TUNL XL

PROGRESS REPORT

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TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

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## Contents

**Introduction** ix

**Personnel** xvii

1 **Fundamental Symmetries in the Nucleus** 1
   1.1 Parity-Mixing Measurements 1
      1.1.1 Parity Violation with Polarized Epithermal Neutrons – (The TRIPLE Collaboration) — General 1
      1.1.2 Parity Violation with Polarized Epithermal Neutrons – (The TRIPLE Collaboration) — Status of Experiments and Analysis 2
   1.2 Time-Reversal Invariance 6
      1.2.1 Neutron-Transmission Tests of Time-Reversal Invariance 6
   1.3 Quantum Chaos in Nuclei 8
      1.3.1 Chaos and Symmetry Breaking in the s-d Shell 8

2 **Few-Nucleon Interaction Dynamics** 10
   2.1 Nucleon-Nucleon Interaction 10
      2.1.1 Double Polarized Neutron-Proton Scattering and Nucleon-Nucleon Tensor Force: An Alternative Analysis 10
      2.1.2 Monte-Carlo Corrections for Neutron-Proton Analyzing Power Data at 12.0 MeV 13
   2.2 Proton-Deuteron Scattering 16
      2.2.1 Proton-Deuteron Scattering at Low Energies 16
   2.3 Neutron-Deuteron Interactions 18
      2.3.1 Neutron-Deuteron Analyzing Power at $E_n = 1.9$ MeV 18
      2.3.2 A New Twist to the $3N$ Analyzing Power Puzzle 21
      2.3.3 Longitudinal $n-d$ Total Cross-Section Difference 24
      2.3.4 Preliminary Analysis for the Space-Star Configurations at 10.3 and 13.0 MeV 26
      2.3.5 $n-d$ Breakup Configurations at 13.0 MeV 28
2.3.6 Status of Data Analysis for n-d Breakup Measurements at 16.0 MeV 30
2.4 The $A = 4$ System .......................... 33
2.4.1 Cross-Section and Analyzing Power Measurements of Proton-$^3$He Elastic Scattering .......................... 33

3 Nuclear Astrophysics and Nuclear Structure 36
3.1 S-Factor Slopes .................................. 36
3.1.1 Slope of the Astrophysical S Factor for the $^6$Li($p$,γ)$^7$Be Reaction .......................... 36
3.1.2 Studies of the $^7$Be($p$,γ)$^8$B Reaction and the Solar Neutrino Problem .......................... 37
3.1.3 The $^{10}$B($p$,γ)$^{11}$C Reaction at Astrophysically Relevant Energies .......................... 40
3.1.4 The Ratio of S Factors for (p,γ) Reactions on $^{12}$C and $^{13}$C at Astrophysically Relevant Energies .......................... 42
3.1.5 Measurement of the Analyzing Power for the $^{13}$C($p$,γ)$^{14}$N Reaction at 450 keV .......................... 45
3.1.6 Evidence for a New Resonance in the $^{14}$N($p$,γ)$^{15}$O Reaction .......................... 47
3.2 Hydrostatic Hydrogen Burning .......................... 50
3.2.1 Thermonuclear Reaction Rate of $^{21}$Na($p$,γ)$^{22}$Mg .......................... 50
3.2.2 Low-Energy Resonance Strengths for $^{23}$Na($p$,α)$^{20}$Ne .......................... 52
3.2.3 The $^{25}$Al($p$,γ)$^{26}$Si Reaction in Novae .......................... 53
3.3 Explosive Hydrogen Burning .......................... 55
3.3.1 Destruction of $^{18}$F via $^{18}$F($p$,α)$^{15}$O Burning through the $E_{c.m.} = 665$ keV Resonance .......................... 55
3.4 Helium Burning .................................. 58
3.4.1 Sub-Coulomb α Transfers on $^{12}$C .......................... 58
3.5 Thermal Equilibration .......................... 60
3.5.1 Thermal Equilibration of $^{26}$Al .......................... 60
3.6 Big-Bang Nucleosynthesis .......................... 62
3.6.1 Analyzing Power Measurements of $\bar{n}$-p Capture at 7.6 MeV .......................... 62
3.6.2 Measurements of $^2$H(d,p)$^3$H and $^2$H(d,n)$^3$He Total Cross Sections at Big-Bang Nucleosynthesis Energies .......................... 64
3.6.3 Measurements of Tensor Polarization Observables in the $^2$H($d$,γ)$^3$He Reaction at Low Energies .......................... 65
3.6.4 A Detailed Study of the $^3$He(d,p)$^4$He Reaction at Low Energies .......................... 68
3.7 Nuclear Level Density .......................... 70
3.7.1 Level-Density Measurements .......................... 70
3.7.2 Average Level Densities and γ-ray Strength Functions .......................... 72

