DOE/ER/10713--T6

Study of Electron and Neutrino Interactions

DOE Contract DE-AS05-80ER10713, Task B

Final Report

A. ABASHIAN, PRINCIPAL INVESTIGATOR

Department of Physics
Virginia Polytechnic Institute and State University
Blacksburg VA 24061

March 18, 1997

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Contents

1. Introduction

This is the final report for the DOE-sponsored experimental particle physics program at Virginia Tech to study the properties of the Standard Model of strong and electroweak interactions. This contract (DE-AS05-80ER10713) covers the period from August 1, 1980 to January 31, 1993. Task B of this contract, headed by Professor Alexander Abashian, is described in this final report.

This program has been pursued on many fronts by the researchers—in a search for axions at SLAC, in electron-positron collisions in the AMY experiment at the TRISTAN collider in Japan, in measurements of muon decay properties in the MEGA and RHO experiments at the LAMPF accelerator, in a detailed analysis of scattering effects in the purported observation of a 17 keV neutrino at Oxford, in a search for a disoriented chiral condensate with the MiniMax experiment at Fermilab, and in an R&D program on resistive plate counters that could find use in low-cost high-quality charged particle detection at low rates.

2. Axion Search

Support for Task B of the DOE particle physics contract at Virginia Tech began in 1981 with an experiment to search for axion-like particles at the Stanford Linear Accelerator Center (SLAC). The work was a collaborative effort with Professor Luke Mo from Virginia Tech and physicists from SLAC.

The experiment consisted in looking for evidence of long-lived weakly interacting neutral particles—such as axions—produced in the beam dump of the 20 GeV electron beam in end station A. At a distance of a few hundred meters from the dump, a set of large proportional wire chambers interspersed with slabs of aluminum were placed to convert photons from the decay $a^\circ \to \gamma\gamma$, where a° was the conjectured axion. By measuring the direction of the resultant electromagnetic shower(s) with high precision, candidates could be selected whose directions were consistent with a particle originating in the beam dump. Together with the requirements imposed by the time structure of the electron beam, the large background of cosmic ray induced events was eliminated.

Results of the experiment formed the basis of the Ph.D. thesis of Virginia Tech graduate student Bin Lu.[1] No evidence for axion-like particles was observed, and limits on the production cross section were obtained. The results were later published in Physical Review.[2]

3. Resistive Tube Calorimetry

In 1982 and 1983, R&D work was begun to study the possibility of using layers of proportional chamber tubes with interspersed sheets of lead as an instrument to detect electromagnetic showers. The use of resistive tubes and cathode plane readouts led ultimately to the design and construction of the AMY electromagnetic counter. The results of the R&D effort were reported in two instrumentation articles.[34]

4. The AMY Experiment

The Virginia Tech experimental effort to study electroweak interactions has been supported by the Department of Energy since 1980. The initial effort, with Professor A. Abashian as Principal Investigator, was the study of e^+e^- interactions at center of mass energies near 60 GeV in the AMY experiment. This experiment,[5] which operated at the TRISTAN collider at the Japanese National Laboratory for High Energy Physics ("KEK") from 1986 to 1994, was proposed by a small contingent of physicists from the University of Rochester, Virginia Tech, and the University of Pennsylvania, and later grew to include over 100 physicists from KEK and other institutions in the U.S., Japan, China and Korea.

The motivation for the experiment was to extend the study of electron-positron interactions beyond the PEP and PETRA energies and below the Z° mass. Searches for particles such as the top quark, the Higgs boson(s), fourth generation leptons and new gauge bosons, as well as studies of electroweak interference effects, two-photon collisions and QCD were aims of the experiment. The new particle searches yielded negative results at TRISTAN—and later also at the higher energies accessible at LEP and SLC.

