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Shining Light on Opacity

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Disclaimer

Shining Light on Opacity *by Peter Beiersdorfer (Lawrence Livermore National Laboratory) and David J. Hoarty (Atomic Weapons Establishment)*

Commissioned just a little over a year ago, the ORION laser at the Atomic Weapons Establishment (AWE) in Aldermaston, England, (see Figure 1) has become a key facility for measuring the properties of hot, dense matter. Experiments require the most advanced equipment for measuring the radiation emitted in a burst of x rays lasting a few picoseconds, i.e., a few trillionths of a second. The experiments are carried out collaboratively between scientists at AWE and at the Lawrence Livermore National Laboratory (LLNL), who have built on expertise developed at the HELEN laser at AWE and at the Europa and Titan lasers at LLNL.[1,2,3]

Energy flow is a crucial element in understanding weapon performance. This energy flow must be simulated in our weapon codes to assess the performance, safety, and reliability of our nation's nuclear stockpile. Incorporating measured or experimentally validated material properties that impede or facilitate the flow of energy is a requisite to improving these simulations. The experiments at ORION aim at measuring the flow of x-rays through hot, dense material to determine a crucial quantity called the opacity.

Opacity measurements have been performed before at the HELEN laser at AWE, the NOVA laser at LLNL, at the Omega laser at Rochester, and at the Z facility at the Sandia National Laboratory.[4,5] The ORION laser is unique in that it allows us to reach much higher densities and temperatures than has been achieved by the other facilities.

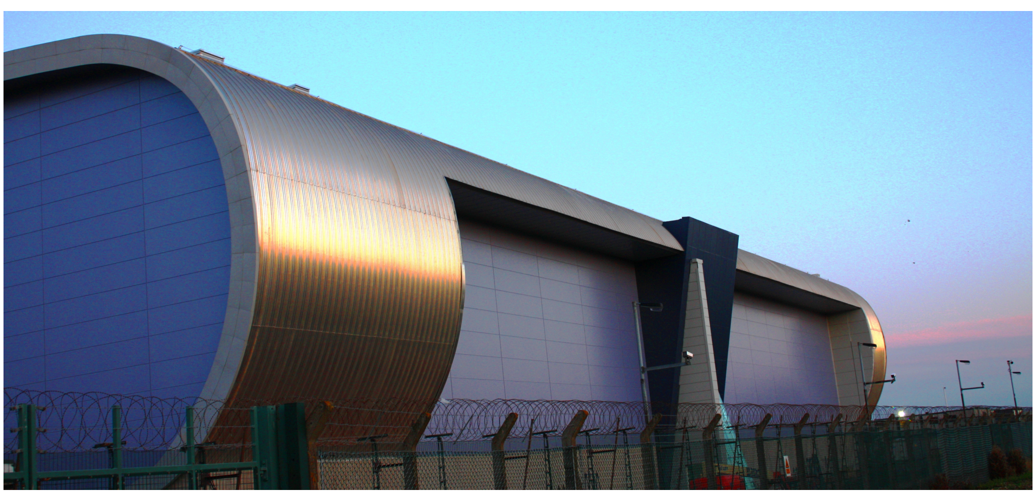

Figure 1. Dawn at the ORION laser facility.

How does it Work?

The ORION laser fires a photon bullet of green light at a dot of sample material smaller than the period at the end of this sentence. This bullet has a duration of 0.5 picoseconds; it has a size less than six thousandths of an inch. This is more than a thousand times shorter than the laser beams produced at LLNL's National Ignition Facility. The shape of this photon bullet is very precisely defined to ensure that all its energy hits the target at once.

The sample material is sandwiched between two layers of carbon in the form of plastic or diamond that prevent it from expanding at these ultrashort time scales (see Figure 2). The result is a sample heated to many million degrees centigrade while maintaining solid density.

The ORION facility also has ten beams operating at a much larger pulse length. These can be used to shock the target and further increase its density.

