We consider atoms in the light of a linearly polarized laser which are probed by linearly polarized x rays (Fig. 1). Such a setting is referred to as a two-color problem and has proved to be a very beneficial to probe strong-field physics and to manipulate x rays [1-7].

We assume a Ti:sapphire laser at 800 nm with $10^{13}$ W/cm$^2$. The atomic ground-state electrons remain essentially unperturbed in the laser light; they are neither excited nor ionized. However, laser dressing of the core-excited states introduces strong-field physics because, for the laser parameters employed here, the Keldysh parameter [8] $\gamma = \sqrt{I_{1s-3p}/(2U_p)} = 1.5 \approx 1$. The ionization potential of a core-excited state with the electron in the $3p$ Rydberg orbital is denoted by $I_{1s-3p}$, and the ponderomotive potential of the laser is $U_p$ [3].

For $\gamma \approx 1$, neither perturbation theory nor a tunneling description is adequate. Therefore, we have developed an ab initio theory described in Ref. 1. The electronic structure of the atom is described in the Hartree- Fock-Slater approximation where a complex absorbing potential (CAP) is used to treat continuum electrons. Nonrelativistic quantum electrodynamics is used to treat the atom in the two-color light. The interaction with the laser is described in terms of a Floquet-type matrix whereas the x-ray probe is treated in second-order (one-photon) perturbation theory [9]. For core-excited states, we need to take into account the Auger decay rate of a K-shell hole in neon $\Gamma_{1s} = 0.27$ eV. The absorption cross section for x rays with photon energy $\omega_X$ is found to be

$$\sigma_{1s}(\omega_X, \vartheta_{LX}) = \sigma_{1s|\omega_X|}^\parallel \cos^2 \vartheta_{LX} + \sigma_{1s|\omega_X|}^\perp \sin^2 \vartheta_{LX},$$

where $\vartheta_{LX}$ denotes the angle between the laser and x-ray polarization vectors [1]. The cross section for parallel x-ray and laser polarization vectors is given by $\sigma_{1s|\omega_X|}^\parallel$; it is $\sigma_{1s|\omega_X|}^\perp$ for perpendicular vectors. The calculations were carried out with the DREYD and PULSEPROP programs [10]. We use the computational parameters from Refs. 1, 3. For the index of refraction (Fig. 4), we need 400 radial wavefunctions.

The calculated x-ray photoabsorption cross section of a neon atom is displayed in Fig. 2 with laser dressing and without. The prominent absorption feature in the top panel at 867.4 eV arises due to the $1s \rightarrow 3p$ resonance. The weaker peaks are associated with $1s \rightarrow np$ transitions with $n \geq 4$. The $K$ edge lies at 870.2 eV. The most eye-catching impact of the laser dressing can be seen in the vicinity of the $1s \rightarrow 3p$ resonance, which becomes transparent for $\vartheta_{LX} = 0^\circ$ [3].

To understand the influence of the laser, we make a $\Lambda$-type model for neon shown in Fig. 3. We use the states $1s^{-1}3p$, $1s^{-1}3s$, and the atomic ground state. The laser photon energy is $\omega_L$, whereas $\Gamma_{Ne1s^{-1}3p}$ and $\Gamma_{Ne1s^{-1}3s}$ denote the decay widths of the respective coreexcited states. We find the overall agreement of the model curves with the ab initio data to be reasonable. The model explains the transparency induced by the laser in the middle panel of Fig. 3 in terms of...
a splitting of the \(1s^{-1}3p\) and \(1s^{-1}3s\) states into an Autler-Townes doublet. Since the laser causes a suppression of resonant absorption, we call this electromagnetically induced transparency (EIT) for x rays [3]. Dipole selection rules dictate that the laser can couple only \(1s\) to \(3s\) in a one-photon process; so only for \(\theta_{LX} = 0^\circ\), EIT occurs. The suppression for \(\theta_{LX} = 90^\circ\) is a consequence of laser-induced line broadening.

The refractive index is a classical quantity from Maxwell’s equations. In Fig. 4, we show the real part \(n(\omega_X)\) for neon in the x-ray regime without laser dressing

\[
n(\omega_X) = 1 + \frac{2\pi n_0 \alpha_1(\omega_X)}{\omega_X^2},
\]

where the number density of neon atoms is \(n_0\). Further, \(\alpha_1(\omega_X)\) is the dynamic polarizability which we compute using

\[
\hat{H}_{I,X} = \alpha \hat{r} \cdot \vec{A}_X + \frac{1}{2} \alpha^2 \vec{A}_X^2
\]

(in atomic units) for the interaction Hamilton with the x rays in dipole approximation [7]. The momentum operator is \(\hat{p}\) and the vector potential is \(\vec{A}_X\). We compare our theoretical results with the data from Fig. 4 of Ref. 11 which was computed from experimental cross section data. The agreement is generally good; only the feature on the \(1s \rightarrow 3p\) resonance is not reproduced by the semi-experimental data due to limited resolution.