Virginia Tech's involvement in AMY from its inception was major and included primary responsibility for the design, construction and installation of the electromagnetic shower counter. Shortly after acceptance of the AMY proposal by the KEK management in late 1983, the Virginia Tech group was joined by Professor Gotow and new research associates and technicians. Also, groups from the University of California at Davis and Rutgers University joined in the construction of this calorimeter. The Advex Corporation fabricated the final calorimeter units under Virginia Tech supervision. Installation of the detector into the AMY magnet in 1986 and early running of the detector further commanded Virginia Tech's attention during the first few years of running.

After running commenced, the technician staffing was eliminated and graduate student staffing expanded to a level of four. In the same period, the research associate staffing was reduced from three to two individials. In 1987, Assistant Professor Leo Piilonen joined the effort. For most of the period since that time, the level of effort and staffing has not changed.

The AMY experiment continued to run beyond the end of this contract period; it terminated data-taking at the end of June 1994. Data analysis of the 340 pb^{-1} of data is expected to continue for into 1998. The AMY experiment has produced many significant experimental results that have confirmed the successful description of nature at the presently accessible level embodied in the Standard Model. For example, observation of the three-gluon vertex and discovery of resolved photon processes in two-photon interactions can be cited among AMY's accomplishments, along with measurements of the running of the strong coupling constant α_s and of forward-backward asymmetries in electroweak interactions at the energies where the Standard Model predicted the maximal interference between the intermediate photon and the Z° boson.

The majority of these studies were carried out as Ph.D. thesis topics by AMY's graduate students. During the contract period, the AMY experiment published 29 articles, produced 33 Ph.D. dissertations—four by Virginia Tech students—and has been well represented at American, Japanese, Korean and multinational conferences on particle physics. The Appendices contain the list of physics-related AMY publications and conference submissions, as well as Virginia Tech's AMY-related Ph.D. dissertations.

5. The MEGA and RHO Experiments

The MEGA experiment[6] at LAMPF is a search for muon- and electron-number non-conserving decay $\mu^+ \rightarrow e^+\gamma$. Observation of this decay mode would be the first direct evidence of physics beyond the presently accepted Standard Model of strong and electroweak interactions. This experiment was proposed in 1985 by 29 physicists from Los Alamos National Laboratory (including L. Piilonen, then a research associate there) and nine other American institutions. Virginia Tech became a collaboration institution with the arrival of Assistant Professor Leo Piilonen in 1987.

The MEGA experiment was approved in 1986, and saw its first engineering data in 1992 after a long period of detector design and construction. The analysis of this first data was carried out by graduate student Yiding Zhang of Virginia Tech, who also developed the analysis tools while writing his Ph.D. thesis under the supervision of Prof. Piilonen. The branching ratio sensitivity of the 1992 data was about 5×10^{-9}, nowhere near the previously published 90% confidence level upper limit of 4.9×10^{-11} obtained by the Crystal Box experiment at LAMPF.[7] However, the data taken in 1993–95 (after the end date of this contract) is expected to improve the branching ratio sensitivity to about 7×10^{-13}.

The RHO experiment[8] was proposed by the MEGA collaborators in 1991, with M. Cooper and R. Mischke of LANL and L. Piilonen of Virginia Tech as cospokespersons, and was approved for running in 1992 and 1993. It is a precise measurement of the

Michel ρ parameter[9] in the normal decay of the muon $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$, using a subset of the MEGA apparatus. Deviation of the positron energy spectrum from its expected shape, parameterized in the four-fermion approximation of the Standard Model by the quantity $\rho = 0.75$, would be an indication of the inadequacy of the Standard Model to predict *all* known basic interactions—for instance, evidence for the presence of right-handed currents in the predominantly left-handed weak interaction.

Engineering data for the RHO experiment were taken in 1992. The primary were taken in Summer 1993 (after the end of this contract period) for analysis by graduate student F. Liu and research associate X. Tu of Texas A&M University. These data are expected to improve the precision on the measurement of the Michel ρ parameter by a factor of three to a level of $\Delta\rho/\rho = 0.001$. A preliminary measurement of a subset of the 1993 data yielded a value of $\rho = 0.7488 \pm 0.0045(\text{stat}) \pm 0.0024(\text{syst})$.[10] This is to be compared with the current best value of $\rho = 0.7518 \pm 0.0026$.

