The Core of the Matter: Measuring the Temperature of Warm Dense Iron

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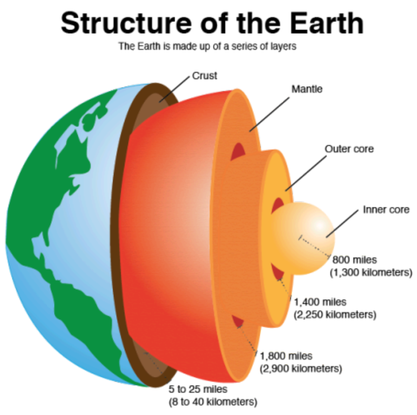
Introduction

What lies at the center of the Earth and other planets?

- Mostly iron and nickel
- Temperatures up to 9000°F
- Pressures up to 360 GPa
- State of matter is *warm dense matter* (WDM)

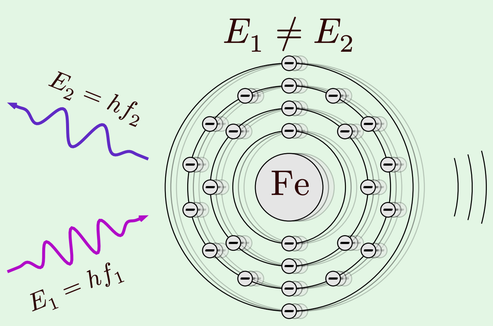


No one truly understands the behavior of matter at these extreme conditions. Even simple quantities like the melting point of iron are not well understood. Finding the temperature of warm dense iron was the goal of the Materials in Extreme Conditions (MEC) group this summer.

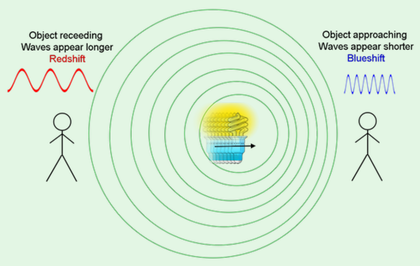
Inelastic X-Ray Scattering

When an X ray travels through a solid, photons are scattered by the electrons in the solid.

- Elastic scattering: atoms are stationary, no energy change
- Inelastic scattering: atoms are moving due to heat, leading to a change in the energy of the photons



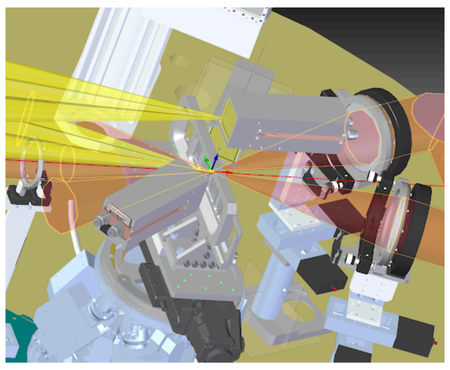
This is due to the Doppler effect (the atom acts as a receiver and source):



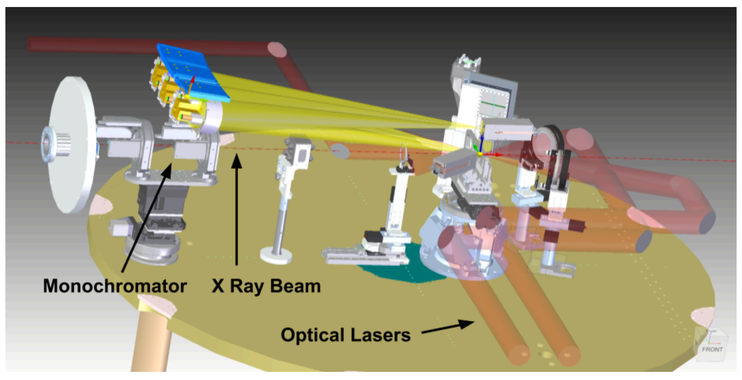
We send in one frequency of X-rays and measure the spread in frequencies of the scattered X-rays.