The impact of the laser dressing on neon is investigated for the dynamic polarizability; it is plotted in Fig. 5 for the three cases considered in Fig. 2. In this paragraph, we follow Ref. 3 and use \(\hat{H}_X = \vec{r} \cdot \vec{E}_X\) in dipole approximation for the interaction with the x rays. The electron position is \(\vec{r}\) and the electric field of the x rays is \(\vec{E}_X\). The overall

\[
\alpha_1(\omega_X) = \frac{n(\omega_X) - 1}{n(\omega_X) + 2}
\]

at normal temperature and pressure [7]. It follows from \(n(\omega_X) = 1 + 2\pi n_0 \alpha_1(\omega_X)\), where the number density of neon atoms is \(n_0\). Further, \(\alpha_1(\omega_X)\) is the dynamic polarizability which we compute using

\[
\hat{H}_{I,X} = \alpha \hat{r} \cdot \vec{A}_X + \frac{1}{2} \alpha^2 \vec{A}_X^2
\]

(in atomic units) for the interaction Hamilton with the x rays in dipole approximation [7]. The momentum operator is \(\hat{p}\) and the vector potential is \(\vec{A}_X\). We compare our theoretical results with the data from Fig. 4 of Ref. 11 which was computed from experimental cross section data. The agreement is generally good; only the feature on the \(1s \rightarrow 3p\) resonance is not reproduced by the semi-experimental data due to limited resolution.

The impact of the laser dressing on neon is investigated for the dynamic polarizability; it is plotted in Fig. 5 for the three cases considered in Fig. 2. In this paragraph, we follow Ref. 3 and use \(\hat{H}_X = \vec{r} \cdot \vec{E}_X\) in dipole approximation for the interaction with the x rays. The electron position is \(\vec{r}\) and the electric field of the x rays is \(\vec{E}_X\). The overall

\[
\alpha_1(\omega_X) = \frac{n(\omega_X) - 1}{n(\omega_X) + 2}
\]

at normal temperature and pressure [7]. It follows from \(n(\omega_X) = 1 + 2\pi n_0 \alpha_1(\omega_X)\), where the number density of neon atoms is \(n_0\). Further, \(\alpha_1(\omega_X)\) is the dynamic polarizability which we compute using

\[
\hat{H}_{I,X} = \alpha \hat{r} \cdot \vec{A}_X + \frac{1}{2} \alpha^2 \vec{A}_X^2
\]
polarizability and its change is small for x rays. Laser dress-
ing causes a suppression near the resonance in contrast to the
optical domain. The Λ-type model [Fig. 3] reproduces the
structure of \(\alpha_I(\omega_X, \vartheta_X)\) [3].

EIT for x rays opens up an exciting novel prospect: it can
be used to imprint pulse shapes of the optical dressing laser
onto a comparatively long x-ray pulse. Yet only amplitude
modulation is practically feasible due to the small refraction
and dispersion in the x-ray domain (Figs. 4 and 5). In Fig. 6,
the propagation of two-color light through a neon gas cell is
shown. First, the x-ray and laser pulses are still outside the
gas cell. Second, the first of the two laser pulses overlaps
with the x-ray pulse inside the gas cell, thereby substantially
enhancing x-ray transmission in comparison to the laser-off
case. Third, after propagation through the gas cell, two ul-
trashort x-ray pulses emerge. This EIT-based pulse shaping
opens up a route to ultrafast all x-ray pump-probe experi-
ments [3]. C.B.’s research was partly funded by a Feodor
Lynen Research Fellowship from the Alexander von Hum-
boldt Foundation. Our work was supported by the Office of
Basic Energy Sciences, Office of Science, U.S. Department
of Energy, under Contract No. DE-AC02-06CH11357.

* Present address: Department of Physics and Astronomy,
Louisiana State University, Baton Rouge, Louisiana 70803,
USA

10. C. Buth and R. Santra, fella - the free electron
laser atomic, molecular, and optical physics pro-
gram package, Argonne National Laboratory, (Ar-
gonne, Illinois, USA 2008), version 1.3.0, with con-
tributions by Mark Baertschy, Kevin Christ, Chris H.
Greene, Hans-Dieter Meyer, and Thomas Sommerfeld,