5.1 The MEGA Experiment

The MEGA experiment at LAMPF was a search for the muon- and electron-number non-conserving decay $\mu^+ \to e^+\gamma$, and is being undertaken by a collaboration of about 70 physicists from 13 institutions. The participants from Virginia Tech were Associate Professor L. Piilonen, research associate D. Haim, and graduate student Y. Zhang. This was the third in a series of experiments at LAMPF search for $\mu^+ \to e^+\gamma$, and was finally expected to reach a branching ratio sensitivity of seven parts in 10^{13}, two orders of magnitude better than the Crystal Box upper limit.

The MEGA apparatus consisted of two "arms" for separately detecting positrons and photons that emerged from muons decaying at rest in a thin planar plastic target tilted at a steep angle relative to the incoming muon beam. The entire detector was contained in a 1.85 m diameter and 2.2 m long superconducting solenoid with a central induction of 1.5 T. This field confined all charged decay products (electrons and positrons) to the central region of the apparatus that contained the electron arm's eight MWPCs and two scintillator barrels. Any photons were unaffected by the magnetic field and traversed the nearly massless MWPCs (3×10^{-4} radiation length maximum) to the three coaxial and independent photon pair spectrometers where they had about 10% chance of converting to an observable e^+e^- pair without significant bremsstrahlung from the daughters.

The intrinsic resolution of the detector elements permitted rejection of virtually all radiative muon decays ($\mu \rightarrow e\gamma\nu\overline{\nu}$) and random coincidences of a positron from one muon decay with a photon from any other source.

Having separate detectors for the positrons and photons allowed us to optimize the performance of each detector arm, and allowed the photon arm to operate in a relatively quiet environment, since it was insensitive to the bulk of muon decays that did not produce an energetic photon. The latter feature allowed us to accept the full rate of muons from the LAMPF Stopped Muon Channel (30 Hz average, 500 MHz instantaneous with a typical 6% duty factor) with only 6×10^{-5} of the decays resulting in a photon with energy above 42 MeV. At the same time, any 20-ns wide snapshot of the electron arm MWPCs (in coincidence with a high energy photon, for example) contained fragments of ten positron tracks on average.

Because of the high activity in the electron arm MWPCs, only the photon arm provided the information for the first-stage trigger in selecting candidate $mu^+ \rightarrow e^+\gamma$ decays. A hardware trigger module continually monitored the pattern of hits in each of the photon pair spectrometers. Upon seeing a pattern indicative of a high energy photon, the sparsified raw data from the entire detector (about 1450 bytes) was stored in the FASTBUS latches, ADCs and TDCs. At the end of a LAMPF macropulse (750 μs duration, 80 Hz rate), the 20 or so stored events were transferred to a farm of eight DECstation 5000/240 servers for intermediate on-line analysis. The filtering of events proceeded from quick and simple-minded partial reconstruction of the end view of the positron arm MWPC information to a full three-dimensional reconstruction of the positron tracks, searching for an energetic positron that was reasonably back-to-back with the photon that triggered the event. Most events were rejected in the early stages of this analysis, with only one in 200 events surviving. The events that met the loose kinematic requirements of this on-line analysis were written on magnetic tape for most stringent off-line analysis.

The first data run of the MEGA experiment occurred over three weeks in 1992, when we recorded candidate $\mu \to e^+\gamma$ decays from approximately 3.5×10^{12} muon decays. At that time, only the two inner layers of the photon spectrometer were assembled, and the available online computing power (only four underpowered processors) limited the instantaneous muon-stopping rate to 60–100 MHz. The analysis techniques that had been developed to that point using simulated events proved to be inadequate for dealing with the real data, since (1) the simulation had not anticipated the level of electronic noise, both correlated and random, that was present in the electron arm MWPCs during the 1992 run and (2) the analysis was not robust enough to cope with chamber inefficiencies gracefully. An entirely new analysis scheme has since been developed and was applied to the 1992 data by Virginia Tech graduate student Y. Zhang. The analysis of the photon arm information has evolved in parallel by the efforts of Houston graduate student M. Dzemedzic. Finally, a new simulation program of the MEGA detector was developed by L. Piilonen that uses the EGS4 package[11] for tracking the histories of electromagnetic particles, and that incorporated the detailed detector geometry as well as all of the channel-by-channel inefficiencies.