4 Sub-Nucleonic Degrees of Freedom 74
4.1 Electromagnetic Form Factors of Nucleons .......................... 74
4.1.1 Measurement of the Ratio of the Electric to Magnetic Form Factor of the Neutron using the \(d(e, e'n)p\) Reaction: JLAB experiment E93-038 74

5 Neutrino Physics 78
5.1 KamLAND ................................................. 78
5.1.1 Overview of the KamLAND Neutrino Detector Project 78
5.1.2 Photomultiplier Testing for the KamLAND Outer Detector 80
5.1.3 Installation and Assembly of the KamLAND Outer Detector 84
5.1.4 Simulation of the KamLAND Water-Čerenkov Veto Detector 88

6 The Many-Nucleon Problem 91
6.1 Phenomenology of Preequilibrium Nuclear Reactions ................................. 91
6.1.1 Complex Particle Channels ..................................... 91
6.1.2 Elastic Scattering and its Relation to Collective Excitations ................ 93
6.1.3 Formal Release of PRECO-2000 ..................................... 94
6.2 Nuclear Data Evaluations ........................................... 95
6.2.1 Data Evaluation Activities ........................................ 95
6.2.2 Evaluated Nuclear Structure and Data Files - ENSDF .................... 96
6.2.3 World Wide Web Services .......................................... 97
6.2.4 Proton-Induced Thermonuclear Reaction Rates for \(A = 20-40\) Nuclei ................................. 98

7 Nuclear Instruments and Methods 101
7.1 Tandem Accelerator ............................................. 101
7.1.1 Tandem Accelerator Operation ..................................... 101
7.2 KN Accelerator .................................................. 103
7.2.1 KN Accelerator .................................................. 103
7.2.2 Laboratory Improvements and Modifications .................................. 104
7.2.3 Planned Improvements to the Laboratory .................................. 106
7.3 LENA ............................................................. 107
7.3.1 Construction of the Laboratory for Experimental Nuclear Astrophysics .................................................. 107
7.3.2 Measurement of Gamma-Ray Coincidence Background at LENA .......... 108
7.4 Polarized Ion Source .............................................. 111
7.4.1 Atomic Beam Polarized Ion Source ...................................... 111
7.4.2 Research on Improved Ionization Techniques for Spin-Polarized H and D Atoms .............................................. 111
7.4.3 An Attempt to Control the Nucleation Rate of Carbon Nanotubes with a Hydrogen Beam Plasma .............................................. 112
7.5 Polarized Targets ................................................. 114
## Contents

7.5.1 Polarized Target Development at TUNL and at HI\(\gamma\)S .......................... 114  
7.5.2 Investigations of Polarized \(^3\)He Target Systems ............................... 115  
7.6 Special Unpolarized Targets ................................................................. 118  
7.6.1 First Hydrogen Runs with the Gas-Jet Target ...................................... 118  
7.7 Ion Sources ............................................................................................... 121  
7.7.1 Negative-Ion Sputter Source ................................................................ 121  
7.8 Ultra-Cold Neutrons .................................................................................. 122  
7.8.1 Progress at LANSCE ............................................................................. 122  
7.8.2 UCN Source Studies Utilizing Solid Deuterium at LANSCE ................. 122  
7.9 Detection Techniques and Detector Development ..................................... 125  
7.9.1 Studies of Weak Capture \(\gamma\)-ray Resonances via Coincidence Techniques ............................................................. 125  
7.9.2 Development of a Compton Suppression Technique based on a Neural Network ................................................................. 127  
7.9.3 Detecting Recoil Protons from Neutron Decay ...................................... 127  
7.9.4 Efficiency Determination of HPGe Detectors ........................................ 128  
7.10 Neutron Polarization ................................................................................ 132  
7.10.1 Measurements of the \(^7\)Li(\(p,\alpha\))\(^7\)Be Polarization-Transfer Reaction at Low Energies ....................................................... 132  
7.11 Data Acquisition System .......................................................................... 134  
7.11.1 Development of the TUNL Real-Time Analysis Package (TRAP) ........ 134  

