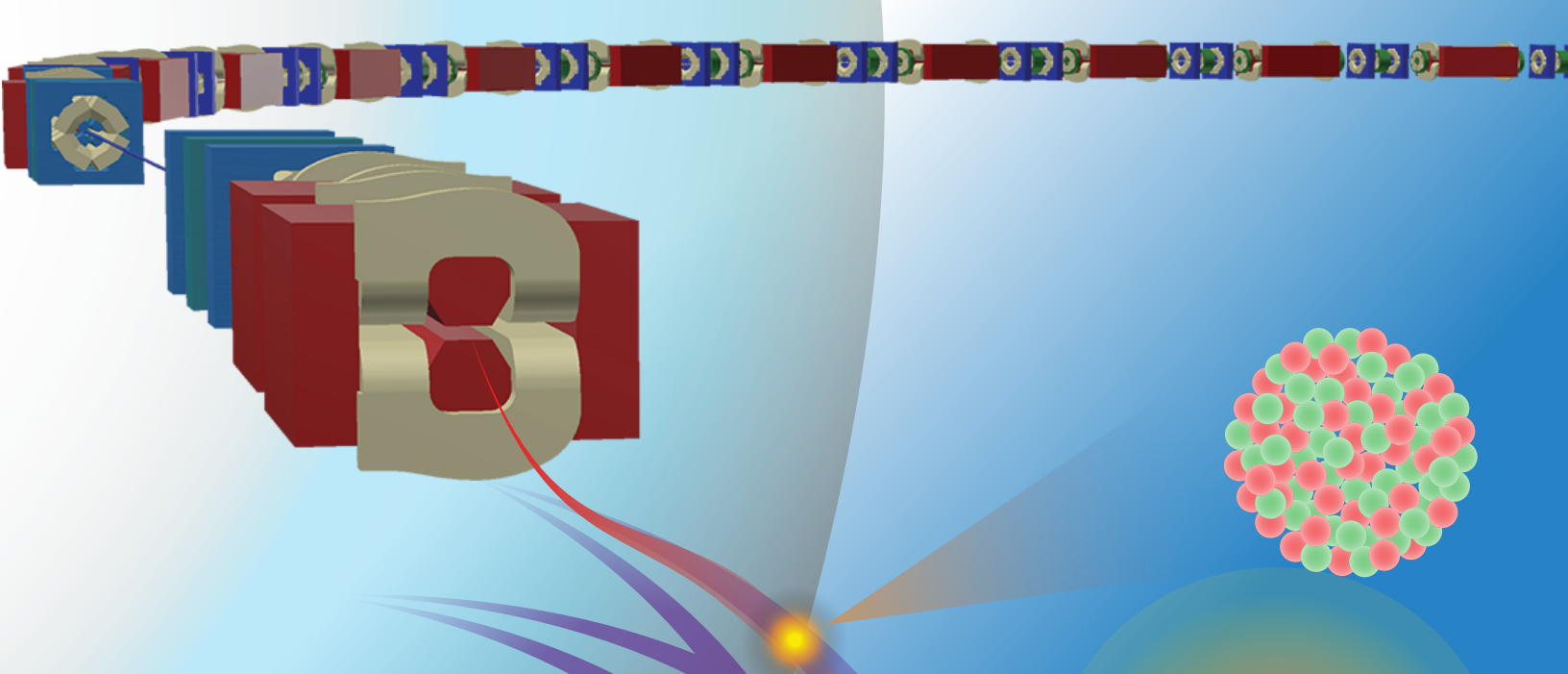

INTERNATIONAL WORKSHOP ON

NEXT GENERATION GAMMA RAY SOURCE

HOSTED BY

TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

Bethesda
Maryland
usa

November 16 - 19, 2016

INTERNATIONAL WORKSHOP ON NEXT GENERATION GAMMA-RAY SOURCE

Bethesda, MD, USA

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International Workshop on Next Generation Laser-Compton Gamma-Ray Source
November 17 - 19, 2016. Bethesda, MD, USA
Hosted by the Triangle Universities Nuclear Laboratory and Supported by the Department of Eenergy, Office of Science

Chapter 1

Executive Summary

The photon is a theoretically well-understood probe for investigating the structure of matter over a wide range of distance and energy scales. The angular-momentum selectivity and unconstrained transfer of isospin in most gamma-ray (γ-ray) induced reactions enable highly precise strategic investigations of nuclear and nucleon structure and collective motion responses of the internal degrees of freedom associated with electric charge and current distributions. In addition, high-energy photons are well suited for non-intrusive material analysis applications in areas such as homeland security, nuclear security, structural integrity assessments, and medical diagnostics.