5.2 The RHO Experiment

The RHO experiment was a precise measurement of the energy spectrum of the decay positrons emitted in the normal decay of the muon, $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$, using a subset of the MEGA apparatus. This experiment is expected to improve by a factor of three the precision on the measurement of the Michel parameter ρ, which characterizes the spectral shape in the four-fermion approximation of the Standard Model's description of this process.

Any deviation from the Standard Model prediction of $\rho = 0.75$ would be an indication of the inadequacy of the Standard Model. It has most often been interpreted in the context of the manifestly left-right symmetric extension of the Standard Model,[12] in which there are three additional gauge bosons with a parity-conserving Lagrangian whose left-right asymmetry arises via spontaneous breaking of the discrete left-right symmetry. The mass eigenstates of the charged bosons are, in this model, light and heavy admixtures of the chirality eigenstates. The positron spectral shape in normal muon decay is sensitive to the mixing angle ζ but quite insensitive to the squared-mass ratio $\epsilon = [m(W_1)/m(w_2)]^2$ of the light and heavy charged boson mass eigenstates.

In this experiment, the muon beam rate was reduced to about 5 kHz (average) to prevent saturation of the data acquisition system. A beam collimator was placed upstream of the solenoid to limit the muon stopping profile on the now vertical, not slanted, target. The magnetic field was reduced from 1.5 T to 1.425 T for part of the run, and the muon beam polarization was reversed by retuning the Stopped Muon Channel for another part of the run. These variations were introduced in order to test for the presence of systematic effects, given that the ultimate precision is expected to be dominated by the systematic uncertainty.

The 1992 RHO engineering data was not analyzed due to difficulties during the run with two of the electron arm MWPCs and the generally high electronic noise level. In the 1993 run, with improved operation conditions and higher rate capabilities of the online computer farm (used here for only modest filtering but aggressive data compaction), we recorded about 500 million muon decay triggers. A subset of this data (16 million triggers) was analyzed by Texas A&M graduate student F. Liu for her doctoral thesis (granted August 1994), with the result $\rho = 0.7488 \pm 0.0045$ (stat) $\pm$ 0.0024 (syst).

6. Resistive Plate Chamber Development

During the late 1980's and early 1990's, our group began to consider the possibility of detecting high energy neutrinos in cosmic rays from point and galactic sources. In the course of these considerations, it became clear that the development of resistive plate chambers as inexpensive large area charge particle detectors with good timing and spatial resolutions had wide applicability as neutrino detectors and as low-rate muon and hadron detectors in accelerator experiments. Research Scientist Norman Morgan was hired with primary responsibility for the development project. During his tenure, he made major progress in developing the technical expertise and understanding of these chambers. Ultimately, they were selected as the active component of the K_L°–μ detector for the BELLE experiment at KEKB.

In the final year of the contract period, we constructed eight 30 cm × 30 cm resistive plate chambers, tested these with cosmic rays at Virginia Tech, then took them to the KEK proton synchrotron for tests in a pion–electron beam. At KEK, a stack of alternating layers of RPCs and iron sheets was exposed to 0.5–3.7 GeV/c pions and 2.0 GeV/c electrons. The RPCs performed well in the beam test, with timing and spatial resolutions more than exceeding the requirements for Belle's KL/MU detector. Detailed results of this beamtest were published.[13]

Curriculum Vitae

Alexander Abashian
Department of Physics, VPI&SU

Post-Secondary Education

B.S. in Physics, Purdue University (1952).
Ph.D. in Physics, Johns Hopkins University (1957).

