X-ray scattering as a dense plasma diagnostic

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We show here that x-ray scattering can be a useful and potentially powerful plasma diagnostic, much in the same way as in liquid metals. The model used in the calculations is briefly described. The basic atomic data used here are obtained from the average atom INFERNO model. Three different configurations were studied: an Al plasma at several eV and a density of 0.1 g/cm^3, which could be produced by radiatively heating an Al foil; an ultradense Al plasma which could be realized using colliding shock waves; and femtosecond laser produced plasmas. In the latter case we show that the applicability of the x-ray scattering method for obtaining information on both electron and ion temperature can be used in order to evaluate the electron-ion relaxation time. It is also shown that small angle scattering provides an equation of state diagnostic. [S1063-651X(98)09304-0]

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INTRODUCTION

In this work we show, in some specific examples of proposed experiments, that x-ray scattering can be a useful plasma diagnostic, much in the same way as in liquid metals. X-ray scattering by dense plasmas was studied by More [1] and More and Boerker [2], and in Ref. [3]. We begin here by describing the model used in the calculations of the x-ray scattering. The model was discussed in Ref. [3], and is based on the formalism derived by Chihara [4]. Results are presented for three different configurations. These are an Al plasma of density 0.1 g/cm^3 and a temperature of several eV, an ultradense Al plasma target of density 12 g/cm^3 and a temperature of 6 eV, and femtosecond laser produced plasmas. In the latter case the possibility of obtaining information on the electron-ion temperature relaxation time was investigated as well as the use of x-ray scattering as a temperature diagnostic. In addition to this it is shown that small angle scattering provides an equation of state diagnostic. Finally the proposed experiments are discussed in more detail, and a preliminary experiment is described.

MODEL

In a previous work (Ref. [3]), the calculation of the x-ray scattering cross section as a function of angle from a dense plasma was given in detail. The calculation, which was based on Chihara [4], was performed by evaluating the bound and free electron contributions to the scattering. The total scattering cross section as a function of momentum change Q is [4]

$$I(Q)=I_{\mathrm{cl}}(Q)[|f_I(Q)+\rho(Q)|^2 S_{II}(Q)+Z_b S_{\mathrm{inc}}^I+Z_f S_{\mathrm{ee}}(Q)] \tag{1}$$

where $I_{\mathrm{cl}}(Q)$ is the classical Thomson electron scattering cross section, $f_I(Q)$ is the bound-electron form factor, and $\rho(Q)$ is the Fourier transform of the free-electron density, which includes the resonance electrons. $S_{II}(Q)$ is the ion-ion static structure factor, Z_b and Z_f denote the number of bound and free electrons, respectively, $S_{\mathrm{inc}}(Q)$ is the incoherent scattering factor of the bound electrons, and $S_{\mathrm{ee}}(Q)$ is the static electron-electron structure factor of the free electrons. The physical quantities appearing in Eq. (1) were discussed in detail in Ref. [3].

For the problems to be discussed below, the major ingredients needed in the calculation are the number and radial density of the bound electrons, the number of resonance electrons, and the ion-ion structure factor. The calculations performed in Ref. [3] employed the Thomas-Fermi model in the so-called correlation sphere, the volume of which is sufficiently large to contain the main details of the ion-ion radial distribution function. In the present calculation, however, the average atom in the cell INFERNO model [5] was used. The major advantage of the latter model is in its inclusion of shell effects. A major discrepancy between both models which could be resolved by x-ray scattering will be pointed out below.

The INFERNO model gives the number and radial density distributions of the bound, resonance, and free electrons. When resonances occur, their electrons are included in Z_b, which multiplies S_{inc}^I in Eq. (1). This assumption should be considered more deeply; however, the effect of this term on the scattering cross section is small. The effective ion charge state which is basic in the calculation of the ion-ion correlations was assumed to be equal to the atomic number Z less the sum of the bound and resonance electrons.

The ion-ion structure factor was obtained from the hypernetted chain (HNC) model with and without screening [6]. The screening length in the case of plasmas with densities of the order of the natural density and higher were obtained from the linearized Thomas-Fermi theory [7]. At densities of 0.1 times the natural density, the formula given in Ref. [8] was used.

