Observation of Radiative Burnthrough in X-Ray Heated Beryllium by Time-Resolved Spectroscopy

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(Received 4 August 1992)

A 0.5-μm-thick beryllium foil is heated by thermal x rays from a laser-irradiated converter foil up to temperatures of a few 10 eV. During the transformation of the solid Be into an ionized gas time-resolved absorption spectra have been measured in the region 100 eV $\lesssim h\nu \lesssim$ 250 eV. The measurements agree well with calculations of the radiation transport, for which electron-impact line broadening was found to be essential. Smoothing of the Be K edge observed in the beginning of the heating, when the foil is still in a partially degenerate state, is attributed to thermal smoothing of the Fermi edge.

PACS numbers: 52.50.Jm, 32.30.Rj, 32.70.Jz, 44.40.+a

The energy released by high-power lasers can be converted with high efficiency into intense thermal x rays [1]. This makes it now possible to generate hot and dense matter by radiative heating and to study opacities and radiation transport in a temperature and density regime which hitherto was not accessible in a laboratory. There is strong interest in this subject for several reasons. In astrophysics, opacities are required for modeling of stars. Recently, the measurement of opacities in a radiatively heated plasma without strong temperature and density gradients has been demonstrated in an astrophysically relevant region [2–4]. Another important application is indirect-drive inertial confinement fusion, in which the pellet is driven by soft (sub-keV) x-ray heating of a low-Z ablator [5].

Radiative heating of matter up to temperatures exceeding 200 eV has been demonstrated recently in several experiments [6–9]. Typical of radiative heating is that an ablative temperature wave is driven into the material by the radiation, which has been studied analytically for high-Z [10] as well as for low-Z material [11]. If the temperature wave propagates in a thin enough foil, it may reach the foil's rear side resulting in "radiative burnthrough." In high-Z material (gold) the propagation of a radiative heat wave has recently been observed in this way [12].

In this Letter we present a detailed study of the radiative burnthrough in a low-Z material by measuring the time-resolved x-ray absorption spectra in the region of the K edge. In this way we observe for the first time in detail the transition from the cold solid first to a partially degenerate plasma and finally to an ionized hot dense gas. Beryllium (with the K edge at 112 eV) has been taken as absorber material. Its simple atomic level structure allows us a detailed comparison with numerical simulations. We have studied the sub-keV photon energy range, where the radiation transport predominantly takes place. We note that a similar experiment with carbon has been carried out recently [13]. However, the expected radiative burnthrough was not observed, for which no clear reason could be given by the authors. A more qualitative indication of radiative burnthrough in aluminum has been reported earlier [14].

In the experiment performed by us a thin gold foil [3000 Å gold on a 1-μm polypropylene (CH_2) substrate] heated by a laser pulse (15 J, 3 ns, $\lambda = 0.53$ μm) served as a converter of laser light into thermal x rays [15]. The laser spot diameter was 200 μm and the laser intensity 10^{13} W/cm^2. The x rays emitted from the rear side of the converter were used to heat an absorber foil (0.5-μm-thick Be, 200 μm in diameter), which was positioned at a distance d behind the converter foil parallel to it. A finite distance d was employed to provide a homogeneous irradiation of the absorber, becuase irregularities in the x-ray source flux caused by hot laser spots on the converter foil are geometrically smoothed out. The x-ray flux (S_x) on the absorber could be varied through the distance d in the range $\leq 10^{12}$ W/cm^2. Contributions of transmitted laser light are $\leq 2\times10^9$ W/cm^2 and therefore negligible. The radiation transmitted through the absorber foil was measured with temporal (50 ps) and spectral (0.5 eV) resolution by a flat-field grazing-incidence spectrometer coupled to an x-ray streak camera. In addition a transmission grating spectrometer coupled to calibrated x-ray film measured the absolute value of the x-ray flux. More details of the experiment are given in Ref. [16].