Bremsstrahlung radiation produced by an electron beam incident on a high-Z target has been the workhorse photon-beam source used in nuclear-physics research and applications for over a century. The energy spectrum of a bremsstrahlung γ-ray beam enables measurements of nuclear structure and reaction dynamics over a continuous energy range in a single experiment. Tagged bremsstrahlung sources provide the capability of associating the energy of the photon inducing a reaction with the photons detected in the final state. Also, coherent bremsstrahlung beams produced using a crystal target offer researchers a partially polarized γ-ray beam at energies near the end point of the bremsstrahlung spectrum. The scientific insight provided by research conducted using these sources is impressive, and facilities with advanced bremsstrahlung photon sources continue to be used in highly productive research programs. However, the continuous energy nature of bremsstrahlung γ-ray beams, which facilitates survey measurements over a broad energy range, also has the adverse effect of creating backgrounds that limit the sensitivity of the experiments. These backgrounds make it difficult to investigate nuclear phenomena with extremely low cross sections or to perform

measurements on targets with small sample sizes, as is the case for isotopes with low natural abundances.

The nearly monoenergetic γ-ray beams produced by laser Compton scattering offers an alternative to bremsstrahlung beams, providing an enhanced signal-to-background ratio in basic and applied research and reducing the radiation exposure in material analysis applications. In addition, laser Compton γ-ray beams can be produced with a beam polarization greater than 95% for both linear and circular polarization. Linearly polarized laser Compton beams enable unambiguous determinations of the spin and parity of excited nuclear states, and beams with both linear and circular polarization are used in studies of the spin structure of nucleons.

Over the last three decades, laser Compton γ-ray beam facilities have provided intense polarized and nearly mono-energetic γ-ray beams for research programs in basic and applied nuclear physics. These facilities include GRAAL at the European Synchrotron Radiation Facility in Grenoble, LEGS at Brookhaven National Laboratory, LEPS at the SPring-8 facility, NewSUBARU at the University of Hyogo, and HIγS at the Triangle Universities Nuclear Laboratory. However, HIγS and LEPS are the only facilities worldwide that are operated with nuclear physics as the primary research focus. These facilities will soon be joined by two more that are currently under construction, ELI-NP in Romania and the γ-ray beam line at the Shanghai Synchrotron Radiation Facility (SSRF) in China. These facilities will produce γ-ray beams with energies below 12 MeV (ELI-NP), and below 20 MeV and above 300 MeV (SSRF).

Given that the time span between initial planning and the end of construction of an accelerator-driven light source is about a decade, consideration for next-generation laser Compton γ-ray sources should start now. Technological advances in electron accelerators, lasers, and optics made during the last decade create new options for producing intense polarized γ-ray beams with narrow energy widths at beam energies from around 1 MeV to several GeV, the energies relevant to nuclear-physics research. A workshop on the *The Next Generation Laser Compton Gamma-Ray Beam Facility*, sponsored by the Office of Nuclear Physics at the Department of Energy, was held November 17–19, 2016 in Bethesda, Maryland. The goals of the workshop were to identify basic and applied research opportunities at the frontiers of nuclear physics that would be made possible by the beam capabilities of an advanced laser Compton beam facility. To anchor the scientific vision to realistically achievable beam specifications using proven technologies, the workshop brought together experts in the fields of electron accelerators, lasers, and optics to examine the technical options for achieving the beam specifications required by the most compelling parts of the proposed research programs. An international as-

sembly of participants included current and prospective γ-ray beam users, accelerator and light-source physicists, and federal agency program managers. Sessions were organized to foster interactions between the beam users and facility developers, allowing for information sharing and mutual feedback between the two groups. The workshop findings and recommendations are summarized below.