RESULTS

Calculations were performed for three different types of experimental systems: a dense Al plasma of the order of

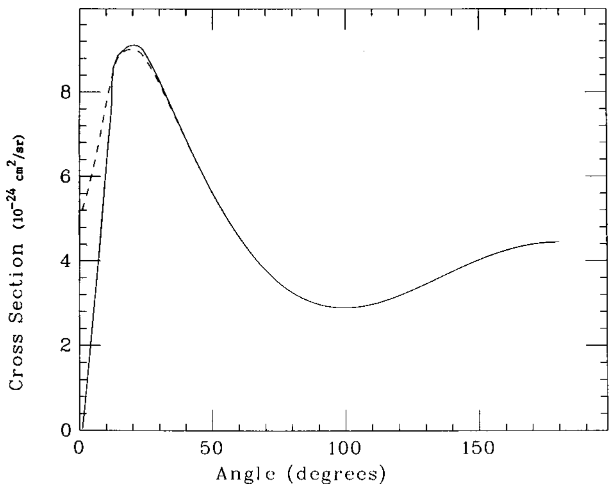

FIG. 1. Angular distribution of scattered x rays from an Al plasma of temperature 4 eV and density 0.1 g/cm^3. The energy of the scattered x rays is 4.75 keV. Full line: no screening of the ion-ion interaction. Dashed line: results of calculations assuming free-electron screening of the ion-ion interaction.

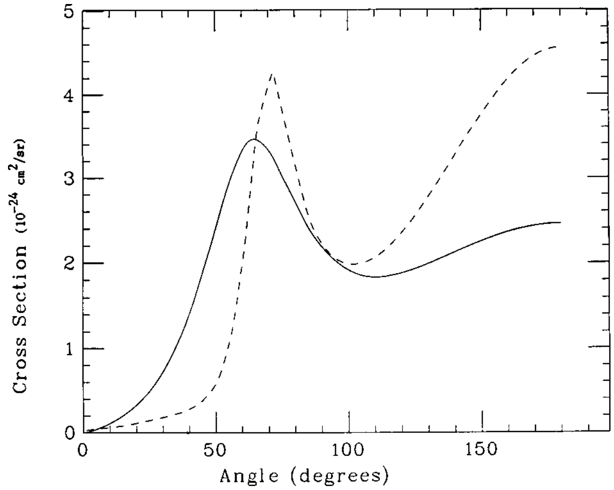

FIG. 2. Angular distribution of scattered x rays from an Al plasma of temperature 6 eV and density 12 g/cm^3. The energy of the scattered x rays is 7.47 keV. Full line: results using the procedure outlined in this paper. Dashed line: results using the Thomas Fermi model as described in Ref. [3].

0.1 g/cm^3 at temperatures of several eV, an ultrahigh density Al plasma, and a dense Cu plasma of the type encountered in femtosecond intense laser plasma interactions.

Figure 1 gives the predicted scattered x-ray distribution as a function of angle for the scattering of 4.75-keV x rays from an Al plasma of density 0.1 g/cm^3 and a temperature of 4 eV. Such a plasma can be obtained by driving an Al target with x rays from a laser-irradiated Au foil at intensity 10^{14} W/cm^2. Although the use of the INFERNO model at such low densities could be open to some question, the number of free electrons obtained from the INFERNO calculation is in good agreement with results obtained from the plasma physics activity expansion code ACTEX [9]. At a density 0.1 g/cm^3 and temperature 5 eV, INFERNO gives 1.68 free electrons, while the result according to ACTEX is 1.8. The decrease in the scattering cross section below 20° is due to the ion-ion correlations.

Small angle scattering can be used as direct equation of state diagnostics. According to the compressibility sum rule [10] the zero momentum ion-ion structure factor is

$$S_{II}(0)=\frac{n_i kT}{\rho(\partial p/\partial \rho)_T}, \tag{2}$$

where n_i is the ion number density, ρ is the density, and p is the pressure. In order to make use of this relation one has to isolate $S_{II}(0)$ from the measured scattering cross sections, using a model for the electrons form factor in Eq. (1). In the limit of weak coupling the ionic structure factor is given by [2]

$$S_{II}(q)=\frac{q^2\lambda_e^2+1}{q^2\lambda_e^2+1+z}, \tag{3}$$

where λ_e is the electron Debye length and z is the degree of ionization. This is the case of the experiment described above, where the equation of state is close to that of an ideal ionized gas [9]. In this case the measurement can be analyzed in terms of the parameter λ_e, and the experiment is actually a check on the evaluation of the Debye length and the degree of ionization. It is seen that, neglecting the dependence of the degree of ionization on the density, which is consistent with weak coupling, Eq. (3) is consistent with the compressibility sum rule [Eq. (2)].