Experience

1952–1955	Junior Instructor—Johns Hopkins University
1955–1957	Research Assistant—Brookhaven National Laboratory
1957–1959	Instructor—University of Rochester
1959–1961	Staff Associate—Lawrence Berkeley Laboratory
1961	Lecturer—University of California at Berkeley
1961–1964	Assistant Professor—University of Illinois
1964–1966	Associate Professor of Physics—University of Illinois
1966–1972	Professor of Physics—University of Illinois
1970–1971	Staff Administrator—Atomic Energy Commission
1972–1980	Program Director—National Science Foundation
1978	Visiting Professor—CERN
1978–1979	Guest Professor—University of Hamburg
1980–1982	Physics Department Head—VPI&SU
1982–	Professor of Physics—VPI&SU
1986–1987	Visiting Staff Physicist—KEK
1987–1990	Director, Institute for High Energy Physics—VPI&SU

Professional Organizations

Fellow	American Physical Society
Member	Division of Particles and Fields, APS
Fellow	American Association for the Advancement of Science

Committees

1966–1969	ZGS Program Committee, Argonne National Laboratory
1971–1972	Trustee, Argonne National Laboratory Users Association
1974	HEP Future Facilities Panel, Woods Hole (ex officio)
1975	HEP Future Facilities Panel, Woods Hole (ex officio)

1977	ZGS Shutdown Committee, Argonne National Laboratory (ex officio)
1980	HEP Woods Hole Panel (ex officio)
1972–1980	DOE High Energy Physics Advisory Panel (ex officio)
1980–1984	SURA Board of Trustees
1982	Technical Advisory Committee for University Pgms, DOE
1982–1983	Chairman, 1983 DPF Annual Meeting
1989–1980	Member, Organizing Committee for 1990 Physics in Collision
1989–1980	Member, Organizing Committee for 1990 SE Conference on SSC

Research Interests

Properties of electroweak interactions
Tests of symmetry principles
Searches for new particles
Detector development

Conferences attended

Over 30 international conferences in high energy physics attended.

Invited Papers

Anomaly in $p + d \to {}^3H + X$—American Physical Society (1961)
Search for CP Violation—American Physical Society (1965)
Measurement of the Cross Section for νe Scattering—American Physical Society (1961)
Results from the AMY Experiment at TRISTAN (1987)
Searches for New Particles (1988)

Contributed Papers

About 60 papers at American Physics Society meetings, international conferences, and workshops.

Awards

Special Merit Scholarship, Purdue University (1948–1952)
Outstanding Performance and Special Achievement Award, NSF (1978)
Superior Accomplishment Award, NSF (1980)

Curriculum Vitae

Kazuo Gotow
Department of Physics, VPI&SU

Post-Secondary Education

B.S., University of Tokyo (1954).
M.S., University of Tokyo (1955).
Ph.D. in Physics, University of Rochester (1959).

Experience

1959–1964	Research Associate—University of Rochester
1964–1969	Associate Professor—VPI&SU
1968–1969	Associate Director—Space Radiation Effect Laboratory; and Adjunct Professor—College of William and Mary
1969–	Professor of Physics—VPI&SU
1971–1972	Visiting Scientist—INS, University of Tokyo
1972	Visiting Lecturer—University of Tokyo
1975–1976	Chairman—LAMPF Low Energy Pion Channel Working Group
1978	Visiting Research Scientist—TRIUMF
1978–1979	Member, NSAC Instrumentation Subcommittee
1983–1985	Member, LAMPF Technical Advisory Panel
1984–1987	Member, TRIUMF Long Range Planning Committee
1985–1986	Visiting Scientist—KEK
1987–1991	Visiting Scientist—KEK (part of each year)

Professional Organizations

Fellow	American Physical Society
Member	Division of Particles and Fields, APS
Member	Sigma Xi

Research Interest

$p-p$ scattering
$\pi -$ nucleon and $\pi -$ nucleus scattering
Lepton number nonconservation
Electroweak and hadronic interactions in e^+e^- collisions

Curriculum Vitae

Leo Piilonen
Department of Physics, VPI&SU

Post-Secondary Education

B.Sc. in Physics, University of Toronto (1978).
M.A. in Physics, Princeton University (1981).
Ph.D. in Physics, Princeton University (1985).

