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Nuclear Photonics for the 21st Century

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Abstract
Lasers and laser-based sources are now routinely used to control and manipulate nuclear processes, e.g. fusion, fission and resonant nuclear excitation. Two such "nuclear photonics" activities with the potential for profound societal impact will be reviewed in this presentation: the pursuit of laser-driven inertial confinement fusion at the National Ignition Facility and the development of laser-based, mono-energetic gamma-rays for isotope-specific detection, assay and imaging of materials.

The demonstration of the first laser in 1960, almost immediately impacted atomic and molecular science. New optical tools were rapidly developed that enabled scientists to control, manipulate and ultimately understand the motion of the valence electrons in atoms and molecules. At the same time ideas also rapidly emerged for the use of lasers to manipulate and control nuclear processes. In particular, in June of 1960 Dr. John Nuckolls and colleagues at the Lawrence Livermore National Laboratory (LLNL) suggested that fusion ignition of a deuterium and tritium target could be achieved via laser drive. This suggestion lead to the eventual establishment of a Laser Programs Directorate at LLNL in 1972 and to the subsequent development of ever larger laser systems for the pursuit of fusion ignition. These efforts have culminated in the construction of the National Ignition Facility (NIF) at LLNL.

NIF is currently the world's most energetic laser system and largest operational laser facility. Its 192 laser beams can create a total UV pulse energy of approximately 2 MJ or nearly 100 times beyond the next most energetic system. NIF as a facility can address variety of missions including demonstration of fusion ignition, high energy density science, laboratory based astrophysics etc.. The demonstration of ignition and the creation of a robust ignition platform in turn will enable fundamentally new, neutron-based science and the development of laser fusion as a new and potentially limitless, source of clean energy.

During its past 5 years of operation, NIF has advanced the state of laser fusion by several orders of magnitude and now stands at the threshold of alpha heating, i.e. that point in the fusion process at which alpha particles initiate a fusion burn wave. This step is key along the path to ignition and fusion gain.

At the same time NIF as a laser system continues to be improved. Through targeted R&D efforts, great strides have been made with respect to the understanding and mitigation of the laser-induced optical damage of key optical components. Technical paths that would enable operation of NIF well beyond 2 MJ have been identified.

The eventual achievement of ignition at the NIF will produce neutrons with up to 100 times more energy than that of the laser used to drive the fusion process. Fusion energy gain of approximately 50 would be sufficient to create commercial, electrical power via fusion if the rate at which laser-controlled fusion could be increased to ~15 Hz and the efficiency of the drive laser could be increased to ~15%. Both appear viable.

Another nuclear process that may be manipulated via photons is nuclear resonance fluorescence (NRF). NRF is the analog to laser excitation of the valence electrons of the atom or molecule. In NRF, however, it is proton motion and not electron motion that is resonantly excited by the photon. The resonant motion of protons in the nucleus is dependent upon both the electro-magnetic force and the nuclear strong force. Therefore, NRF transition energies are a function of the number of nucleons in the nucleus and are thus signatures of the isotope and not of the element. Different isotopes of the same element have fundamentally different and to first order completely unrelated NRF spectra. In addition most NRF transitions of interest occur at energies between 1 MeV and 3 MeV. This energy range is commonly known as the "minimum" attenuation range as it is region for all materials for which electron-medicated scattering decreases and pair production has not yet become dominant. In this region it is possible for photons to penetrate large quantities of material (of order a meter or more). As a consequence, NRF excitation and detection may be used to non-destructively identify the isotopic as well as the elemental content of an object even if it is obscured or hidden behind other material. Possible applications include the detection of clandestine, hidden nuclear materials, precision assay of nuclear fuels and identification of isotopes within radioactively hot nuclear waste. The latter is of particular importance to societal grand challenges such as the clean up of the Fukushima nuclear facility.

NRF transitions are very narrow. Line widths are typically of order a few eV, i.e. a part in a million. Efficient excitation requires a mono-energetic or quasi-mono-energetic gamma-ray source. Such sources are now being created via laser-Compton scattering. A laser-Compton source produces quasi-mono-energetic gamma-rays via the interaction of a high-energy (joule-class), short-duration laser pulse with relativistic (few hundred MeV) electrons. The head on (180 degree) Compton process produces up-scattered photons with maximum energy equal to four times the normalized energy of the electron squared times the energy of the incident laser photon. Effectively this process uses few eV visible photons to produce beams of few MeV gamma-rays. The peak brilliance of laser-Compton machines at a few MeV can exceed the bending magnet output of the world's largest synchrotrons by more than 15 orders of magnitude. Properly designed laser-Compton gamma-ray sources can be narrow bandwidth (of order keV), highly collimated (of order 100 micro radians) and polarized (same polarization as the laser). Initial laser-Compton proof of concept machines demonstrated the ability to detect and image objects based on excitation of NRF even in the presence of significant shielding.

Large-scale (several $100M) projects to create next-generation laser-Compton machines for basic science and critical nuclear materials management applications are now being pursued in Europe, Japan and the USA. These new machines which will come on line by the end of the decade, may have outputs of up to 8 orders beyond the present state of the art and promise to do for isotopic science and applications in the 21st century what the laser did for atomic and molecular science and applications in the 20th.

Dr. Christopher P. J. Barty is the Chief Technology Officer for the National Ignition Facility and Photon Science Directorate at the Lawrence Livermore National Laboratory. At LLNL he has led efforts to develop kJ-class ultrahigh intensity lasers to probe nuclear fusion at the National Ignition Facility and has invented and developed new mono-energetic gamma-ray technologies that enable isotope-specific material detection, assay and imaging. His academic background includes B.S. degrees in Chemistry, Physics and Chemical Engineering from North Carolina State University and an M.S and Ph.D. in Applied Physics from Stanford University. Dr. Barty is a Fellow of the Optical Society of America, a Fellow of Society of Photo-optical Instrumentation Engineers, a Fellow of the American Physical Society, a Senior Member of Institute of Electrical and Electronics Engineers and co-chair of the International Committee on Ultrahigh Intensity Lasers (ICUIL).

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