Examples of streaked spectra are presented in Fig. 1. In Fig. 1(a) we show the source spectrum emitted by the converter alone (no absorber). It has no pronounced spectral features and can be approximated by a Planck function with ≈ 50 eV temperature. The temporal modulation is caused by modulations of the laser pulse. The spectrally integrated x-ray source pulse (plotted in Fig. 4) has a duration of 1.4 ns (FWHM). In Fig. 1(b) the absorber is placed at a large distance ($d = 350$ mm), where it remains cold. One recognizes the sharp K edge of cold solid Be. Above the K edge (photon energy ≥ 112 eV) the cold foil is optically thick (optical thickness ≈ 10) and no x rays are transmitted [the faint background above the K edge present in Fig. 1(b) is caused by instrumental noise and small higher-order contributions from photons at higher energy].

If the absorber is brought close to the source [$d = 130$ μm, corresponding to an x-ray flux $S_x = 5\times10^{11}$ W/cm^2, Fig. 1(c)], it is transformed into a hot dense gas of ion-

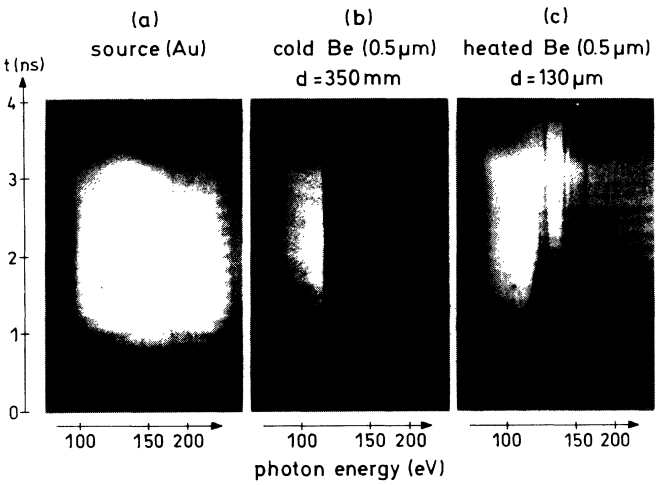

FIG. 1. Time-resolved spectrum obtained (a) with the source alone, (b) with a cold, and (c) with an x-ray heated 0.5-μm-thick beryllium foil.

ized Be atoms. At first only the shape of the K edge changes; it becomes less steep than the K edge of the cold material. Also, in the beginning, when the K edge becomes visible on the streak camera picture [Fig. 1(c)], it is slightly shifted to energies below the cold K edge. With subsequent heating it then moves to higher energies. This is demonstrated in more detail in Fig. 2, in which we plot the spectral shape of the K edge obtained from Fig. 1(c) at the times $t=0.95$ ns and $t=1.5$ ns in comparison to the K edge of cold Be [Fig. 1(b)]. Quite rapidly, at $t\approx 2$ ns, the region above the K edge becomes transparent with an absorption spectrum characteristic of ionized Be. It is plotted in Fig. 3 at $t=2.6$ ns. One sees clearly the absorption lines $1s^2$-$1s2p$ and $1s^2$-$1s3p$ of Be^{2+}. The

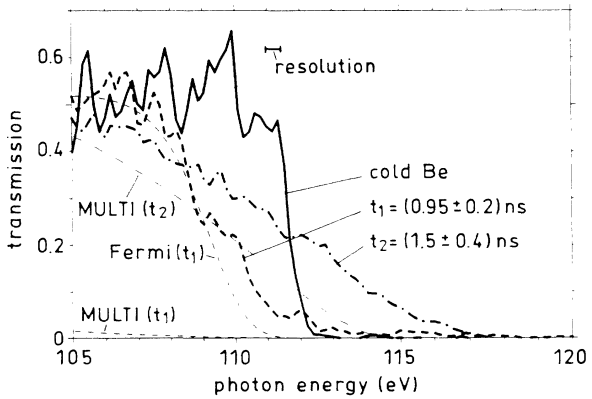

FIG. 2. Temporal development of the Be K edge during the early phase of heating. Thick lines: measured transmission [obtained by normalizing the data of Figs. 1(b) and 1(c) to the source Fig. 1(a); the data are averaged over the given time intervals]. Thin lines: theoretical results from computer modeling (labeled "MULTI") and from a simple model, which considers thermal smoothing of the Fermi edge (labeled "Fermi").