Experience

1985–1987	Postdoctoral Fellow—Los Alamos National Laboratory
1987–1993	Assistant Professor—VPI&SU
1993–	Associate Professor—VPI&SU

Professional Organizations

Member	American Physical Society
Member	Division of Particles and Fields, APS

Research Interest

Tests of symmetry principles (CP, T, lepton non-conservation)
Study of strong and electroweak interactions
Searches for new particles
Charged-particle detector development

Conferences attended

XII International Workshop on Weak Interactions and Neutrinos, Israel (1989).
Joint Lepton-Photon Symposium and Europhysics Conference, Switzerland (1991).
PF91, Vancouver, Canada (1991).
XII Rencontres Moriond, Les Arcs, France (1992).
Workshop on Physics at the SSC and Existing Accelerators, ANL (1993).
XIV International Workshop on Weak Interactions and Neutrinos, Korea (1993).

Invited papers

Recent Results from TRISTAN, XII International Workshop on Weak Interactions

and Neutrinos (1989)
Electroweak Physics with AMY, PF91 (1991).
On the Strength of the Evidence for the 17 keV Neutrino, XII Rencontres Moriond (1992).
Recent Results from TRISTAN, Workshop on Physics at the SSC and Existing Accelerators (1993).
MEGA: A Search for the Rare Decay $\mu^+ \to e^+ \gamma$, XIV International Workshop on Weak Interactions and Neutrinos (1993).

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[1]Bin Lu, *Search for Axion-like Particles in the SLAC Beam Dump*, Doctoral thesis, Virginia Polytechnic Institute and State University (1987).

[2]J.D. Bjorken *et al.*, *Search for Neutral Metastable Penetrating Particles Produced in the SLAC Beam Dump*, Phys. Rev. **D38**, 3375 (1988).

[3]F. Kajino, A. Abashian and K. Gotow, *Cathode Charge Distributions of Resistive Plastic Proportional Counters*, Nucl. Instr. and Meth. **A245** (1986) 507.

[4]A. Abashian *et al.*, *The AMY Barrel Electromagnetic Shower Counter at TRISTAN*, NIM **A317** (1992) 75.

[5]*TRISTAN Proposal for EXP-003*, KEK November 1984.

[6]M. D. Cooper *et al*, *MEGA: Search for the Rare Decay* $\mu^+ \rightarrow e^+ \gamma$, LAMPF Research Proposal 969, 1985.

[7]R. D. Bolton *et al.*, Phys. Rev. Lett. **56**, 2641 (1986).

[8]J. F. Amann *et al*, *A Proposal to Measure the Michel Parameter Rho with the MEGA Positron Spectrometer*, LAMPF Research Proposal 1240, 1991.

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[10]F. Liu, *Measurement of the Michel Parameter* ρ *with the MEGA Positron Spectrometer*, Doctoral thesis, Texas A&M University, 1994.

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[12]M.A.B. Beg, R.V. Bundy, R. Mohopatra and A. Sirlin, Phys. Rev. Lett. **38**, 1252 (1977).

[13]N. Morgan, A. Abashian, K. Gotow, S. Hadley, D. Haim, C. Miller, and L. Piilonen, *Polyvinylchloride Resistive Plate Counters for Charged Particle Detection*, Nucl. Instrum. and Meth. **A340**, 341 (1994).

Appendix A. Conference Proceedings

1. *Search for Neutral, Penetrating, Metastable Particles Produced in the SLAC Beam Dump*, Proc. of the 4th Moriond Workshop on Massive Neutrinos in Particle Physics and Astrophysics, La Plagne, France (1984) 227.

2. *The AMY Electromagnetic Calorimeter*, Proc. of the Fermilab Gas Sampling Calorimetry Workshop, Batavia, IL (1985) 536.

3. *DPF 1983: Proceedings of the Annual Meeting of the Division of Particles and Fields of the American Physical Society*, A. Abashian (Ed.). New York: AIP (1984). 296 pp.