8 Spallation Neutron Source ................................................................. 137  
8.1 Activities at TUNL .................................................................................... 137  
8.1.1 Workshop on Fundamental Physics with Pulsed Neutron Beams .......... 137  
8.1.2 Fundamental Neutron Physics Beamlines at the Spallation Neutron Source ............................................................. 141  

9 HIGS Facility at the DFELL ................................................................. 143  
9.1 Big-Bang Nucleosynthesis Studies .......................................................... 143  
9.1.1 A Measurement of the Asymmetry in Photodisintegration of the Deuteron at Low Energies ...................................................... 143  
9.1.2 Photodisintegration of the Deuteron between \(E_\gamma = 2.4\) and 4.0 MeV ................................................................. 146  
9.2 Nuclear Resonance Fluorescence ........................................................... 149  
9.2.1 A Program of Nuclear Resonance Fluorescence Studies: The Assignment of Parity to Nuclear Levels in Even-Even Nuclei ...................................................... 149  
9.3 Applications Research ........................................................................... 153  
9.3.1 A Search for Nuclear Isomers for Use in a Nuclear Battery ................ 153  
9.4 Nucleon Properties and Meson-Nucleon Degrees of Freedom ...................... 156
Contents

9.4.1 Compton Scattering of a 100% Polarized $\gamma$-ray Beam from Protons 156
9.4.2 Photodisintegration of $^3$He at HI$\gamma$S ................................. 157
9.5 Resonance Studies ................................................................. 159
  9.5.1 Nuclear Resonance Studies of the $^{13}$C($\gamma,n)^{12}$C at HI$\gamma$S ... 159
9.6 Nuclear Astrophysics ............................................................... 162
  9.6.1 Remarks on Nuclear Astrophysics Studies at HI$\gamma$S ................. 162
9.7 Detector Developments .......................................................... 165
  9.7.1 Development of a Compton-Scattering-Based Beam-Intensity Monitor at the HI$\gamma$S Facility .......................... 165
  9.7.2 $\gamma$-Ray Beam Flux Monitoring with Improved Scintillator Paddles .. 167

Appendices 169
Introduction

The Triangle Universities Nuclear Laboratory (TUNL) – a collaboration of Duke University, North Carolina State University, and the University of North Carolina at Chapel Hill – has had a very productive year. The following reports cover parts of the first and second year of a three-year grant between the U.S. Department of Energy and the three collaborating universities.

During the current grant period TUNL physicists have achieved major successes:

- **KamLAND**: We completed the installation of the outer (water Čerenkov) detector for KamLAND, which consisted of 225 water-proofed 20” phototubes mounted and cabled inside a 20-m high by 20-m diameter cylindrical cavity. The outer walls of the cavity and the inner detector sphere and support pillars were lined with light-reflecting Tyvek. Water filling is currently in progress.

- **Photodisintegration of the deuteron at HIγS**: The BLOWFISH neutron detector array and the TUNL NTOF neutron polarimeter were used to obtain photodisintegration data on the deuteron using the HIγS 100% linearly polarized γ-ray beam in the energy range from $E_\gamma = 2.4$ to 10 MeV. These data are relevant to Big-Bang nucleosynthesis and to the GDH sum rule of the deuteron.

- **Nucleon-deuteron analyzing power puzzle**: Our new data for $n$-$d A_y(\theta)$ below $E_n = 2$ MeV reveal a new twist to the long-standing $3N$ analyzing power puzzle. The new data clearly establish a substantial difference between the energy dependence of the discrepancy between $A_y(\theta)$ data and rigorous calculations for $n$-$d$ and $p$-$d$ elastic scattering, consequently making the $3N A_y(\theta)$ puzzle even more elusive.