Simulations show that 7 kJ of a 0.35-μm light of pulse duration of 2 ns can produce, by means of colliding shocks, an Al plasma of 12 g/cm^3 at a temperature of 6 eV. Here as in the other proposed experiments, an x-ray backlighter is used for the scattering source. The x-ray scattering cross section was calculated using both the Thomas-Fermi model of Ref. [1] as well as the INFERNO model used for the calculations presented in this paper. The Thomas-Fermi calculation gives only six bound electrons, while the INFERNO calculation yields a total of ten bound electrons, emphasizing the influence of shell structure on the results. In Fig. 2 we plot the angular distribution of scattered 7.96-keV x rays as a function of angle for both of the above-mentioned models. The main difference between the graphs is in the ratio of the cross section in the region of 150° to that in the region of 60°. The substantially larger number of free electrons in the Thomas-Fermi calculation is responsible for the significantly larger cross section in the backward scattering region. It is worth noting that the number of bound electrons could be discerned by an accurate measurement of the energy of the $K\alpha$ line.

An interesting possible application of x-ray scattering deals with the study of plasmas produced by intense femtosecond laser pulses. In particular, it could be possible to investigate the electron-ion relaxation time. The case investigated here is that of a Cu target with an electron temperature of 100 eV. It is assumed that the plasma could be probed at different times during the course of the ion-electron equilibration time, which, according to the simple Spitzer formula [11] is $\sim$400 fs. The full line in Fig. 3(a) assumes that the ion temperature is 5 eV, and that the density is still that of the initial target, and the dashed line corresponds to an ion temperature of 100 eV (equilibrated with the electron temperature) again assuming no change in density. In the low

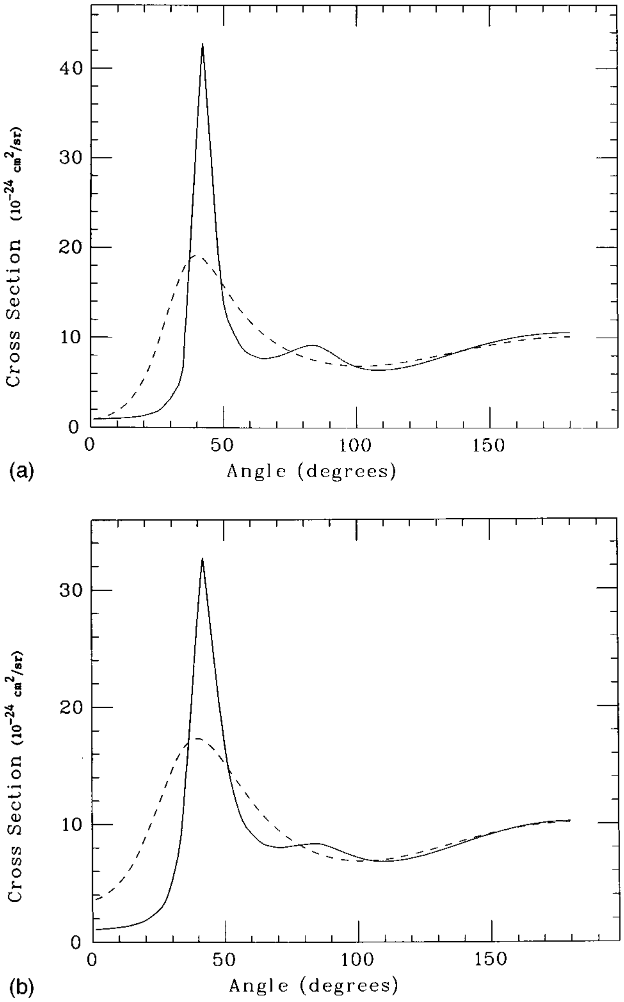

FIG. 3. Angular distribution of scattered x rays from Cu plasma that could be produced in a femtosecond laser plasma interaction experiment. The electron temperature is 100 eV. The ion temperatures are 100 eV for the dashed curve and 10 eV for the full curve. The plasma density is 7.97 g/cm^3, and the energy of the scattered x rays is 8 keV. (a) The calculation assumes no interionic screening. (b) The calculations assume interionic screening due to free electrons.

ion temperature case the peak at 40° is significantly more pronounced than that in the high ion temperature case. The effect is due to the much greater ion-ion coupling at the low ion temperature. The energy of the scattered x rays is 8 keV. Figure 3(b) describes the same situation, but includes screening in the HNC calculation.