4. *Properties of e^+e^- Interactions at $\sqrt{s} = 50\,\mathrm{GeV}$ and $52\,\mathrm{GeV}$*, 1987 Int. Symp. for Lepton and Photon Interactions at High Energy, Hamburg, West Germany (1987).

5. *A Search for Mark-J Events at TRISTAN*, Int. Conf. on High Energy Physics, Munich, Germany (1988).

6. *A Search for New Heavy Quarks using Hadronic Events Containing Leptons*, Int. Conf. on High Energy Physics, Munich, Germany (1988).

7. *A Search for Charged and Neutral Heavy Leptons in e^+e^- Annihilations at $\sqrt{s} = 56\,\mathrm{GeV}$*, Int. Conf. on High Energy Physics, Munich, Germany (1988).

8. *Measurement of Cross-Sections and Charge Asymmetry for $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to \mu^+\mu^-$ for $\sqrt{s} = 52\,\mathrm{GeV}$, $55\,\mathrm{GeV}$, and $56\,\mathrm{GeV}$*, Int. Conf. on High Energy Physics, Munich, Germany (1988).

9. *The Physics of Jets Produced in Electron-Positron Collisions at Center-of-Mass Energies from 50 GeV to 56 GeV*, Int. Conf. on High Energy Physics, Munich, Germany (1988).

10. *Hadron Production in Gamma-Gamma Collisions at Large Q^2 at AMY*, Int. Conf. on High Energy Physics, Munich, Germany (1988).

11. *A Study of QED Processes in the Electron-Positron Interactions and Search for Excited Leptons at* $\sqrt{s} = 50\,\text{GeV}$ *to* $56\,\text{GeV}$, Int. Conf. on High Energy Physics, Munich, Germany (1988).

12. *Detection of* $H_o \to \gamma\gamma$ *at the SSC*, Proc. of the DPF Snowmass Summer Study (1988) 98.

13. *Multi-Hadronic Event Properties in* e^+e^- *Annihilation at* $\sqrt{s} = 52\,\text{GeV}$ *to* $57\,\text{GeV}$, Int. Symp. on Lepton and Photon Interactions, Stanford, CA (1989).

14. *A Search for Heavy Leptons and New Particles Beyond the Standard Model in* e^+e^- *Annihilations at* $\sqrt{s} = 50\,\text{GeV}$ *to* $60.8\,\text{GeV}$, Int. Symp. on Lepton and Photon Interactions, Stanford, CA (1989).

15. *Measurement of R for* e^+e^- *Annihilation at TRISTAN*, Int. Symp. on Lepton and Photon Interactions, Stanford, CA (1989).

16. *Measurements of the Cross-section for* $e^+e^- \to \gamma\gamma$ *at TRISTAN*, Int. Symp. on Lepton and Photon Interactions, Stanford, CA (1989).

17. *Determination of the QCD Renormalization Scale and* $\Lambda_{\overline{MS}}$ *from Multi-Jet Events Produced in Electron-Positron Collisions*, Int. Symp. on Lepton and Photon Interactions, Stanford, CA (1989).

18. *A Study of Multi-Hadron Events with Isolated Leptons Produced in* e^+e^- *Annihilations at* $\sqrt{s} = 50\,\text{GeV}$ *to* $61.4\,\text{GeV}$, Int. Symp. on Lepton and Photon Interactions, Stanford, CA (1989).

19. *A Study of* e^+e^- *Annihilation into Four-Lepton Final States*, Int. Symp. on Lepton and Photon Interactions, Stanford, CA (1989).

20. *A Measurement of the Photon Structure Function* F_2 *at an Average* Q^2 *of* $67\,\text{GeV}/c^2$, Int. Symp. on Lepton and Photon Interactions, Stanford, CA (1989).

21. *Recent Results from TRISTAN*, Int. Workshop on Weak Interactions and Neutrinos, Ginosar, Israel (1989).

22. *Bose-Einstein Correlations in Pion Production at TRISTAN*, Int. Conf. on High Energy Physics, Singapore (1990).