- **Neutron electric form factor measurements**: The E93-038 collaboration has completed measurements of the ratio of the electric and magnetic form factors ($g_n = G_{En}/G_{Mn}$) at three $Q^2$ values, 0.45, 1.14, and 1.47 (GeV/c)^2. The measurements were made in Hall-C at JLab using the polarization-transfer technique. These are the first data for $g_n$ at $Q^2$ values above 1.0 (GeV/c)^2.
Introduction

- **$p$-$^3$He elastic scattering:**
  A supersonic gas jet of hydrogen from our recently refurbished gas-jet target was employed to measure the relative cross section for $p$-$^3$He scattering to within a few percent. Data of this quality are needed to interpret the 4N analyzing power puzzle, i.e., the 50% difference between rigorous 4N calculations and high-precision data for the $p$-$^3$He analyzing power.

- **Big-Bang nucleosynthesis:**
  Data relevant to Big-Bang nucleosynthesis have been obtained for the $^2$H$(d,n)^3$He and $^2$H$(d,p)^3$H reactions in the c.m. energy range between 240 and 330 keV.

- **High-resolution resonance measurements:**
  Study of nuclear level densities in the $1f$-$2p$ shell are being performed with an improved energy resolution (250 eV). Recent results for chromium isotopes yield approximately 50% more resonances than observed in the best previous measurements.

- **Strong evidence for a new resonance in the $^{14}$N($p,\gamma$)$^{15}$O reaction:**
  Using frozen ammonia targets and HPGe detectors we found evidence for a resonance in the $^{14}$N($p,\gamma$)$^{15}$O reaction at $E_p = 126$ keV. This reaction plays a key role in the CNO cycle, and the new resonance has a factor of 10 effect on the reaction rate at $10^8$ K.

- **Broad resonance in three-nucleon system:**
  Discrepancies between calculations and data for neutron-deuteron breakup, proton-deuteron breakup and neutron-deuteron capture at incident particle energies below 20 MeV are strongly suggestive of a resonance in the three-nucleon system at a c.m. energy of 9.3 MeV. Early inspection of these discrepancies indicates that the resonance would have a width of about 5 MeV and would likely be a spin doublet ($s = 1/2$) with an orbital angular momentum of either $l = 1$ or $l = 2$.

- **Nuclear Resonance Fluorescence (NRF) studies at HI-βS:**
  Using the monoenergetic and 100% linearly polarized γ-ray beam with intensities up to $10^7 \gamma/s$ on target, NRF measurements were made on several targets in the 4 to 8 MeV γ-energy range. With this powerful new technique, parity assignments were made to 18 dipole excitations in $^{138}$Ba. All had negative parity, including the level at 5.644 MeV, which was previously assigned $1^+$. 

- **S-factor ratio for the $^{12}$C($p,\gamma$)$^{13}$N and $^{13}$C($p,\gamma$)$^{14}$N reactions:**
  We have determined the ratio of S factors for these reactions at $E_p = 160$ keV. This ratio is a sensitive quantity for testing models of the CNO cycle and their predictions for the relative abundance of $^{12}$C and $^{13}$C, which is an important measure of stellar evolution.
Introduction

- **Sub-Coulomb α-transfer reactions:**
  We are studying the $^{12}\text{C}(α,γ)^{16}\text{O}$ reaction indirectly by measuring $^{12}\text{C}({}^6\text{Li},d)^{16}\text{O}$ at sub-Coulomb energies. New measurements of particle-gamma correlations provide tests of this new technique.

- **Chaos in the nucleus:**
  Established complete spectroscopy for $^{30}\text{P}$. The large effect of the small isospin-symmetry breaking on the spacing distribution that was first observed in $^{26}\text{Al}$ is confirmed in $^{30}\text{P}$. The deviation of the reduced transition matrix elements from the Porter-Thomas distribution is also observed in $^{30}\text{P}$.

- **Three-nucleon dynamics:**
  New measurements of the kinematically complete neutron-deuteron ($n-d$) breakup at $E_n = 10.3$ MeV confirm the space-star anomaly in $n-d$ breakup which is also observed at higher energies. Our data are about 15% higher than rigorous calculations.

- **HI$^3$S instrumentation:**
  A University of Virginia, University of Saskatchewan, TUNL, DFELL collaboration installed and commissioned an 88 neutron detector array (BLOWFISH).