Findings of Topical Working Groups:

The topical sessions at the workshop focused on five main subjects: low-energy quantum chromodynamics (QCD), nuclear structure, nuclear astrophysics, fundamental symmetries, and applications. All research discussed at the workshop, with the exception of low-energy QCD (LEQCD), could be carried out using γ-ray (γ-ray) beams at energies below about 20 MeV. The research presented by the LEQCD working group requires γ-ray beams with energies from about 60 to 350 MeV. Descriptions of the research opportunities are in the science sections of this document. Summaries of the findings of the topical working groups are given below.

- *Low-Energy QCD:*
  The emergence of hadron structure and the nuclear force from QCD is a key scientific problem. These phenomena are a consequence of quarks and gluons interacting at confinement-scale distances, where color forces are strong. The beams at a next generation laser Compton γ-ray source (NGLCGS) will enable measurements that uniquely probe hadron structure and hadronic interactions in this non-perturbative regime of QCD. The experimental program at the NGLCGS will investigate LEQCD phenomena with unprecedented precision in the photon energy range from about 60 MeV to the nucleon-to-Delta(1232) transition. Key elements of the program are high-precision measurements of the scalar and spin nucleon polarizabilities by Compton scattering and measurements of photopion production near threshold. Both rely on polarized beams striking polarized targets. Such measurements, together with advances in calculations using lattice QCD and QCD-based effective field theories, will explore the QCD origin of nucleon structure and charge-symmetry breaking in novel contexts and with unprecedented sensitivity.

- *Nuclear Structure:*
  The beams at an advanced γ-ray source will enable systematic studies of weak collective dipole and quadrupole nuclear excitations with unprecedented precision. Such studies will provide nuclear structure details and information about the symmetry energy of the nuclear equation of state that are difficult to obtainable

by other means. The increased γ-ray beam intensities at the next generation γ-ray source will enable mapping of M1 states in nuclei with a level of detail and breadth that will contribute to modeling of coherent neutrino-nucleus scattering and to calculating nuclear matrix elements for neutrinoless double-beta decay. Also, a next-generation γ-ray beam facility will enable new exclusive measurements of photodisintegration of few-nucleon systems with a precision that provides the highest sensitivity to long-range three-nucleon interactions in such reactions.

- *Nuclear Astrophysics:*
  New γ-ray beam capabilities will enable measurements that contribute broadly to open questions in nuclear astrophysics, questions such as big-bang nucleosynthesis, helium burning in massive stars, and synthesis of heavy nuclei. One of the most important reactions in stellar modeling is ^{12}C(α,γ)^{16}O. The rate of this reaction relative to the carbon forming reaction $3\alpha \rightarrow^{12}$C determines the fate of massive stars. The grand challenge at an advanced γ-ray beam facility will be measurement of the reaction rate the ^{16}O(γ,α)^{12}C reaction at energies approaching the temperatures at the core of stars.

- *Fundamental Symmetries:*
  The beams at an advanced γ-ray beam facility will enable measurements of parity violating photodisintegration of few-nucleon systems. In particular, a measurement of parity violation in deuteron photodisintegration near threshold is sensitive to a nucleon-nucleon (NN) PV amplitude that is not accessible using other systems. Such measurements sample the short-range part of the NN interaction, providing unique quantities for comparison with calculations using lattice gauge theory.

- *Applications:*
  The intense mono-energetic γ-ray beams from a next generation Compton γ-ray beam facility will enable photonuclear reaction measurements important for technologies and techniques used in homeland security and nuclear safeguards. It would also help several security programs for an advanced γ-ray beam facility to have a target area equipped for evaluating concepts for γ-ray beam interrogation of cargo, nuclear fuel, and special assemblies. The new beam facilities will also find applications in medicine.