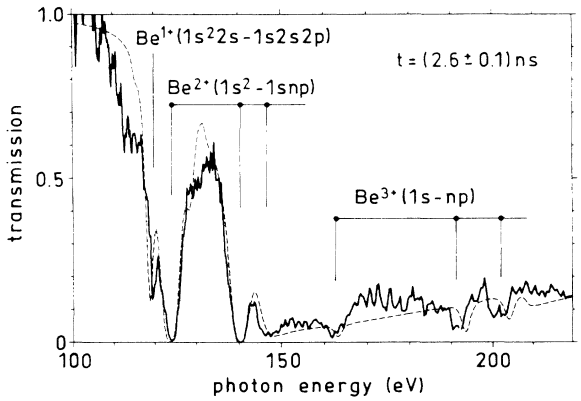

FIG. 3. Spectral transmission at $t=2.6$ ns through the x-ray heated Be foil. Thick solid line: measured transmission (obtained by the same procedure as in Fig. 2); thin dashed line: computer modeling.

more energetic lines of this series are not observed. This is attributed to continuum lowering due to the high density of the material (although it expands during heating) which shifts the K edge of the isolated Be^{2+} ion at 154 eV down by ≈ 10 eV. In fact this edge and its slow motion to higher photon energies as the Be expands with time are clearly visible in Fig. 1(c). In addition to Be^{2+} one also observes in Fig. 3 absorption lines of Be^{3+} and Be^{1+}. The rapid onset of the burnthrough above the K edge at $t=2$ ns is exhibited by Fig. 4, in which we plot the time variation of the characteristic transmission window between the Be^{2+} absorption lines $1s^2$-$1s2p$ and $1s^2$-$1s3p$. The burnthrough time depends on the distance d between absorber and converter. At $d=0$ ($S_x=10^{12}$ W/cm^2) the burnthrough occurs already at $t=1$ ns. No transmission above the K edge is observed at distances $d\geq 300$ μm ($S_x\leq 10^{11}$ W/cm^2).

The hydrodynamic motion of the Be absorber has been simulated with the MULTI code, a one-dimensional hydro-

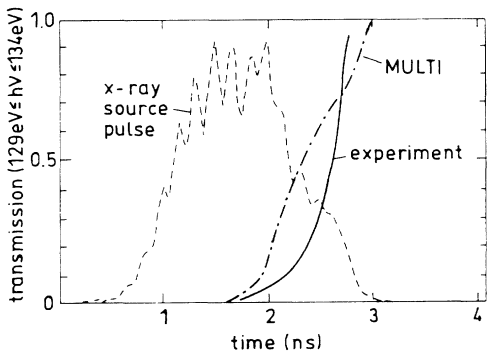

FIG. 4. Time dependence of the burnthrough in the transmission window between the $1s^2$-$1s2p$ and $1s^2$-$1s3p$ transitions in Be^{2+} at around 130 eV according to the measurement and the simulation. For comparison the heating x-ray source pulse is also plotted (in arbitrary units).

code with multigroup radiation transport [17] (80 spectral groups have been taken here). For the opacity we used local-thermodynamic-equilibrium values calculated with the SNOP code [18], which has been improved for low-Z material by using tabulated energy levels and bound-free absorption cross sections [19]. Line broadening is of particular importance because the radiative transport preferentially takes place between the absorption lines in a region where the line wings overlap. We used electron impact broadening with a Lorentz profile as the dominant mechanism [20] (for simplicity we set the Gaunt factor $=1$). For the heating x rays the measured temporal (the pulse shown in Fig. 4 has been smoothed for this purpose) and spectral dependence was employed. The latter was approximated by a Planck function times a factor which allows for the dilution of the radiation with distance d. The calculations are performed in plane geometry.