Other cases of interest are the dense Cu plasma assuming equal ion and electron temperatures of 0.5 and 5 eV, and a density of 8.93 g/cm^3. Such a plasma could also be produced in femtosecond laser plasma interactions. The number of resonance electrons in the 0.5-eV plasma is 9.5, while at 5.0 eV it is 8.7. In Fig. 4 are presented the cross sections for the scattering of 8-keV x rays as a function of angle for both plasma temperatures. The difference between them due to the ion-ion correlations are clearly discernable. Hence it is possible to obtain information on the ion temperature.

In all these calculations it had been assumed that the ion-ion interaction is given by the Coulomb or screened Coulomb potentials. More realistic effective interaction potentials could be used, e.g., an extension of the Harrison-Wills potential [12] to dense plasma conditions. We believe that for the feasibility study of this work the simplified potential is sufficient.

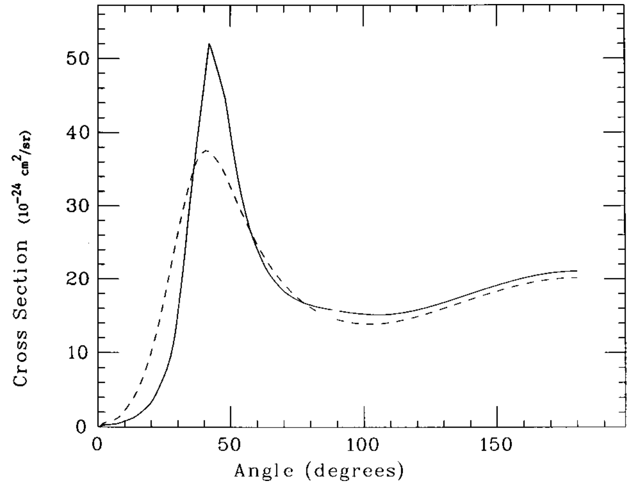

FIG. 4. Angular distribution of scattered x rays from Cu plasma that could be produced in a femtosecond laser plasma interaction experiment. The electron temperatures are 0.5 (full curve) and 5 eV (dashed curve). The ion temperatures in both cases are assumed to be equal to the electron temperature. The plasma density is 8.93 g/cm^3, and the energy of the scattered x rays is 8 keV. The calculations assume no interionic screening.

PROPOSED EXPERIMENTAL TECHNIQUES

Recent experiments have demonstrated that by using Au burnthrough foils [13] it is possible to generate approximately 20 J/Sr in x rays above 0.5 keV for 1-kJ, 1-ns duration laser pulses at a wavelength 0.53 μm. These photons penetrate relatively far in Al foils, and a sample 1 μm thick can be heated more or less volumetrically to temperatures of a few eV, if the burnthrough foil is a few millimeters from the sample foil. Such a foil has around 2×10^{17} scattering atoms if it is 2 mm in diameter. The work of Phillion and Hailey [14] showed that, for a He α line of Ti (4.75 keV), approximately 5×10^{12} photons/Sr can be generated with a 60-ps duration pulse of 100 J of 0.53-μm laser light. By combining these elements, an experiment can be designed in which the total number of photons scattered into a resolution element of 6×10^{-3} Sr($\pm2.5°$ in the horizontal plane) is in the range 30–300 from minima to peaks. For an appropriately placed cooled charge coupled device (CCD) array camera (e.g., 1024×256 pixels where each pixel is 27×27 μm), each resolution element can consist of a 50×50 pixel section, thus the chance of two photons hitting the same element is only 1%. The statistical noise in the peak cross section is of order 6% for one shot. This technique was used in a preliminary experiment [15] that showed that, by histogramming the CCD counts, the line radiation scattered from the target could be separated quite clearly from the background M-band radiation also scattered from the target foil. However, in this preliminary experiment the plasma conditions were not well diagnosed [15].

A further technique for generating dense plasmas is to compress solid targets with laser driven shocks. Experiment and simulation [16,17] have shown that for typical focused irradiances of the order 10^{14} W cm^{-2}, with nanosecond pulses, pressures of several megabars are easily generated at the ablation surface. This drives a strong shock which compresses the target to densities of several g/cm^3 at temperatures of several eV. By using colliding shocks, densities of up to ten times solid are possible. By using short wavelength laser light, high pressures can be achieved while moderating the temperature in the ablated plasma [18]. This means that bremsstrahlung emission can be kept to a level that will not swamp the scattered line radiation. Simulations with the MEDUSA hydrocode have shown that a 24-μm aluminium foil, tamped with CH, can be compressed to 12 g/cm^3 at 6 eV with two opposing 2-ns beams of 351-nm laser light focused to 4×10^{14} W cm^{-2}. For an energy of 3500 J per beam, the compressed region has approximately 10^{18} scattering ions contributing to the signal.