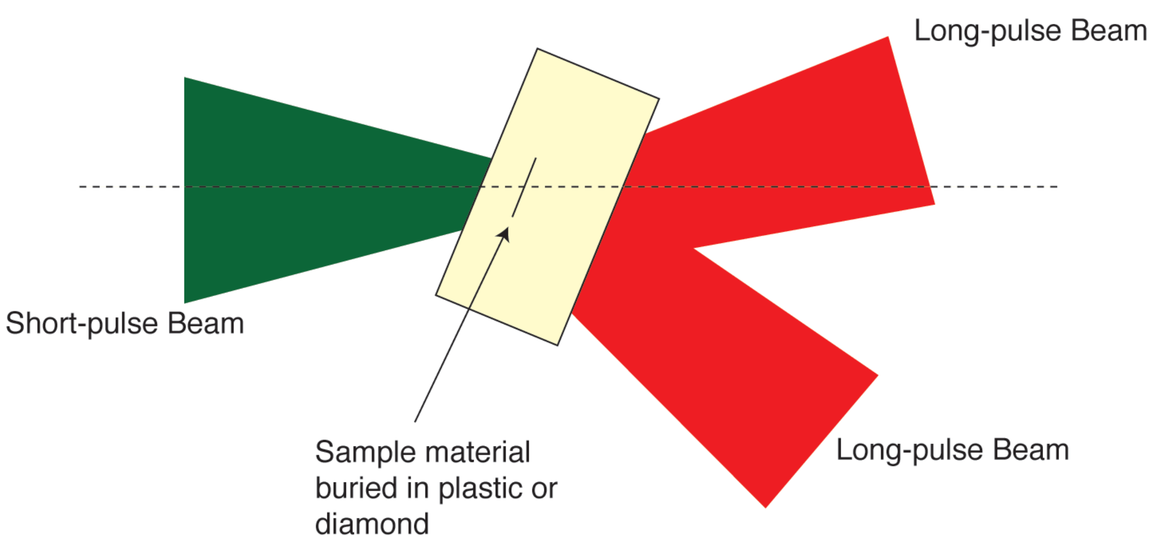

Figure 2. Target arrangement for opacity measurements on ORION. The diameter of sample is two thousands of an inch, its thickness is less than 10 millionth of an inch. The plastic or diamond that surrounds the sample is twenty to fifty times thicker.

Diagnostics are Key

In order to infer the parameters that determine the flow of light in hot, dense matter, we measure the x rays produced by the sample itself. These x rays carry information about the density, temperature, and radiative energy loss of the sample as well as on the sample's state of ionization, i.e., the degree to which the electrons have been peeled off the atoms in the sample.

The ultrashort duration of the laser-matter interaction requires that measurements be carried out with ultrahigh time resolution, stressing the leading edge of the scientific instrumentation.

We use the world's fastest cameras that streak the sample's x-ray emission with sub-picosecond resolution (see Figure 3).[6] These measurements are augmented with absolutely calibrated, time-integrating crystal spectrometers, which provide high spectral resolution. Pin-hole imagers measure the size of the material illuminated by the laser beam.

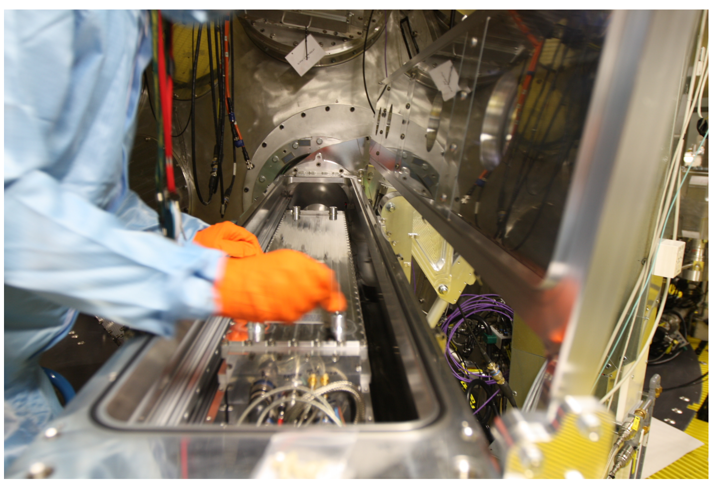

Figure 3. US-built time-resolved x-ray spectrometer installation on ORION.

Material Properties at the Quantum Edge

The high density and temperatures in the sample bring out quantum mechanical effects that change the material properties and are challenging to quantify theoretically from first principles. Having precise handles on the density and temperature in our experiments, we can watch as a given atom loses its ability to hold on to its electron through a process called Ionization Potential Depression (IPD). IPD is an effect where the atom has fewer quantum mechanical states as the density is increased, thus reducing its ability to keep its electrons.

IPD models are crucial inputs for our ability to predict material properties. Recent experiments at the Linac Coherent Light Source (LCLS) facility at Stanford have called into question the validity of the most widely used IPD model.[7] We conducted experiments on the ORION facility to explore IPD in the hot, dense matter regime not accessible by the LCLS measurements (see Figure 4). We found that the standard model give the best description of IPD in this regime.[8] However, the predictions do not perfectly match our data, which indicates that improvements in the model and new measurements on an even finer density scale are warranted.