Findings of Gamma-Ray Source Working Group:

Details of the various technology options considered are presented in the chapter on

laser Compton sources. A summary of the findings of the accelerator physics and light-source working group is below.
It is unlikely that a single γ-ray beam source can meet the requirements of both the low-energy (E_γ < 20 MeV) and medium-energy (E_γ > 60 MeV) parts of the field as described in the working group summaries above and in the science sections of this document. In the options discussed, the γ rays are produced by Compton scattering of electrons from photons in an optical cavity that is pumped with an external laser. The electron beam accelerators considered for the low-energy γ-ray source include an energy-recovery linac with superconducting RF cavities and a storage ring. For the medium-energy γ-ray source, a storage ring was the primary option. There is confidence that a high-quality electron beam with low emittance and low energy spread can be maintained in modern storage-ring lattices, thereby enabling production of γ-ray beams with low energy spread. The new facility construction cost of the storage-ring option for either a low-energy or medium-energy next-generation Compton γ-ray source will be over about 150M. The working group cautions that this estimate is extremely uncertain; it is intended only to set the scale within about a factor of two. For the low-energy sources, less expensive options, such as upgrades to existing facilities, were also discussed.

Recommendations:
The working groups through consensus make the following recommendations. This listing is not prioritized.

- High intensity γ-ray beams with circular and linear polarizations will be produced at next-generation γ-ray sources by Compton scattering of photons from relativistic electrons inside a high finesse optical cavity. The optical cavity will be pumped by a laser system with high precision control of beam polarization. The electron beam accelerator will use proven technologies, either an energy-recovery linac or a storage ring. The main technological challenge is the production of reliable optical cavities with the technical specifications required for the next-generation γ-ray sources.

  The highest priority R&D for the next-generation γ-ray source should be the development of high finesse optical cavities and the associated laser and optical systems. It is important for this work to include testing and optimization of the cavity under γ-ray production conditions.

- For photopion production experiments, small angle electron scattering (virtual photon tagging) with intense electron beams was discussed as an alternative to measurements using tagged bremsstrahlung sources or γ-ray beams produced by Compton scattering. This alternative technique would be implemented with high-current electron beams, possibly in a storage ring, and with thin targets that allow detection of the low-energy charged particles produced in the reaction. This method promises to be much more effective than conventional photon tagging techniques.

  R&D should be supported to develop an alternative to Compton scattering for producing γ rays with energies above the pion-production threshold. A system for virtual photon tagging in small-angle electron scattering is a promising candidate for study.

- Low-energy QCD phenomena will be explored at the NGLCGS with unprecedented precision at energies from below the pion-production threshold through to the Delta(1232) resonance region. The core experimental programs will involve Compton scattering to study the spin-dependent electromagnetic response of nucleons and near-threshold photopion production to investigate the QCD origin of charge-symmetry breaking. Both programs require polarized beams and targets. The measurements enabled by the NGLCGS, together with advances in calculations using Lattice QCD and QCD-based effective field theories, will explore the QCD origin of nucleon structure and charge-symmetry breaking.

  Investments in polarized targets are needed to prepare for experiments at the NGLCGS facilities.

  Investments in nuclear theory are needed to support the planning and analysis of low-energy QCD experiments at the NGLCGS facilities.

- The ^{12}C(α,γ)^{16}O reaction helps regulate the efficiency of helium burning in massive stars and ultimately determines the mass of the iron core in the incipient supernova. The uncertainty in the measured cross section for this reaction substantially limits our understanding of the late stages of the life of massive stars and the details of the nucleosynthesis under the explosive conditions of supernovae. The beams at the NGLCGS will enable measurements of the ^{16}O(γ,α)^{12}C reaction that

determine the reaction rate of α-particle capture on ^{12}C at center-of-mass energies lower than have been achieved with other techniques. Measurements of angular distributions require thin targets to allow detection of the α particles along with charged-particle detectors with wide angle coverage. Options include time projection chambers with optical and charge readout and silicon strip detectors with thin solid or gas targets.

Investments in active targets, such as time projection chambers, are needed to carryout the highest impact nuclear astrophysics measurements at NGLCGS facilities.