Experimental Setup

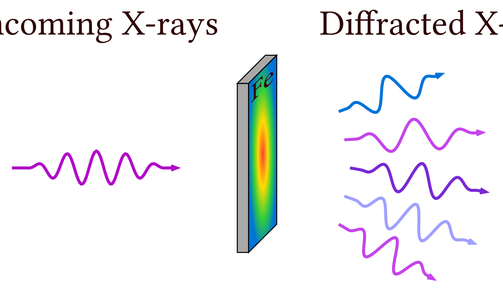
Step 1: two optical lasers are fired and focused on the back of the sample as shown below. It sends a shockwave through the sample leading to high pressure and temperature.



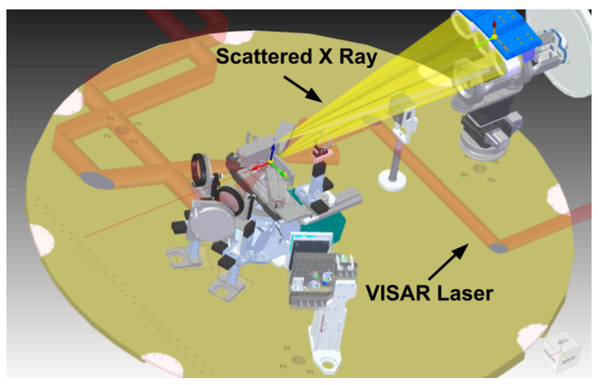
Step 2: an X-ray pulse is shot quickly after and passes through a *monochromator* which uses Bragg diffraction to select a single wavelength of X-rays, making the IXS analysis possible.



Step 3: The X-ray pulse passes through the heated sample, diffracting in random directions.



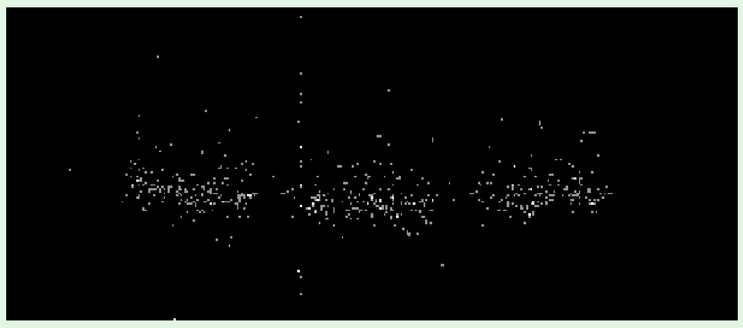
Step 4: Two detectors are used to do diffraction analysis and other scattered X-rays are sent to a set of crystal analyzers which spread out the X-rays by their energy and direct them to another detector.



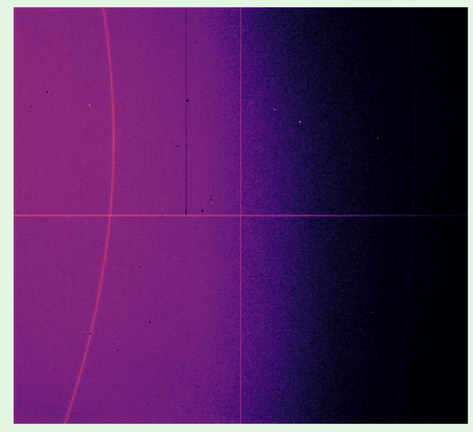
We can also use a laser interferometer called a *VISAR* (labeled above) to measure the velocity of the shockwave in the sample which can be used to calculate the pressure.

Results and Analysis

The raw IXS data (shown below) was analyzed to observe the broadening of the X-ray energies:



The diffraction data shows *Debye-Scherrer rings* which are the diffraction patterns of the grains of iron in the sample:



These occur since the X-rays can only be diffracted at certain angles, leading to a ring pattern in the detector. We can then use these to:

- Check if the sample is still crystaline
- Detect a change in the crystal structure of iron under pressure as seen below:

We are still conducting the data analysis to see if this change is visible in the data.

Acknowledgements

Thank you to my mentor, Bob Nagler, along with all the other amazing people at MEC for their kind guidance, support, and trust in my ability. Thank you to the LCLS internship program for making this summer possible.

Note: All data shown here is preliminary and has not been fully analyzed.

References

[1] S. H. Simon, *The Oxford Solid State Basics*. University of Oxford Press, 2018.

[2] N. W. Ashcroft and N. D. Mermin, *Solid State Physics*. Harcourt College Publishers, 1976.