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Science Day 2005 Poster Abstracts: Light and Matter

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The Quantum Nature of Light: Using Highly Charged Uranium to Test Quantum Theory with Unprecedented Accuracy

Peter Beiersdorfer

Modern atomic spectroscopy makes it possible to study, with ultrahigh precision, the discrete energy quanta of light predicted in one of Einstein's 1905 papers. LLNL's electron beam ion trap, called SuperEBIT, produces highly charged ions of any element, including uranium with all electrons removed. SuperEBIT measures the energy of the light quanta given off by these ions to detect energy shifts caused by large relativistic effects associated with the very high velocity at which an electron orbits the nucleus of a highly charged ion. This velocity approaches a significant fraction of the speed of light. Such relativistic effects are another manifestation of one of Einstein's papers from 1905. Super EBIT measurements are precise enough for testing theories that go beyond Einstein: quantum electrodynamics that predicts further energy shifts due to vacuum fluctuations from position–electron pair production and annihilation based on a combination of Einstein's famous $E = mc^2$ concept and the Heisenberg Uncertainty Principle, as well as the interaction of a given electron with its own sea of "bound" photons. Our recent SuperEBIT measurement of U^{89+} (i.e., uranium with only three remaining electrons) is the most accurate in the world for testing quantum theories in the superhigh fields of highly charged ions.

Hot Hohlraums and Albert Einstein

Marilyn Schneider

Visible lasers are converted into x-ray sources inside tiny cylindrical cavities called hohlraums, which means "hollow rooms" in German. The radiation spectrum, or how much energy is present at each wavelength inside the hohlraum, is described by the blackbody formula derived by Max Planck in 1900. This formula assumed that light energy can only occur at certain discrete values, or quanta. In 1905, Albert Einstein explained why light is quantized: light has a dual nature—it is both a wave and a particle.

Hot hohlraums are hotter than other hohlraums because all the available laser energy is put into a smaller container in a shorter time. The laser energy ionizes and evaporates (or ablates) the hohlraum wall material, forming a plasma, which quickly fills the tiny hohlraum and scatters the laser light. The description of the plasma is based on kinetic theory. In 1905, Albert Einstein's paper on kinetic theory and Brownian motion developed the fundamental equations that described the motion of atoms (and later ions) in fluids and plasmas. This poster describes recent experiments on hot hohlraums on the NIF laser that have led to new understanding of laser–plasma coupling.

Short-Pulse Laser Absorption and Solid-Target Heating at Relativistic Laser Intensities

Ronnie Shepherd

We have embarked on an exciting new program to study the effects of solid matter heated with short-pulse, high-intensity (>10^{18}W/cm^2) laser beams. At these laser intensities, the electric field of the laser is so large that it can accelerate electrons to relativistic velocities. As a result, the pondermotive force begins to alter the density profile, an electrostatic-driven ion shock is predicted to form, the relativistic mass of the electrons increases the penetration depth of the laser, and magnetic fields that can exceed 3 gigagauss are generated inside the target. Furthermore, the oscillatory velocity (v_{os}) asymptotically becomes large compared to thermal velocity (v_{th}), suggesting a significant amount of vacuum heating and relativistic $\boldsymbol{J} \times \boldsymbol{B}$ heating. The poster presents theory and experimental data showing the laser absorption and subsequent target heating resulting from high-intensity, short-pulse generation of relativistic electrons in laser–solid interactions.

Relativistic Plasma Simulations

A. B. Langdon

Short-pulse lasers concentrate as much as a kilojoule of energy down to a picosecond and into a very small area. The very large electromagnetic fields near the focal spot oscillate electrons to nearly the speed of light. As described by the special theory of relativity, the electrons' mass increases at such speeds. The resulting nonlinearity in plasma response to the wave produces a rich variety of light propagation instabilities and accelerates electrons to relativistic energies. The Fast Ignitor concept for inertial confinement fusion exploits some of these properties. "Particle-in-cell" computer models provide a first-principles treatment of the relativistic, nonlinear, and kinetic effects.

Pair Production and Positron Annihilation

Scott Wilks

In this poster, we present recent experimental and theoretical research devoted to creating relativistic pair plasmas. Positrons, the antimatter equivalent of electrons, are identical to electrons in everyway except that positrons have a positive charge. Being antimatter, positrons cannot exist long on Earth as they annihilate after about a billionth of a second when they collide with electrons, i.e. matter. This annihilation is perhaps the most striking example of the equivalence of mass and energy because all of the mass of these two particles (an electron and a positron) is turned completely into energy, usually in the form of two gamma rays. Similarly, with enough energy in a small volume of space, one can create electron–positron pairs out of pure energy. Our current research does just this, creating a large number of pairs using ultraintense lasers. In addition, it turns out that the pairs we create are extremely energetic, so energetic that we must use relativity (as described in the first of Einstein's 1905 papers) to describe their motion properly. Astrophysicists think relativistic pair plasmas are present in many compact objects throughout the Universe. We hope to create such plasma in the laboratory for a fraction of a second, in hopes of gaining a better understanding of the cosmos around us.