The generation of solid density plasmas at temperatures of 1–1000 eV with femtosecond laser pulses is currently a matter of great interest. However, the generation of an ultrashort pulse of hard x rays would be a necessary prerequisite to obtaining data related to the dense hot material produced just after laser heating.

One possible method is to use a second femtosecond pulse focused tightly onto a second target, to generate fast electrons by a resonance absorption type process [19] or other processes [20]. These would then generate $K\alpha$ radiation which could then be allowed to fall on the sample plasma in a restricted range of angles, by use of a pinhole. Quantitative measurements of $K\alpha$ yield for this method [21] have indicated that for 1.5 mJ on target in a sub-100-fs pulse 2.5×10^7 photons/Sr are generated for Al $K\alpha$. Since this production mechanism relies on the suprathermal electron generation driven by the laser field, the pulse duration of the x rays will be as short as the laser pulse itself. Alternatively [22], it has been suggested that kilovolt x rays can be generated by the interaction of a sufficiently short (<100 fs) laser pulse incident on a solid target at irradiances above 10^{17} W cm^{-2}. In each case the photon production will be small enough to necessitate summing over hundreds of shots, as discussed below.

Synchronization of the pump and probe pulse would be maintained by deriving both from a single beam split into two, with an appropriate partition of energy. The accuracy of the synchronization would then depend on the quality of the spatial positioning of lenses. Pump-probe measurement of target reflectivity during the first few hundred femtoseconds after heating have been made by several authors [23,24]. As we have already stated, the resolution set by the x-ray pulse duration may be <100 fs for hot electron $K\alpha$ emission. The probe pulse can be used to study the plasma at times starting from 0 to 0.1 ps from the start of the pump pulse. Apart from this issue, the principal difficulty of such an experiment is to ensure that scatter from unheated parts of the target is kept to a minimum. This means that careful alignment is necessary to be certain that the scattering x rays are only incident within the focal spot area. This problem need not be too difficult. The recent development of short pulse lasers means that energies of order 1 J are possible in 100 fs at repetition rates of 1 Hz. This means that a large focal spot ($\sim$1 mm) can be used with irradiances still above 10^{14} W cm^{-2}, which is enough to create a strongly coupled plasma at $\sim$10 eV [25]. Such a large focal area makes good alignment easier to achieve in practice. In addition, there is the problem of x rays scattering from deep within the target. For example, the absorption depth of 8-keV photons in Cu is about 20 μm, whereas a 100-fs laser pulse heats only a few hundred Å depth during the pulse. The obvious way around this problem is to make targets that are only just thicker than the heated depth. this can be achieved by evaporating a thin ($\sim$0.1 μm) layer of Cu onto a submicron layer of Mylar. The major difficulty would then be the rastering of the target over the many shots needed in these circumstances to build up a cross-section measurement. However, the large focal spot used to attain moderate heating intensity would allow a series of delicate thin film targets to be successively moved into position without creating focusing difficulties.

We can estimate the number of shots required by taking the Al $K\alpha$ yields [21], a typical cross section ($\sim10^{23}$ cm^2/sr) for Cu, and estimating 10^{16} target atoms for the thin Cu layer heated by the pump pulse. For a resolution element of approximately 10^{-2} sr, we have 1 in 10^9 incident photons scattered into the resolution element. For good statistics we therefore need about 10^{11} photons incident in 10^{-2} sr. From the data of Ref. [21], we can estimate that a 1-J 100-fs laser would require 600 shots. This would only take 10 min at 1 Hz; with a cooled CCD this presents no real difficulty. The use of electronic recording and storage of signals, would also mean that the data need not be collected in one quick burst of shots, thus allowing time for targets to be changed.

CONCLUSIONS

In conclusion, the work presented here provides an improved model for the calculation of x-ray scattering from dense plasma. The use of the INFERNO model provides the possibility of bringing into account shell effects as well as the effect of resonances. Thus it is possible to analyse proposed x-ray scattering diagnostic experiments in a Cu plasma produced by femtosecond laser interaction. The same techniques could be applied to transition metals. Shell effects also manifest themselves in an ultradense Al plasma, which can be produced in colliding shock experiments. Finally preliminary experimental results on an Al laser produced plasma indicate that x-ray scattering experiments from a plasma radiatively heated can be diagnosed by a syncronized short probe pulse. Thus the examples discussed indicate that feasible x-ray scattering measurements can yield important information on the electronic and ionic structures of interesting dense strongly coupled plasmas.

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