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Abstract. Compton scattering has been developed for accurate measurements of densities and temperatures in dense plasmas. One future challenge is the application of this technique to characterize compressed matter on the National Ignition Facility where hydrogen and beryllium will approach extremely dense states of matter of up to 1000 g/cc. In this regime, the density, compressibility, and capsule fuel adiabat may be directly measured from the Compton scattered spectrum of a high-energy x-ray line source. Specifically, the scattered spectra directly reflect the electron velocity distribution. In non-degenerate plasmas, the width provides an accurate measure of the electron temperatures, while in partially Fermi degenerate systems that occur in laser-compressed matter it provides the Fermi energy and hence the electron density. Both of these regimes have been accessed in experiments at the Omega laser by employing isochorically heated solid-density beryllium and moderately compressed beryllium foil targets. In the latter experiment, compressions by a factor of 3 at pressures of 40 Mbar have been measured in excellent agreement with radiation hydrodynamic modeling.

1. Introduction

Accurate characterization of dense and compressed matter is important for inertial confinement fusion and high-energy density physics experiments.[1,2] In particular, the capability to measure electron temperature and density in dense matter allows us to test dense plasma modeling and can also be directly applied to implosion experiments to determine capsule performance by providing the ratio of electron to Fermi temperature, i.e., the fuel adiabat and compression. The Compton scattering technique has been developed on the Omega laser facility[3] employing isochorically heated[4] and laser shock-compressed matter[5]. These experiments access matter at solid density and above approaching electron densities of $n_e = 10^{24}$ cm^{-3}. Besides demonstrating the diagnostic capability for future studies, e.g., on the National Ignition Facility, present experiments address fundamental physics questions such as the equation of state in dense matter, structure factors in two-component plasmas, limits of the validity of the random phase approximation, and the role of collisions.

X-ray scattering experiments employ powerful laser-produced x-ray sources that penetrate through dense and compressed materials with densities of solid and above. Ly-alpha or He-alpha radiation from nanosecond laser plasmas have been applied at moderate x-ray energies of E = 3 - 9 keV that fulfill the stringent requirements on photon numbers and bandwidth for spectrally-resolved x-ray scattering measurements in single shot experiments. Experiments have been performed in the non-collective and collective scattering regime. In backscatter geometry, the scattering spectrum yields the Compton feature[4] while plasmons, i.e., electron density (Langmuir) oscillations, are observed in forward scatter geometry.[6]

In the Compton scattering regime, the scattering process is non-collective and the spectrum shows the Compton down-shifted line that is broadened by the thermal motion of the electrons. In degenerate systems, the width of the Compton scattering line is thus determined by the Fermi energy providing a measurement of the electron density. On the other hand, in non-degenerate heated matter the electron velocity distribution function transitions to a Maxwell-Boltzmann distribution yielding the electron temperature.

For measuring densities and temperatures of extremely dense compressed plasmas, there are several advantages of Compton scattering over forward scattering experiments. The intensity and the widths of the Compton down-shifted line are readily measured with standard laser-produced K-shell x-ray probes while plasmon intensities and shifts are inherently small.[6] Moreover, with the appropriate choice of the scattering angle, the main restriction for accessing the Compton scattering regime is the x-ray probe energy needed to penetrate through the dense plasma. On the other hand, plasmons can only be observed with moderate x-ray energies and are thus ultimately limited to moderately compressed or lower areal density plasmas. Finally, the theory of collective phenomena in dense matter is not complete, so the role of model-dependent collisional effects and structure factors in inferring plasma conditions are presently being investigated by comparing forward scattering measurements[6] with Compton scattering results. In the latter case, sophisticated theoretical approximations that use local field corrections or the Mermin approach agree well with the standard random phase approximation, thus allowing us to infer plasma conditions with high accuracy.[7]

2. Compton scattering

For conditions where the energy of the scattered radiation is close to the incident x-ray probe energy, E_0, i.e., for small momentum transfers, the scattering geometry and the probe energy determine the scattering vector $\mathbf{k}$ through the relation

$$k = |\mathbf{k}| = 4\pi \frac{E_0}{hc} \sin\left(\frac{\theta}{2}\right). \tag{1}$$

In the non-collective scattering regime, the individual electron motion of the plasma is probed since scale lengths smaller than the plasma screening length, λ_S, are accessed. For a degenerate system, λ_S can be approximated by the Thomas-Fermi length, λ_{TF}, and for classical plasmas, the usual Debye screening length, $\lambda_D = \sqrt{(\varepsilon_0 k_B T_e / n_e e^2)}$, is applied. Here, ε_0 is the permittivity of free space, k_B is the Boltzmann constant, T_e is the electron temperature, and n_e is the electron density. For weakly degenerate plasmas, calculating the Debye length at an effective temperature will result in a smooth interpolation between the degenerate and classical plasma limits.