Electron Speedometer for Solid-Density Plasmas

Gianluca Gregori

Expanding on Einstein's explanation of the photoelectric effect, the theory of scattering of x rays by electrons was formulated in the 1920s by several illustrious physicists (Debye, Compton, Dirac, and Chandrasekhar). They and others realized that the Doppler shift caused by an x ray scattering off an electron could be used to infer the speed and direction of electrons in solid matter (the Compton effect). Today, we are using this effect as a probe of the transient electron velocity distribution, and hence temperature, of solid-density, low-atomic-number plasmas that are prevalent in high-energy-density physics and inertial-confinement-fusion capsules, but cannot be measured through optical or x-ray spectroscopy means. The data are being used to validate various equation-of-state models developed by the statistical plasma physics community. New research has also begun in extending the technique to probe collective electron motion in dense plasmas for which no experimental data exist.

Superconducting Ultrahigh-Energy-Resolution X-Ray, Gamma-Ray, and Neutron Spectrometers

Stephan Friedrich

Superconducting spectrometers operated at temperatures of ~0.1 K offer an order of magnitude improvement in energy resolution over conventional semiconductor Ge and Si(Li) detectors. This greatly increases the sensitivity in a wide area of scientific applications, ranging form high-energy astrophysics to biophysics and material science. The Advanced Detector Group is developing sensors based on the resistive superconducting-to-normal transition, as well as the refrigeration and readout technology to make detector operation at ~0.1 K user-friendly. This poster presents the current state-of-the-art superconducting detector technology, and illustrate its wide potential with representative high-precision measurements on active metal sites in proteins, novel semiconductors and special nuclear materials.

Hyperspectral Imaging

Charlie Bennet

One of Einstein's most important contributions to physics was the elucidation of the multidimensional nature of space-time. Relativity theory intimately connects the three dimensions of space with the fourth dimension of time. In his later years, Einstein tried heroically to develop a unified theory of physics that brought in extra dimensions. In recent years, string theorists have suggested that there may actually be ten spatial dimensions.

In the field of hyperspectral imaging, the data from imaging spectrometers are represented as having a large number of extra dimensions, with an extra dimension corresponding to each of the different spectral colors observed. Among its various applications, hyperspectral imaging has proven effective for detecting and identifying art forgeries and has been used in the medical arena for health diagnostics.

Past, Present, and Future of Relativistic Optical Technology at LLNL

Chris Barty

For nearly two decades, LLNL has been at the forefront of high-peak-power, short-pulse laser technology development. This technology makes it is possible to enter a new regime of laser–matter interactions in which the focused laser field strength is sufficient to accelerate free electrons to relativistic velocities on a single half-cycle of the laser oscillation. This new regime, which has been called the "relativistic optical" regime, occurs at focused laser intensities of approximately 10^{18}W/cm^{2} and can be easily reached with modern terawatt and petawatt laser technology. In the relativistic optical regime, the extreme velocities and strong magnetic fields in the laser focus lead to a new and fundamentally different "longitudinal" coupling of the laser light to matter. With relativistic intensities, it is possible to produce intense, forwardly directed beams of tens of keV to multiple-MeV electrons, which may in turn be used to create unique sources of short-duration, high-energy, x-rays and collimated beams of energetic protons and ions. This poster reviews the past, present and future development of relativistic optical technology at LLNL. The history ranges from the production of some of the first terawatt-peak-power laser pulses on a single benchtop, to demonstration of the first petawatt pulses on the Nova laser system, to the development of new technologies that may eventually enable exawatt-peak-power pulse production on NIF. In all phases, LLNL has played a leadership role in the development of advanced short-pulse laser architectures and advanced laser component technology.

Watching Crystals Melt in Real Time with Ultrafast X-Ray Vision

Fred Hartemann

LLNL is developing new ultrafast x-ray and gamma-ray sources to resolve fundamental unanswered solid-state physics questions, including the dynamics of crystals on the femtosecond time scale (millionth of a billionth of a second) and phase transitions (melting and freezing) under extreme conditions, and to help detect dangerous materials remotely. These novel sources make practical use of two of Einstein's main ideas: special relativity and photons. The x-ray photons are produced by colliding relativistic electrons with an ultrashort, coherent laser pulse. The Doppler effect (analogous to the increasing pitch of an approaching police siren) dramatically shortens the wavelength of the incident light, from approximately 1 μm down to 0.1 Å. This poster will introduce the relevant physics concepts and the advanced technologies used in our research, and highlight our progress and results.