The simulations typically show a temperature wave penetrating into the foil. It is generated because a large fraction of the incident x rays in the spectral region above the K edge are initially absorbed in the front layers of the foil. Subsequently they penetrate deeper into the foil because of the decrease of the opacity with heating. Only a smaller fraction of x rays (with frequencies mainly below the K edge) penetrate the whole foil already in the beginning, causing some preheating in its rear part. For the conditions of Fig. 1(c) the temperature wave reaches the rear side of the foil after about 2 ns. At $t=2.6$ ns, the time for which we plotted the spectrum in Fig. 3, the values for the average temperature and density in the foil are ≈ 25 eV and $\approx 5\times 10^{-3}$ g/cm^3, respectively. The foil has expanded at this time to a thickness of 70 μm (FWHM of the density profile). This value is smaller than the absorber diameter (200 μm). Thus lateral flow is not very important and the motion of the foil should be well approximated by the planar geometry of the simulations.

The absorption spectra were calculated by a postprocessor which solves the radiation transport equation for the density and temperature profiles calculated by MULTI. In addition to directly transmitted light from the source, self-emission has also been taken into account. It becomes important only at the end of the pulse when the source intensity drops to small values. The comparison of the simulations with the observed spectra (Fig. 3) and the temporal development of the burnthrough (Fig. 4) shows a quite satisfying agreement. We note that the simulations depend sensitively on the line broadening (for example the merging of the Be^{2+} series with the continuum is strongly influenced by the scaling of the electron-impact broadening with the principal quantum number, $\Delta\nu \propto n^4$). The good agreement achieved confirms that the employed electron-impact broadening is the dominant mechanism for the conditions here.

We finally discuss the behavior of the K edge at early times (Fig. 2). It is of particular interest because it is related to the transition from the degenerate solid to an ionized gas. In the simulations described above, the Be is treated as an ionized gas consisting of a mixture of different ion species. The spectra calculated by this model (the curves labeled "MULTI" in Fig. 2) exhibit, as the measurement, a smoothed edge. However, in the beginning (at t_1 in Fig. 2) the smoothing is considerably overestimated (the calculated slope of the edge is at this time much smaller than the measured one). The shape of the calculated spectra is caused by the red wing of K- to L-shell line transitions, mainly of the $1s^2 2s$-$1s2s2p$ line transition at 119 eV in Be^{1+}, the most dominant ion at $t\approx 1$ ns. The blue line wing merges with the strongly lowered continuum (the K edge of isolated Be^{1+} is 136 eV) resulting in zero transmission on the blue side of the line. The slope of the red line wing is determined by electron-impact broadening, which is extremely large in the beginning because of the low temperature (≈ 1 eV) and the high density not much below the solid Be density. Under these conditions, however, the plasma is in a partially degenerate state, i.e., the applied collisional broadening theory [20], which is based on binary collisions between electrons and ions, is no longer valid. We consider this as the main reason for the strong disagreement at time t_1. At later times the foil has sufficiently expanded, so that it is no longer in a degenerate state. Therefore the agreement between the calculated and measured spectra becomes better at later times (t_2 in Fig. 2).

