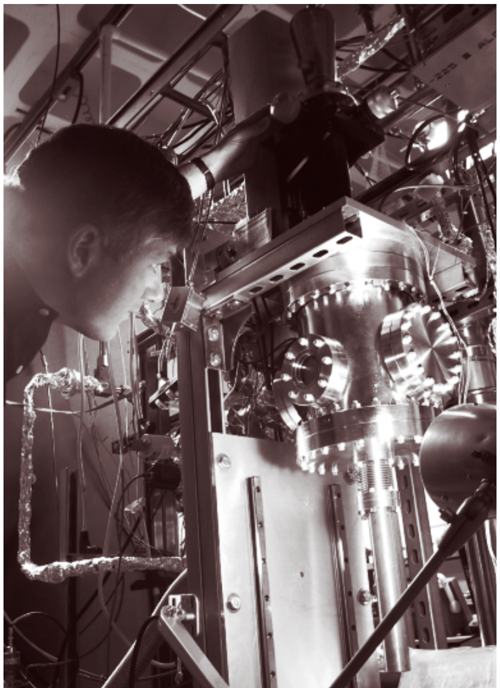
ENRICHED XENON OBSERVATORY (EXO)

Two SLAC research groups are collaborating with the Stanford Physics Department, and with others, in an R&D program to test the feasibility of a large-scale double-beta-decay experiment. Known as EXO, for Enriched Xenon Observatory, the proposal utilizes a large quantity (>1 ton) of Xe enriched in the Xe^{136} isotope as both a decay and detection medium. The double beta decay process,

$$\mathrm{Xe}^{136} \rightarrow \mathrm{Ba}^{136++} + e^- + e^- \ (+\ 2\nu)$$

can proceed in the two neutrino ($2\nu\beta\beta$) mode expected from the Standard Model, which has already been observed in several nuclei other than Xe^{136}, or possibly in the neutrinoless ($0\nu\beta\beta$) mode. The $0\nu\beta\beta$ process is expected to occur only if neutrinos are Majorana particles (as opposed to Dirac particles) at a rate proportional to the square of an "effective" neutrino mass, hence, its observation would serve a mass measurement and as the first demonstration that Majorana neutrinos occur in nature. These issues together represent two of the most important and enduring mysteries remaining after over seven decades of neutrino physics research.

In recent years neutrino oscillation experiments studying solar neutrinos, nuclear-reactor-produced neutrinos, and cosmic-ray-induced "atmospheric" neutrinos have conclusively shown that neutrino flavor oscillations between electron, muon, tau, and possibly other neutrino flavors do occur. This fact indicates that neutrinos have mass, but the results are restricted to measurements of the relative mass *differences* between neutrinos of different flavor. The oscillation data also constrain the neutrino flavor "mixing angles"; the same mixing angles that determine, in conjunction with the mass values, the value of the effective mass for $0\nu\beta\beta$ decay. The oscillation data points to an expected range



Prototype for Ion Capture in Liquid Xenon.

for the $0\nu\beta\beta$ effective mass that is within the reach of a large enough ($\sim$1 ton scale) experiment.

Xenon's excellent calorimetric properties (necessary to distinguish the broad beta spectrum of the electron energy sum in the $2\nu\beta\beta$ process from the line spectrum in the two-body $0\nu\beta\beta$ decay), readily achievable purity, and lack of worrisome radioactive isotopes make this element an attractive candidate for a low background experiment. In addition, the rare decay search is operated in a coincidence mode, by identifying the barium daughter nucleus of double beta decay on an event-by-event basis. Barium identification is accomplished by a laser florescence technique that is sensitive enough to observe a single ion and, in principle, to distinguish the various barium isotopes.


A Purity Monitor for Liquid Xenon Used in EXO.

