White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
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Title:	Fundamental opacity studies of photo-ionized plasmas
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)

- ***Describe the research frontier* and importance of the scientific challenge.**

Opacity is a crucial mechanism ruling astrophysical heating. It is the resistance by matter in all forms to transport the energy carried by photons. It is the universal mechanism linking hot, compact bodies to colder, interstellar matter. This property is so fundamental that cosmic evolution cannot be understood without precise opacity data. While recent advances in computational power allowed scientists to use extremely detailed physical models to calculate opacity values from first principles, the validation of these models still requires experiments. These models could be simplified using experimental data. Ultimately, an accurate model should capture the essence of a particular regime, while shedding unwanted complexity, responsible for slowing down numerical computations. Since assumptions are required, it is understandable that opacity calculations can sometimes fall short of predicting complex systems when these assumptions happen to be incorrect. For instance, the revised standard model of the Sun[1] and its photosphere spectral analysis[2] led to discrepancies which could be resolved if the value of the mean opacity of the Sun's interior was increased[3]. Experimental measurements were able to confirm that this increase may be justified[4].

Over the years, scientists have realized that opacity is not only an irreducible factor of celestial mechanics but it is also linked to day-to-day life problems such as entry of comets and asteroids into planet atmospheres, the Earth's radiation balance, or the cooling of inertial confinement fusion plasmas. All the

answers to these problems rely on a precise understanding of opacity. Further, opacity is at the heart of many modern diagnostic techniques such as absorption spectroscopy or Thomson scattering. Since opacity depends strongly on the regime matter is in, it is not possible to undertake a scope of research that would encompass all states of matter. Rather, this white paper discusses opacity models and measurements relevant to astrophysical and inertial fusion plasmas, where medium energy photons (50 eV< $h\nu$ <50 keV) interact with electrons via free-free absorption (bremsstrahlung) and bound-free absorption (photo-ionized). Using high energy density plasmas (HEDP) to study the opacity of matter under extreme conditions is at the frontier of plasma science.

At the moment two main approaches exist to compute opacity. The first one supposes that the plasma is in a local thermal equilibrium[5] (LTE). In this case, one can use the equation of radiative transfer to compute energy transport, including polarization[6,7], dispersive media[8] as well as relativistic effects[9]. In this framework different opacity models can be developed such as the Rosseland mean opacity model[10]. The other case deals with non-LTE systems. Such systems have several temperatures which exist simultaneously for different species. Some systems cannot be defined in terms of thermodynamical quantities at all and the notion of temperature does not make physical sense. For instance the last stages of Z-pinch implosions are strongly dominated by kinetic effects. For this fast evolving, low-collisionality systems general non-LTE opacity models have been defined and require the computation of emission and absorption properties for each ionization level and each species[11]. Fundamentally opacity calculations are facing in two distinct grand challenges:

1. *Can standard opacity models be extended or modified to capture the interaction between photons and high energy density plasmas?*
2. *Can modern techniques speed up the computation of opacity using non-LTE models?*

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Clearly, answering these questions requires verifying opacity calculations against experimental measurements. Limiting our discussion to the opacity of matter to medium energy photons, we believe that experimental HED platforms such as Z, at Sandia National Laboratories, NIF, at Lawrence Livermore National Laboratory, and OMEGA and OMEGA-EP, at the Laboratory for Laser Energetics, are well suited to generate photo-ionized plasmas which can be probed using high intensity x-ray sources. Several experiments have delivered already outstanding information on opacity relevant to stellar interiors[4,12]. We propose to advance the frontier of opacity research by coupling both drivers and use them for what they do best. High intensity lasers make outstanding HEDP[13] or warm dense matter[14] targets. Pulsed-power machines are outstanding at generating large amounts of x-rays with uniform spectrum across a reasonably large bandwidth[15] and with a quality allowing Laue diffraction experiments[16]. The opacity of a laser-produced plasma could be diagnosed successfully using a pulsed-power generator. Small and large facilities could be used, depending of the required sample and source properties. Pulsed-power facilities where PW lasers are not available can be used to generate HEDP and WDM samples. Another requirement is improving the sensitivity and resolution of VUV and x-ray detectors. The quality and reflection efficiency of x-ray crystals together with the sensitivity of image plates is desirable. Finally the development of high-gain gated x-ray detectors is primordial.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

The opacity of matter under extreme conditions is primordial to understand the evolution of the universe. Experiments where such matter can be produced and its opacity carefully measured would enable new models to be devised and possibly new computational techniques to be developed. The experimental results and their derived models would impact the field of astrophysics, in particular stellar evolution. It would also help inertial fusion scientists to understand the capsule-fuel mixing. Reducing mixing would

improve fusion yields at a given laser energy. Ultimately innovative opacity models and their computation could also be used in other regimes, broadening the spectrum of opacity research.

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Figures (maximum 1 page)