- **Search for a resonance in $^{28}\text{Si}$:**
  Data were taken at the Holifield Radioactive Ion Beam Facility and the Yale ESTU Van de Graaff accelerator to identify a resonance near $E_{c.m.} = 450$ keV.

- **Nuclear data project:**
  In preparation for the publication of “Energy Levels of Light Nuclei $A = 8–10$,” a review of $A = 9$ has been distributed and a review of $A = 8$ is nearly complete. Through our efforts Elsevier has posted an archive of Fay Ajzenberg-Selove’s “Energy Levels of Light Nuclei” series. Our online services are expanding to provide an interactive interface within our reviews, for example in HTML format, and to permit simplified cross-referencing of tables, figures and supporting journal articles.

TUNL seeks to be on several of the physics research frontiers identified in the 1996 NSAC Long Range Plan and its successor, the 2001 NSAC Long Range Plan. The TUNL research program focuses on the following areas:

1. **NUCLEAR ASTROPHYSICS**
   with emphasis on measurements which are important for the solar-neutrino problem, stellar evolution and nucleosynthesis.

   Specific experiments address:
Introduction

- the abundance anomalies in globular clusters
- the explosive nucleosynthesis in novae
- the evolution of massive stars
- the origin of galactic radioactivity
- the solar-neutrino problem
- big-bang nucleosynthesis

The instrumentation available at TUNL includes the Enge split-pole spectrometer, the Low-Energy Beam Accelerator Facility (LEBAF), the new Laboratory for Experimental Nuclear Astrophysics (LENA) with its 200 keV accelerator for high-intensity unpolarized beams and its 1 MeV Van de Graaff, and the 3.5 MeV KN Van de Graaff accelerator at the High-Resolution Laboratory. In addition, the HiγS facility, which is presently under development at the Duke Free-Electron Laser Laboratory, has already been used for important experiments using polarized and monoenergetic γ rays.

Off-site facilities used by TUNL faculty include ORNL, ANL, Yale, and Notre Dame.

2. NEUTRINO PHYSICS
with the main emphasis on:

- anti-neutrino oscillation studies at KamLAND
- study of double-beta decay to excited 0^+ states
- preparation for neutrinoless double-beta decay searches at WIPP
- preparation for neutrino-physics studies at the SNS

3. FEW-NUCLEON SYSTEMS
with the aim of testing and refining the description of the nuclear force and its currents.

Specific experiments address:

- the role of non-nucleonic degrees of freedom in radiative-capture reactions on hydrogen isotopes
- the role of three-nucleon forces in the 3N and 4N continuum using hadronic and electromagnetic probes
- the strength of the tensor force in the NN interaction
- the search for “scaling” in the three-nucleon continuum
- the analyzing power puzzle in 3N and 4N scattering
- the role of charge-symmetry breaking in specific components of the NN interaction
• the quark structure of nucleons in experiments at JLAB

4. FUNDAMENTAL-SYMMETRY STUDIES
   with focus on
   • parity violation
   • isospin-symmetry breaking
   • time-reversal invariance
   • non-unitarity tests of the CKM matrix

Off-site facilities include LANSCE and Gammasphere. Preparations are under way for fundamental physics studies with neutron beams at the SNS.

5. R & D
   Developments in technology and instrumentation are vital to our research and training program. We continued our innovative work in:
   • polarized beam development
   • polarized target development
   • detector development
   • polarimeters for charged particles, neutrons and $\gamma$ rays
   • improving high-resolution beams for the KN and FN accelerators
   • completion of a Laboratory for Experimental Nuclear Astrophysics for radiative-capture studies of astrophysical interest.

6. NUCLEAR DATA PROGRAM

   • Nuclear Data evaluation for $A = 3–20$ for which TUNL is now the international center. Extensive services are provided for the international nuclear physics community through our WWW site. The services are being improved and expanded continuously.