In the non-collective scattering regime, the scattering parameter $\alpha < 1$, with α being defined as

$$\alpha = \frac{1}{k\lambda_S}. \tag{2}$$

For example, to access non-collective scattering in a weakly degenerate solid-density beryllium plasma with $n_e = 3 \times 10^{23}$ cm^{-3}, and with electron temperatures of order of the Fermi temperature, $T_e = T_F = 15$ eV, requires near-backscattering geometry, e.g., with $\theta = 125°$ and x-ray probe energies of order $E_0 = 4.75$ keV ($\lambda_0 \approx 2.6$ Å), e.g., the titanium He-α line. Here, the scattering experiment is predominantly probing k-vectors with $k = 4$ Å^{-1}. In these conditions, we find $\alpha = 0.3$, a Compton energy shift of $E_C = 74$ eV, an electron non-ideality parameter of $\Gamma = 1$, and an ion-ion structure factor of $S_{ii} \sim 1$. Similar scattering parameters can be accessed when compressing beryllium plasmas to densities of $n_e = 7.5 \times 10^{23}$ cm^{-3} and with higher energy x-ray probe radiation of $E_0 = 6.2$ keV ($\lambda_0 \approx 2$ Å), i.e., the Mn He-α line. The increased density results in a Fermi energy of 30 eV, and a Fermi-degenerate plasma state. In these two cases, the spectral features show significantly different sensitivity to temperatures and densities.

3. Compton scattering on isochorically-heated non-degenerate plasmas

In backscattering geometry, the momentum transfer to the electrons results in a measurable frequency shift to the scattered radiation, i.e. the Compton effect. The incident photons transfer the momentum $\hbar k$ and the energy $\hbar\omega = \hbar^2 k^2 / 2m_e$ to the electrons that are free or weakly bound with binding energies less than the Compton energy. In non-degenerate warm plasmas, where the outer-shell electrons are mostly ionized, the Compton line will be dominated by the contribution of free electrons that carry the information on the electron temperature of the plasma resulting in a spectral broadening, $\omega = \mathbf{kv}$. The spectrum directly reflects the velocity distribution function along the scattering direction, which for a Maxwell-Boltzmann distribution function is a Gaussian spectral profile with a width ~ $\sqrt{T_e}$.

On the other hand, bound electrons with ionization energies larger than the Compton energy cannot be excited by the scattering process. The corresponding spectral feature is a quasi non-shifted elastic scattering component. Clearly, with increasing temperature and ionization state, tightly bound electrons become available for inelastic Compton scattering, and the ratio of elastic to inelastic scattering is a measure of the ionization state. In isochorically heated matter, where the mass density is known *a priori*, the electron density can be deduced from $n_e = 6 \times 10^{23}$ Z/A ρ cm^{-3} with ρ = 1.85 for Be, and for Z = 2.5, we find $n_e = 3 \times 10^{23}$ cm^{-3}.

Figure 1 shows an example of a back-scattering spectrum from isochorically-heated beryllium.[4] Elastic scattering from both the titanium He-alpha radiation at 4.75 keV and Ly-alpha radiation at 4.96 keV is observed together with the downshifted Compton scattering feature. The spectrum is fit with a theoretical scattering profile by applying the dynamic form factor S(**k**,ω). Thus, the spectrum provides temperatures and densities from the broadening of the Compton downshifted line and the intensity ratio of elastic and inelastic scattering components, respectively.

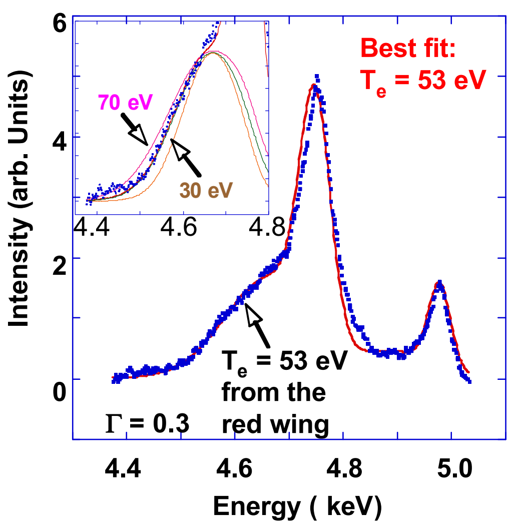

Figure 1. Compton scattering data from isochorically heated Be. The best fit provides an electron temperature of T_e = 53 eV. The inset shows the sensitivity of the shape of the red Compton scattering wing to the electron temperature; T_e is inferred from these data with an accuracy of about 10%. The fit to the relative intensity ratio of the Compton scattering component to the elastically scattered radiation at E_0 = 4.75 keV yields the charge state and hence free electron density of $n_e = 3.3 \times 10^{23}$ cm^{-3}. The latter is inferred with an error bar of 20%. These results are consistent with ionization balance calculation for isochorically-heated beryllium.

4. Compton scattering on shock-compressed Fermi-degenerate plasmas

Fermi-degenerate dense plasmas have been accessed in laser shock-compressed beryllium foils with 11 laser beams at the Omega laser facility.[3,8] The lasers directly illuminate the foil with laser intensities of $I = 10^{14} - 10^{15}$ Wcm^{-2} producing pressures in the range of 20-40 Mbars[5] and compressing the foil by a factor of 3. The Compton scattering spectrum of the 6.18 keV Mn He-α and 6.15 keV intercombination x-ray probe lines shows a parabolic spectrum as expected from a Fermi-degenerate plasma; the width of the Compton spectrum provides the Fermi energy, $E_F \sim n_e^{2/3}$. Unlike for plasmas with a Maxwell-Boltzmann distribution, the width is sensitive to the electron density. In addition, the intensity ratio of the elastic to inelastic scattering feature from Fermi-degenerate plasmas is sensitive to the ion temperature because elastic scattering is dependent on the ion-ion structure factor.