Chapter 6

Appendix

6.1 Workshop Agenda

Thursday, November 17, 2016 | **Overview Sessions**, Grand Ballroom A			
Time	*Title*	*Speaker*	Affliation
8:45	Welcome and remarks	Calvin Howell	Duke U & TUNL
Compton Gamma-Ray Sources			
9:00	a) Global Review of Compton γ-Ray Sources	Ying Wu	Duke U & TUNL
9:06	b) Facility Talks		
	b.1) HIGS and CGS Projects in the U.S.	Ying Wu	Duke U & TUNL
	b.2) ELI-NP and CGS Projects in Europe	Calin Ur	ELI-NP
	b.3) Compton γ-Ray Sources in Japan	Ryoichi Hajima	NIRS, Japan
	b.4) Compton γ-Ray Sources in China	Chuanxiang Tang	Tsinghua U, China
9:54	c) Possible Technologies for Next-Generation Sources		
	c.1) High Power Lasers and Optics	Fabian Zomer	LAL, France
	c.2) Accelerator Technologies	John Byrd	LBNL
	c.3) Compton Source Configuration Strategies	Ying Wu	Duke U & TUNL
10:30	**Break**, Salons A&B Foyer		

Thursday, November 17, 2016 | **Overview Sessions**, Grand Ballroom A

Low-Energy QCD

Time	*Title*	*Speaker*	Affliation
10:50	What to Learn from Nucleon Polarizabilities	Harald Griesshammer	GWU
11:15	Compton Experiments I	Phil Martel	U Mainz & Regina
11:30	Compton Experiments II	Gerald Feldman	GWU
11:45	Testing Confinement Scale QCD With Low-Energy Electromagnetic Pion Production	Aron Berstein	MIT
12:35	**Lunch**, Salons A&B Foyer		
14:00	**Hadronic Parity Violation**	W. Michael Snow	Indiana U
14:25	**Nuclear Structure**	Deniz Savran	GSI, Germany
14:55	**Nuclear Astrophysics**	Carl Brune	Ohio U

Applications

Time	*Title*	*Speaker*	Affliation
15:20	Homeland Security	Calvin Howell	Duke U & TUNL
15:35	National Nuclear Security	Matthew Durham	LANL
15:50	Medical Diagnosis	Anuj Kapadia	Duke U
16:05	**Charge to Working Groups**	Calvin Howell	Duke U & TUNL
16:15	**Break**, Grand Ballroom Salons A&B Foyer		
16:45	**Working Group Meetings**		

	Group	*Location*
	1) Gamma-Ray Source	Grand Ballroom B
	2.a) LE QCD: Nucleon Polarizabilities	Grand Ballroom A
	2.b) LE QCD: Photopion Physics	Grand Ballroom A
	2.c) LE QCD: Hadronic Partity Violation	Bethesda
	3) Nuclear Structure and Astrophysics	Chevy Chase
	4) Applications	Rockville
18:30	**Banquet**	Congressional Ballroom

Friday, November 18, 2016 | **Working Group Sessions**		
09:00	**Working Group Meetings**	
	Group	*Location*
	1) Gamma-Ray Source	Grand Ballroom B
	2.a) LE QCD: Nucleon Polarizabilities	Grand Ballroom A
	2.b) LE QCD: Photopion Physics	Grand Ballroom A
	2.c) LE QCD: Hadronic Partity Violation	Bethesda
	3) Nuclear Structure and Astrophysics	Chevy Chase
	4) Applications	Rockville
10:30	**Break**	Salons A&B Foyer
11:00	Working Group Meetings	Same Locations
12:30	Lunch	Salons A&B Foyer
14:00	Working Group meetings	Same Locations
15:30	Break	Salons A&B Foyer
16:00	Information Exchange Session	Salon A
17:30	Dinner (on your own)	
Saturday, November 19, 2016 | **Working Group & Closeout Sessions**		
09:00	Working Group Meetings	Same Locations
10:00	Break	Salons A&B Foyer
Closeout Sessions		
10:15	**Working Group Summaries** | Grand Ballroom	
	1.a) LE QCD: Nucleon Polarizabilities	
	1.b) LE QCD: Above the Pion-Production Threshold	
	1.c) LE QCD: Hadronic Partity Violation	
	2) Nuclear Structure	
	3) Nuclear Astrophysics	
	4.a) Applications: Homeland and Nuclear Security	
	4.b) Applications: Medicine	
	5) Gamma-Ray Source	
11:35	**Open discussion**	
12:00	**Summary and Closing Remarks**	
12:10	**Workshop Adjourned**	

6.2 Working Group Conveners

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