7. NEW INITIATIVES and ACTIVITIES
   DOE has approved the funding of the TUNL/DFELL proposal to develop an intense beam of polarized $\gamma$ rays. DOE will provide a total of $3.2$ M to the project, TUNL will redirect $785,000$, and Duke University will contribute $650,000$. This High-Intensity Gamma-ray Source (HI$\gamma$S) will utilize the facilities of the Duke Free-Electron Laser Laboratory (DFELL). The DFELL currently includes a 270 MeV LINAC injector, a 1.1 GeV electron storage ring, and the OK-4 undulator. It is possible to tune the
electron beam in a manner which allows the FEL photons produced by one electron bunch to backscatter from a second electron bunch, all within the ring. This leads to an intense beam of almost 100% polarized γ rays whose energy can be readily tuned from about 2 MeV to greater than 200 MeV. Furthermore, beam energy spreads of less than 1% can be obtained solely by geometrical collimation. Maximum γ-ray fluxes of $10^7$ γ/s on target have recently been obtained for γ-ray energies below 20 MeV. In order to achieve the full range of energies and even higher γ-ray fluxes, it will be necessary to upgrade the energy of the injected beam to 1.2 GeV and to make modifications to the FEL storage ring. Funds for a 1.2 GeV synchrotron booster injector, which will allow us to produce γ rays up to about 220 MeV, will constitute the major part of the project. The upgrade project is scheduled for completion in the summer of 2005.

TUNL conducted its second year as an NSF supported Research Experience for Undergraduates (REU) program site. Fourteen students participated in this 10 week summer program.

The TUNL seminar program continues with characteristic vigor (18 invited speakers), supplemented by 17 in-house lectures on TUNL instrumentation and safety procedures and 5 lectures on Advances in Physics. A related program, the Triangle Nuclear Theory colloquia, is also beneficial to TUNL faculty and students.

The talents and enthusiasm of the 17 faculty members, 10 research staff and post-doctoral associates, and more than 30 graduate students from the three Triangle universities are responsible for the successes of our research program. We also benefit from collaborations with Tennessee Technological University, North Georgia College and State University, North Carolina A&T State University, Fayetteville State University, University of North Carolina at Wilmington, Penn State Altoona, State University of New York-Genesee, Idaho State University, Gettysburg College, China Institute of Atomic Energy and Tsinghua University (Beijing), Jagellonian University (Cracow), and Istituto Nazionale di Fisica Nucleare (Pisa).

The TUNL Advisory Committee - Drs. David Balamuth (University of Pennsylvania), Baha Balantekin (University of Wisconsin), James Friar (Los Alamos National Laboratory), Gerald Garvey (Los Alamos National Laboratory), and Steven Vigdor (Indiana University) - continues to provide valuable advice on the research program.

The research summaries presented in this progress report are preliminary. They should not be referenced in other publications. If you wish to know the current status of a project, please contact the person whose name is underlined in the author list or a senior author.
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xviii
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<td>Poole, J.</td>
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<td>Foster, R.</td>
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<td>Rowland, C.</td>
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<td>Harley, E.</td>
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<td>Runkle, R.</td>
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<tr>
<td>Hoë, C.\textsuperscript{4}</td>
<td>Duke</td>
<td>Sabourova, A.</td>
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<td>Hornish, M.</td>
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<td>Sabourova, K.</td>
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<td>Hutcheson, A.</td>
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<td>Tajima, S.</td>
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<td>Joshi, K.</td>
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<td>Tavukcu, E.</td>
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<td>Keener, G.</td>
<td>NCSU</td>
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\textsuperscript{1} Left 11/00
\textsuperscript{2} Graduated with M.S. Degree and left between Sept. 00 and Aug. 01
\textsuperscript{3} Graduated with Ph.D. Degree and left between Sept. 00 and Aug. 01
\textsuperscript{4} Transferred to Duke Free Electron Laser Laboratory
### Visiting Scientists