Figure 2 shows the scattering data along with synthetic scattering spectra for which the electron density (left) and the temperature (right) has been varied. For the analysis we assume $T_e = T_i$ and Z = 2 consistent with calculations and with the measurements from isochorically heated Be. Density and temperature obtained in this way are $n_e = 7.5 \times 10^{24}$ cm^{-3} and T = 13 eV representing a Fermi temperature of E_F = 30 eV and scattering parameter $\alpha = 0.48$. The error bars for these measurements are 10% and 25%, respectively due to noise. The latter also includes uncertainties of Z, but these effects are limited because the shape of the Compton scattering profile provides an additional constraint. These parameters match radiation hydrodynamic simulations of this experiment to 10% and also agree with the results of forward scattering measurements that independently measure n_e and T_e from the plasmon spectrum.[8]

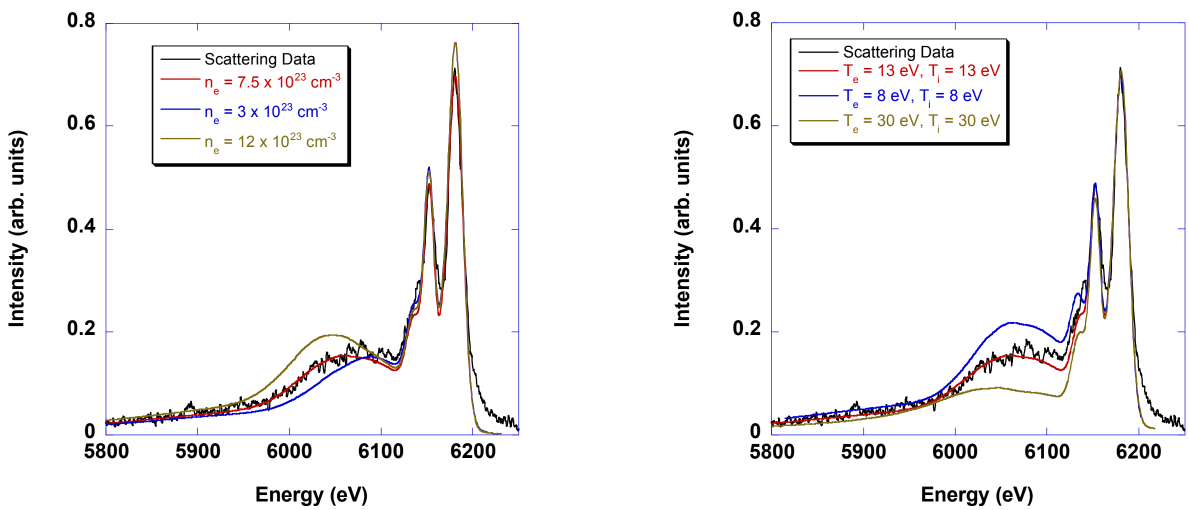

Figure 2. Compton scattering spectrum from compressed Fermi-degenerate beryllium. The width of the Compton feature is sensitive to density and its relative intensity is sensitive to ion temperature.

5. Conclusion

Spectrally-resolved Compton scattering has been shown to provide accurate measurements of densities and temperatures in high energy density physics experiments. Measurements on isochorically heated solid-density non-degenerate beryllium plasmas have shown that the width and relative intensity of the Compton scattering feature provides a sensitive measure of electron temperature and density. On the other hand, experiments on Fermi-degenerate compressed beryllium have shown that these features provide electron density and ion temperature, respectively. The plasma parameters inferred from the scattering spectra agree with hydrodynamic simulations and independent scattering measurements on plasmons. These results further demonstrate the utility of Compton scattering to measure the compressibility and adiabat of compressed matter.

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References

[1] J. D. Lindl, P. Amendt, R. L. Berger *et al.*, Phys. Plasmas **11**, 339 (2004).
[2] M A. Kritcher, P. Neumayer, M. K. Urry *et al.*, High Energy Density Physics **3**, 156 (2007).
[3] J. Soures *et al.*, Fusion Technology **30**, 492 (1996).

[4] S. H. Glenzer, G. Gregori, R. W. Lee *et al.*, Phys. Rev. Letters **90**, 175002 (2003).
[5] H. Sawada, S. P. Regan, D. D. Meyerhofer *et al.*, Phys. Plasmas *in print* (2007).
[6] S. H. Glenzer, O. L. Landen, P. Neumayer *et al.*, Phys. Rev. Letters **98**, 065002 (2007).
[7] R. Redmer, H. Reinholz, G. Röpke et al., *IEEE Trans. Plas. Sci.,* **33**, 77 (2005).
[8] H. J. Lee *et al.*, *to be published* (2007).