The Wave/Particle Duality of Light

Richard Bionta

Einstein's 1905 work was the first use of light's wave/particle duality—the notion that light sometimes behaves as waves and sometimes behaves as particles—to explain the subtle particle behavior of visible light. Scientists at the time were confused because the long wavelengths of visible light overwhelmed its particle properties. In contrast, the wave properties of x rays are difficult to observe because of their short wavelengths, and the particle properties of x rays are dominant because of the large energy packed into each x-ray quantum.

The Linac Coherent Light Source (LCLS), now under construction at Stanford Linear Accelerator Center and scheduled to become operational in 2009, will be the world's first x-ray free electron laser, producing a coherent (wave-like) beam of intense x rays (10 trillion coherent photons) in 250-fs pulses for studies of short, fast interactions of light and matter and its movement (Brownian motion) on very short time scales. Since the LCLS produces a coherent x-ray beam, the wave properties are tremendously enhanced over conventional x-ray sources, allowing us to explore new states of matter, follow chemical reactions and biological processes in real time, image materials on the nanoscale level, and image noncrystalline biological materials at atomic resolution.

Shining New Light on High-Energy Physics: Photon Colliders at the High-Energy Frontier

Jeff Gronberg

To the scientists of the 19th century, light was composed of amorphous electromagnetic waves that permeated space but could not interact with each other. The groundbreaking experiments of Einstein on the photoelectric effect turned this understanding on its head. With this understanding, a way to create photons of enormous energy was revealed: simply bounce light from a charged particle of high energy, like billiard balls colliding. Photon colliders can produce photons with energies only seen in nature in the explosions of supernovas. These high-energy photons can be a unique probe into elementary particle physics. When two photons collide, they can be converted into a charged-particle/antiparticle pair. Through the $E = mc^2$ formula, the entire energy of the photons is converted into the mass-energy of the particle/antiparticle pair, allowing particles that have not existed since the Big Bang to be produced.

Exploiting the Duality of Light in Photonic Integrated Circuits and Fiber-Based Systems

Tiziana Bond

The wave-particle dual nature of light is explored for complex signal processing, communication, and detection functionalities and achieved with both miniature-size integrated circuits on a chip and fiber-based systems on a bench. Photons generated in lasers are coupled and propagated as electromagnetic waves along optical waveguides, then manipulated to import external signal features or improve their spectral and time characteristics, to eventually be detected in forms of photons again through the photoelectric effect. This poster shows how we are putting photons to work, from the infrared to the ultraviolet, for all-optical switching by exploiting class III-V semiconductors and advanced etching techniques, from high-speed digital logic circuits, to highly sensitive radiation detectors and recorders at both the integrated and discrete levels.

X-Ray Tomography from High-Energy-Density Physics Targets to Michelangelo's David

Harry Martz

In one stroke, Einstein showed both that light is a stream of particles and also that there was solid evidence for the existence of waves. His theory could satisfactorily explain all the known properties of the photoelectric effect and was the first result derived from quantum theory of the interaction between radiation and matter. Light, i.e., the electromagnetic spectrum, behaves like a wave under certain conditions and like a stream of particles under others. In other words, it has a *dual nature*: we can understand it as either wave or particle, depending on our context of observation. We are taking advantage of the dual nature of x rays and their interaction with matter to conduct nondestructive characterization of objects as small as poppy seeds, through NASA space shuttle components, to Michelangelo's David.

Our study examines the refractive wave effects of x rays at low energies (a few keV) and high-spatial (~1-μm) resolution to characterize the deuterium–tritium ice-gas boundary layer in inertial-confinement-fusion targets. The photoelectric nature of x rays is useful to characterize high-energy-density physics targets in three dimensions. Medium energy (~100-keV) x rays are useful for characterizing NASA space shuttle components, and high-energy (~4-MeV) x rays can help inspect surface cracks in the ankles of Michelangelo's 500-year-old marble statue of David, which is located in the Galleria dell'Accademia museum in Florence. Assessing the volumetric extent of these cracks will provide information to the museum's art-conservation experts about how the cracks may affect the long-term structural stability of the statue.