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Affiliation</th>
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<tbody>
<tr>
<td>Frank Avignone</td>
<td>1/01</td>
<td>University of South Carolina</td>
</tr>
<tr>
<td>Alexander Barabash</td>
<td>1/01, 8/01</td>
<td>ITEP, Moscow, Russia</td>
</tr>
<tr>
<td>Z. Berant</td>
<td>5/01</td>
<td>Negev Research Center/Yale University</td>
</tr>
<tr>
<td>Zemin Chen</td>
<td>7/01–8/01</td>
<td>Tsinghua University, Beijing, China</td>
</tr>
<tr>
<td>David Davis</td>
<td>9/00</td>
<td>University of Kuwait</td>
</tr>
<tr>
<td>Antonio Fonseca</td>
<td>6/01</td>
<td>Lisbon, Portugal</td>
</tr>
<tr>
<td>Chris Frankle</td>
<td>3/01</td>
<td>Los Alamos National Laboratory</td>
</tr>
<tr>
<td>Ru Igarashi</td>
<td>6/01–7/01</td>
<td>University of Saskatchewan</td>
</tr>
<tr>
<td>Jordi Jose</td>
<td>7/01</td>
<td>University of Catalonia</td>
</tr>
<tr>
<td>Nasser Kalantar</td>
<td>7/01–present</td>
<td>KVI, Groningen, The Netherlands</td>
</tr>
<tr>
<td>Norm Kolb</td>
<td>6/01</td>
<td>University of Saskatchewan</td>
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<tr>
<td>Wolfgang Kretschmer</td>
<td>4/01</td>
<td>Erlangen, Germany</td>
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<tr>
<td>Xuqin Lu</td>
<td>9/00–10/00</td>
<td>China Institute of Atomic Energy</td>
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<td>Cal Moss</td>
<td>3/01</td>
<td>Los Alamos National Laboratory</td>
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<tr>
<td>Blaine Norum</td>
<td>6/01–7/01</td>
<td>University of Virginia</td>
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<tr>
<td>Ron Pedroni</td>
<td>9/00–present</td>
<td>North Carolina A&amp;T State University</td>
</tr>
<tr>
<td>Norbert Pietralla</td>
<td>5/01–6/01</td>
<td>Yale University</td>
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<tr>
<td>Rob Pywell</td>
<td>6/01</td>
<td>University of Saskatchewan</td>
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<tr>
<td>Edouard Sharapov</td>
<td>9/00–11/00, 8/01–present</td>
<td>JINR, Dubna, Russia</td>
</tr>
<tr>
<td>Ivo Slaus</td>
<td>7/01</td>
<td>Rudjer Boskovic, Zagreb, Croatia</td>
</tr>
<tr>
<td>Henryk Witala</td>
<td>8/01</td>
<td>Jagellonian University, Cracow, Poland</td>
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### Temporary Graduate Student Personnel

<table>
<thead>
<tr>
<th>Name</th>
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<tbody>
<tr>
<td>Braizinha, B.</td>
<td>University of Lisbon</td>
</tr>
<tr>
<td>Hoedl, S.</td>
<td>Princeton University</td>
</tr>
<tr>
<td>Ives, J.</td>
<td>University of Saskatchewan</td>
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<tr>
<td>Marts, B.</td>
<td>Duke University</td>
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<td>Sawatzky, B.</td>
<td>University of Virginia</td>
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### Undergraduates

<table>
<thead>
<tr>
<th>Name</th>
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<tbody>
<tr>
<td>Asentzer, D.</td>
<td>University of North Carolina</td>
</tr>
<tr>
<td>Amthor, M.</td>
<td>North Georgia Coll. &amp; State University</td>
</tr>
<tr>
<td>Carpenter, A.</td>
<td>NC State University</td>
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<tr>
<td>Colarusso, M.</td>
<td>Queen’s University</td>
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<tr>
<td>Copp, B.</td>
<td>University of Texas - Dallas</td>
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<tr>
<td>Personnel</td>
<td>Institution</td>
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<tr>
<td>Jeffries, P.N.</td>
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<tr>
<td>King, D.</td>
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<td>LaViolette, P.</td>
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<td>Machado, T.J.</td>
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<tr>
<td>Metz, G.</td>
<td>University of North Carolina</td>
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<tr>
<td>Miller, S.</td>
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<tr>
<td>Pinnaduweage, D.</td>
<td>Austin College</td>
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<tr>
<td>Rellergert, W.</td>
<td>University of Missouri - Columbia</td>
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<tr>
<td>Stanton, M.</td>
<td>Rice University</td>
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<tr>
<td>Uehara, J.</td>
<td>UCLA</td>
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<tr>
<td>Wells, K.</td>
<td>Lincoln University</td>
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<td>Whitehead, L.</td>
<td>Vanderbilt University</td>
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