In order to take into account the effect of degeneracy at early times, we have calculated the absorption by a simple consideration, which is independent of the MULTI simulations. It starts from the level structure of cold solid Be, which has a sharp $1s$ state, whereas the $2s$ and $2p$ (and the higher) levels form a broad energy band, which is filled at zero temperature with electrons up to the Fermi edge. Its distance to the $1s$ level is $E_F=112$ eV corresponding to the K edge of cold Be. The absorption in this situation is essentially caused by photoionization and may be described by the following plausible formula:

$$\kappa=\kappa_K(1-f)+\kappa_L\,. \tag{1}$$

κ_K and κ_L are the bound-free mass absorption coefficients for K- and L-shell electrons. Their values have been taken from the tables of Henke *et al.* [21] for cold solid Be (which are practically identical with the calculations [19] for isolated Be^{0+} apart from the fact that the K edge of isolated Be^{0+} is at 124 eV). $f=\{\exp[(h\nu-E_F)/kT]+1\}^{-1}$ is the Fermi energy distribution of electrons; the factor $1-f$ describes the availability of vacant levels in the vicinity of the Fermi edge. It is a step function for $T=0$, i.e., Eq. (1) reproduces the sharp K edge of cold solid Be. At finite temperature the factor $1-f$ causes smoothing of the K edge and also allows that states below

the Fermi edge become available for photoionization of K-shell electrons. Considering the temperature as a fit parameter we find with $kT=1$ eV (and with $E_F=112$ eV, the value for cold solid Be) a reasonable fit for the transmission measured at the time t_1 [the curve labeled "Fermi" in Fig. 2 is the calculated transmission $=\exp(-\kappa m)$ with κ from Eq. (1) and m the areal mass density of the foil]. We note, that $kT=1$ eV is in accordance with the MULTI simulations, in which it is approximately the average temperature in the rear part of the foil at $t=t_1$. The simple calculation given above neglects the spatial variation of the temperature and density in the foil and its detailed influence on the level structure and the opacity. Nevertheless, it describes the shape of the K edge observed at early times quite well simply by assuming the existence of a thermally smoothed Fermi edge. A more complete calculation would require a theory for the opacity in the regime of the transition from the degenerate solid state with band structure to an ionized gas consisting of different individual ions which to our knowledge does not exist.

In conclusion, we have studied the radiative burnthrough in thin Be foils heated by thermal x rays. The measured absorption spectra and the temporal development of the burnthrough agree well with calculations, which are based on numerical simulations of the hydrodynamic motion of the foil and the radiative transport. Two aspects have to be emphasized. First, the radiative transport in low-Z material with few widely spaced lines is quite sensitive to the line broadening far from the line center. For attaining good agreement between experiment and theory electron-impact broadening was crucial. Second, this experiment allows us to study the early phase of heating, when the crystalline solid dissolves, but the matter is still in a partially degenerate state. We found that the smoothing of the K edge observed in the beginning may be related to thermal smoothing of the Fermi edge. Finally we would like to note that the results reported here are obtained with low laser energies ≤ 15 J, i.e., opacity studies, at least in a modest temperature range of a few 10 eV, are possible with lasers of table top size.

The authors would like to thank H. Griem, J. Meyer-ter-Vehn, R. Sigel, M. C. Richardson, and G. D. Tsakiris for helpful discussions. This work was supported in part by the Commission of the European Communities in the framework of the Euratom-IPP Association.

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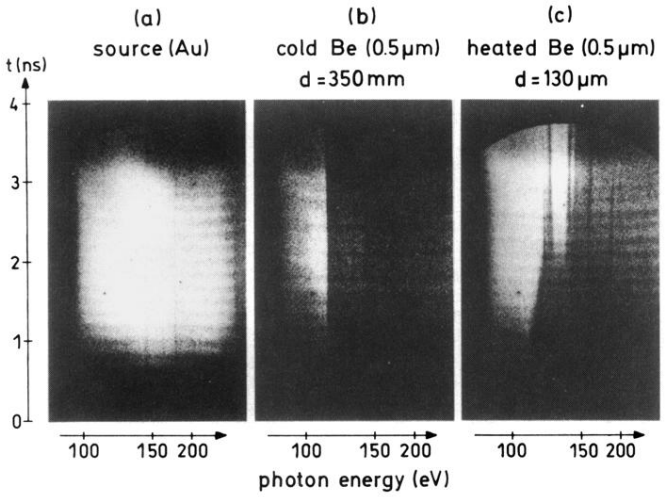

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