The Solid-State Heat Capacity Laser

Bob Yamamoto

The Laboratory, under the sponsorship of the U.S. Army's Space Missile Defense Command (Huntsville, Alabama), has developed the world's most powerful solid-state (i.e. electric), diode-pumped laser called the solid-state heat capacity laser (SSHCL). The current laser system configuration has produced over 150 J/pulse at a pulse repetition rate of 200 Hz, equating to an average output power in excess of 30 kW. Because this laser produces significant amounts of power in a very small footprint, the military can use the laser as a directed-energy weapon in a variety of mobile configurations (land-, sea- and air-based). Potential target include rockets, artillery, and mortars; buried and exposed landmines; and improvised explosive devices (IEDs).

From the onset of the SSHCL program, LLNL has incorporated into their laser architecture several key enabling technologies supplied by industry. This was done to expedite the process of transforming a laboratory device into a hardened, battlefield-ready laser system. Present plans call for a 100-kW laboratory SSHCL to be ready in 2007, with the potential for a megawatt-class SSHCL soon thereafter.

Janus Intense Short Pulse: The Next Ultrahigh Intensity Laser at LLNL

Andrew Ng

The Janus Intense Short Pulse (JISP) upgrade is being developed at LLNL to provide a high-energy (hundreds of joules), short duration (0.5 to 200-ps) laser pulse with variable delay from a second, high-energy (up to 1kJ), long-duration (0.2 to 20-ns) laser pulse on target. A new target chamber will allow the angle between the long and short pulse beams to be varied from about 35° to nearly 180°, thus creating a unique Laboratory capability to support a wide range of experiments. For example, in the area of high-energy-density science, this new facility, called Janus II, will enable studies of dynamic material properties and equation of state under extreme conditions. In inertial confinement fusion, Janus II provides an experimental platform for fast ignition science. JISP is a significant tool in high-field-physics studies such as the production of antimatter (electron–positron) plasmas for exploring laboratory astrophysics. Commissioning of the system will begin in the summer of 2005.

Mapping Phonons at High-Pressure: Phase Transformation, Phase Stability, and Elastic Anisotropy

Dan Farber

This project represents LLNL's participation in an international collaboration to develop new techniques for mapping phonon dispersion curves (PDCs) at high pressure in the diamond anvil cell using high-resolution inelastic x-ray scattering (HRIXS). The project will focus on probing PDCs in a number of physically novel systems: (1) Ce (an element often used as a surrogate for Pu) at or near the solid–solid singular point; (2) V at ultrahigh pressures; and (3) the high-pressure form (hexagonal closely packed) of Fe. If successful, this project will open a new field of research directed at probing the dynamics of systems at extreme conditions with HRIXS. Understanding the role of phonons in phase transitions is critical to our ability to describe the underlying physics that controls phase stability and a range of transport properties in lanthanide and actinide systems.

Ultrafast Science

Art J. Nelson

Ultrafast x-ray, electron beam and optical techniques combined with femtosecond lasers are powerful tools that can be used to probe the electronic and structural dynamics of molecules, biological systems, liquids, solids, surfaces, and interfaces as processes are occurring. Our work using these tools builds upon LLNL’s research efforts in stockpile stewardship, which requires detailed knowledge of how materials respond to strong shocks and other extreme, nonequilibrium conditions. Experimental protocols, new physical concepts, and supporting theoretical tools are being developed to fully exploit the potential of such time-resolved techniques. LLNL has now embarked on a new strategic effort to develop time-resolved experimental capabilities that will position LLNL to become a world leader in the advancement of science and methodologies in this new field.

Brownian Motion for Photons

Bill Bateson

Brownian motion describes the trajectory of a test particle being knocked about by ambient particles.□For the most part, the test particle moves in a straight line until random, impulsive collisions change its trajectory.□The Einstein equations for radiation describe a similar process.□Photons move in a straight line at a fixed speed.□If the photon is absorbed by matter, then the matter shortly follows with spontaneous emission; thus the incident photon appears to have been scattered.□This process of fixed-speed, straight-line motion with random scattering can be captured analytically.

Asymptotic Freedom in the Diffusive Regime of Neutron Transport

Britton Chang

The accuracy of a numerical method for solving the neutron transport equation is controlled by the smallest mean free path in the problem. Since problems in the asymptotic diffusive regime have vanishingly small mean free paths and computer memory is limited, solving these problems seems hopeless. However, we have found that the accuracy of a numerical method improves as the scattering ratio increases with the mean free path and the grid spacing held fixed for problems in the asymptotic diffusive regime. This phenomenon is independent of the numerical method and can be explained on physical grounds. Accuracy improves as the scattering ratio increases because fewer neutrons are removed from the system. As a result, scattering frees the neutron distribution function from the rapid spatial variation, which is caused by absorption. Numerical results by the Diamond Difference Method are given to show this phenomenon.

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