To date, the research and development efforts have focused on a liquid xenon (LXe) TPC design, where the barium identification would be accomplished by removing the ion from the LXe using an electrostatic probe, and then delivering the ion to an as-yet-unspecified laser system. The collaboration has successfully constructed and operated a laser-illuminated ion trap for barium and has observed single barium ions. A Xe purification system has been constructed that is operating at ultra-high vacuum along with a purity monitor (XPM). The XPM drifts electrons produced from a UV-laser-illuminated cathode in LXe across a gap and measures the transport efficiency. Electron lifetimes of $>$2 milliseconds in purified LXe, corresponding to attenuation lengths $>$3m have been achieved.

A series of experiments test the feasibility of electrostatic ion extraction from Xe. The “probe–test cell” incorporates a movable electrostatic probe, and an instrumented (PMTs, Si barrier detectors) volume for LXe or gaseous Xe containing a pair of HV electrodes. One of the electrodes holds a weak U^{230} source which undergoes two α decays and emits radioactive Th^{228} and Ra^{222} ions into the Xe. The apparatus has been used to measure ion mobility in LXe, an important issue as the barium ions will be produced in an electric field. Recently, the probe was replaced with a “cryoprobe” where the probe tip is cooled to below the Xe freezing point, and ions are trapped in Xe ice, to demonstrate that captured ions may be released by thawing the Xe ice.

Schemes for charge collection, induced signal collection and the integration with light collection have been studied, along with the design of readout electronics. While ionization provides our primary signal, if this is supplemented by the collection of the 175 nm Xe scintillation light, improvements in energy resolution have been demonstrated. Work is underway studying light collection technologies for the prototype.

The largest effort is now focused on the construction of a $\sim$200 kg prototype that does not employ barium identification. The device will be installed in a DOE-operated underground facility in Carlsbad, New Mexico in 2005. SLAC is involved in the design and construction of the clean rooms housing the experiment, the low noise electronics and data acquisition, the Xe vessel and the associated ionization and photon detectors, the Xe purification and handling systems, and the refrigeration system. The design of a full-scale device incorporating barium identification will follow pending the results of our research and development effort.

FRACTIONAL CHARGE SEARCH

All the known basic elementary particles that can be isolated have either zero electric charge or a charge whose magnitude is equal to the charge of the electron e. This includes the charged leptons, the neutrinos, the photon, the W and the Z. Only the quarks, which to the best of our experimental knowledge cannot be isolated, have charges $\frac{1}{3}e$ or $\frac{2}{3}e$, that is, have a fraction of the charge of the electron. The known composite elementary particles, namely the baryons and mesons, obey a similar rule, their charge is either zero or an integer multiple of e. Therefore it is an old experimental question as to whether there exist elementary particles with fractional electric charge, fe, that can be isolated. Here f would have a non-integer value such as $\frac{1}{2}$ or $\frac{1}{3}$ or 0 .7 or π.

Our group has been looking for fractional electric charge elementary particles in bulk matter using a modern, high-technology, automated version of the Millikan oil-drop experiment. These are non-accelerator, table-top size experiments. In the past we have concentrated on searching in silicone oil. We have not found any fractional electric charge particles and have set an upper limit of less that one fractional charge particles per 10^{22} nucleons in the bulk matter we have investigated.

The search is now focusing on fractional charge particles in meteoritic material. This material that comes from asteroids is one of the least processed materials in the solar system, and is one of the best candidates for containing fractional charge particles. It is believed that asteroidal material is about one million times more likely to contain fractional charge particles, if they exist, compared to terrestrial material. In the course of this research new technology for small drop production, measurement and manipulation has been developed. This technology has applications in other fields of science.

A related interest is in searching for massive, stable, elementary particles in bulk matter, particles with masses in the range of 10^8 to 10^{16} GeV/c^2. Such particles might be produced in the early universe and would be much too massive to be produced in accelerators. No practical and affordable method to carry out searches for such massive particles has been found, but our interest continues because this mass region is largely unexplored.

SLAC Graduate Student Working on the Fractional Charge Search.