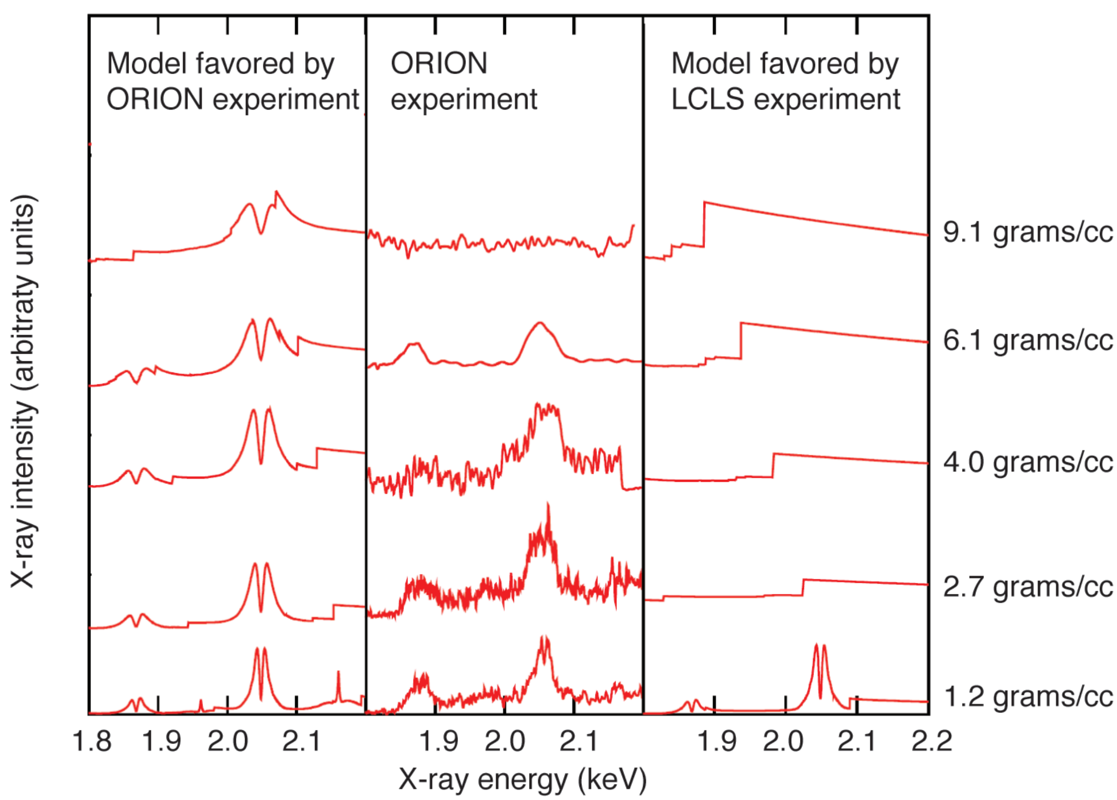

Figure 4. Comparison of ORION experimental data of aluminum (shown in the center panel) with two IPD model predictions (shown in the right and left panels). The density increases from bottom to top (from 1.2 to 9.1 grams per cubic centimeter) for each of the red curves. Our experimental data rule out the model favored by the recent LCLS experiment. Instead, the experimental data favor the predictions in the leftmost panel, but the agreement is not perfect.

Opacity Measurements

If all relevant parameters in the sample have thermalized, i.e., they can be described by a single temperature, the sample is said to be in local thermodynamic equilibrium (LTE). Materials in LTE are much easier to model than those that are not in LTE, because a statistical approach can be used. If the sample deviates from LTE by only a small amount, the absolute x-ray emissivity can still be compared with LTE spectral predictions invoking an equivalent ionization temperature for a particular density as given by scaling relations developed by Busquet.[9] LTE models are a subset of the more general non-LTE models, which calculate the processes in the sample in detail without resorting to statistical averages. Non-LTE models are being developed at AWE and LLNL and are also being benchmarked against the Orion data. In addition to temperature and density the sample thickness, emission duration, and emission area together with the response function of the detectors must be known to make a meaningful comparison. Fulfilling all of these criteria simultaneously is a grand challenge of opacity measurements.

Our initial measurements showed that ORION heated the sample more than expected so that the sample was too far from the required LTE conditions. Achieving higher temperatures than planned is a better situation than finding that it is too low. We have now redesigned our targets to lower the temperature to the desired values.

On ORION we have another knob to approach near-LTE conditions: We can use the aforementioned sample compression to increase its density. At sufficiently high densities collisions overwhelm radiative processes and thereby bring the statistical occupation of the available quantum mechanical states to near LTE. We have now started to implement long-pulse compression in our opacity experiments.

The Future

The ORION laser facility is still evolving. Expected upgrades to the facility in the coming year will double the available energy of the green laser light, allowing us to investigate larger samples with more homogeneous conditions and to obtain more signal in our time-resolved measurements. AWE is planning additional major upgrades of the laser within a five-year horizon that will push the accessible parameter range to new regimes of interest to Stockpile Stewardship.

Concurrently, our instrumentation is evolving to match the signal produced by the ORION laser. We are in the process of building a second sub-picosecond streak camera. A time-resolved pin-hole imager, a radiation thermometer, and a focusing x-ray spectrometer with very high spectral resolution are expected to join the existing suite of leading edge diagnostics in the coming year.

Together, our collaboration will explore new density and temperature regimes needed to refine our predictive understanding of nuclear weapons.

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