23. *Measurement of the* $ee^+e^- \to b\bar{b}$ *Cross-section and Forward-Backward Charge Asymmetry at a Center-of-Mass Energy of* $57.2\,\text{GeV}$, Int. Conf. on High Energy Physics, Singapore (1990).

24. *Measurement of the Polarization of Tau Leptons from* e^+e^- *at* $\sqrt{s} = 57\,\text{GeV}$, Int. Conf. on High Energy Physics, Singapore (1990).

25. *Comparison of Quark and Gluon Jets using Three Jet Events from e^+e^- Annihilation at TRISTAN*, Int. Conf. on High Energy Physics, Singapore (1990).

26. *A Search for Charged Higgs Bosons in e^+e^- Annihilation using the AMY Detector at $\sqrt{s}$ = 50 GeV to 61.4 GeV*, Int. Conf. on High Energy Physics, Singapore (1990).

27. *Comparison of the Next-to-Leading Logarithm QCD Approximation with TRISTAN Data and a Determination of $\Lambda_{\overline{MS}}$*, Int. Conf. on High Energy Physics, Singapore (1990).

28. *Measurements of Heavy Quark Fragmentation at TRISTAN*, Int. Conf. on High Energy Physics, Singapore (1990).

29. *On the Strength of the Evidence for the 17 keV Neutrino*, XIIth Moriond Workshop on Progress in Atomic Physics, Neutrinos and Gravitation, Les Arcs, France (1992).

30. *Measurements of Inclusive Jet Production in Almost Real Gamma Gamma Collisions at TRISTAN*, XVI Int. Symp. on Lepton and Photon Interactions, Ithaca, NY (1993).

31. *Recent Results from AMY*, Workshop on Physics at the Supercollider and Existing Accelerators, Argonne, IL (1993).

32. *The MEGA Experiment*, Int. Workshop on Weak Interactions and Neutrinos, Seoul, Korea (1993).

Appendix B. Publications

1. F. Kajino, A. Abashian and K. Gotow, *Cathode Charge Distributions of Resistive Plastic Proportional Counters*, Nucl. Instr. and Meth. **A245**, 507 (1986).
2. H. Sagawa *et al.* (AMY Collaboration), *Measurements of R and a Search for Heavy-Quark Production in* e^+e^- *Annihilation at* $\sqrt{s} = 50$ *and* 52 GeV, Phys. Rev. Lett. **60**, 93 (1988).
3. S. Igarashi *et al.* (AMY Collaboration), *Search for Isolated Leptons in Low-Thrust* e^+e^- *Annihilation Events at* $\sqrt{s} = 50$ *and* 52 GeV, Phys. Rev. Lett. **60**, 2359 (1988).
4. J.D. Bjorken *et al.*, *Search for Neutral Metastable Penetrating Particles Produced in the SLAC Beam Dump*, Phys. Rev. **D38**, 3375 (1988).
5. S.S. Myung *et al.* (AMY Collaboration), *Experimental Mass Limit for Fourth-Generation Sequential Lepton from* e^+e^- *Annihilation at* $\sqrt{s} = 56$ GeV, Phys. Rev. Lett. **61**, 911 (1988).
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Appendix C. VPI dissertations

1. Kangping Hu, *Study of Photon Production in e^+e^- Collisions at TRISTAN*, PhD thesis, Virginia Polytechnic Institute and State University (August 1991).

2. Anzhi Lai, *Study of Bhabha Scattering at Center-of-Mass Energies from 52 GeV to 58 GeV*, PhD thesis, Virginia Polytechnic Institute and State University (May 1992).

3. Kevin L. Sterner, *Electron-Positron Annihilation into Photons at Center-of-Mass Energies from 50 to 64 GeV*, PhD thesis, Virginia Polytechnic Institute and State University (August 1993).

4. Mark E. Mattson, *Inclusive Hadron Production in Electron-Positron Collisions with Center-of-Mass Energies from 50 to 61.4 GeV*, PhD thesis, Virginia Polytechnic Institute and State University (January 1994).