Strong-Field-Enhanced Forward Scattering of High-Order Harmonics

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Abstract: We show that scattering of ultrashort XUV pulses from strong-field driven electron wavepackets is enhanced as compared with normal weak scattering from bound or free electrons. We predict large XUV amplification in high-order harmonic generation.

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We consider the interaction of an atom with an intense ultrashort infrared (IR) pulse combined with a weak attosecond pulse of central photon energy much higher than the principal atomic resonances [1, 2]. Specifically, we address the influence of the high-intensity IR field on the scattering of weak XUV radiation from atoms in high-order harmonic generation (HHG) processes. By solving the time-dependent Schrödinger equation in the single-atom strong-field approximation (SFA), we show that forward scattering is enhanced when the weak XUV attosecond pulse is synchronized with the amplitude maxima of the IR intense pulse. It is shown that this enhancement effect can be used for the amplification of coherent XUV radiation in the HHG cutoff spectral region to power levels that might be useful for most applications [3].

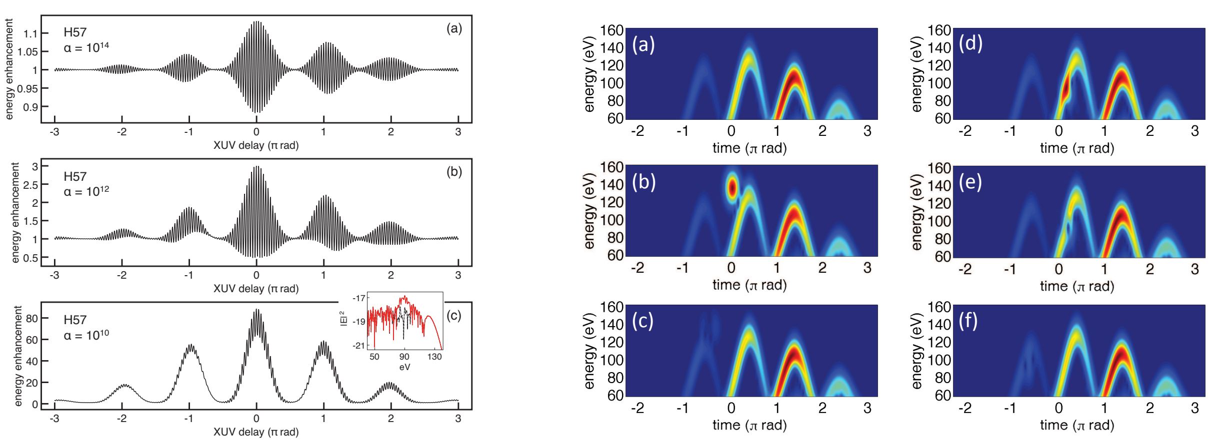

Fig. 1. **Left:** Energy enhancement of the 57th harmonic of a 800 nm IR intense driving field in Helium, for different ratios between the IR and the XUV pulse peak intensities (α), as indicated, as a function of the delay between the IR and the XUV pulses. The delay is given in parts of half a cycle of the IR pulse, in radiants, so that 2π rad $\equiv \lambda_{IR}/c \approx 2.66$ fs. The inset in (c) shows the spectrum around the 57th harmonic, in the case of considering only the IR pulse (black dotted line) and for the combination of IR+XUV pulses (red full line). **Right:** Frequency-time analysis of some of the spectra shown in the figure at left with $\alpha = 10^{12}$. In (a) the He atom interacts only with the Gaussian IR pulse. In (b) and (c) the IR pulse is combined with its 87th harmonic at a delay of 0.014π rad and -0.48π rad, respectively. In (d), (e) and (f) the IR pulse is combined with its 57th harmonic at the delays 0.206π rad, 0.223π rad and -0.6π, respectively.

Figure 1 at left shows how the HHG yield is enhanced by the addition of the weak attosecond XUV pulse, and that this enhancement is governed by the delay at which the XUV pulse is added. The effect is more important for delays coinciding with higher values of the IR field, in such a way that the shape of the IR pulse is clearly reproduced. The enhancement calculated in Fig. 1 (left) is given by $\int_{H_-}^{H_+} E^2_{IR+XUV} dH / \int_{H_-}^{H_+} E^2_{IR} dH$, where H_- and H_+ are the photon energies of the previous and next harmonics, respectively, with respect to the harmonic that coincides with the central wavelength of the XUV pulse, so that the integral comprises the bandwidth of a single harmonic. E_{IR+XUV} is the HHG spectral field amplitude in the case that the interaction is performed by combining the IR and the XUV pulses, and E_{IR} corresponds to the case with the IR pulse alone. dH denotes the integration over the photon energy. The frequency-time analysis of the spectra reveals that the enhancement observed is due to XUV forward scattering from the non-stationary electronic wave packet promoted by the intense IR driving field, which is shown in Fig. 1 at right.

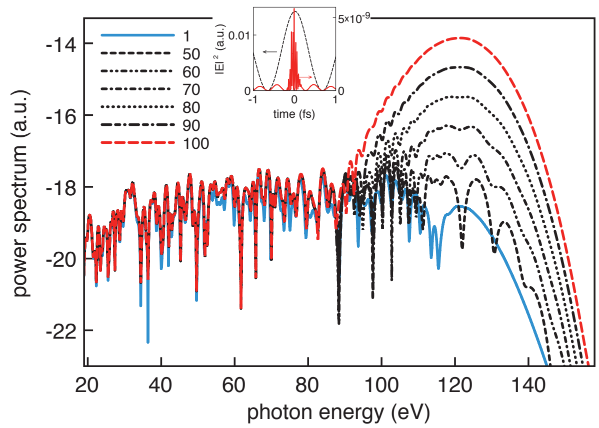

Fig. 2. XUV yield amplification obtained by filtering the harmonics spectrum at 80 eV with 120 eV spectral bandwidth. The filtered XUV is combined with the IR pulse as delayed as it comes out from the output of the interaction, in all iterations. The different lines correspond to the different iteration number, as indicated. The inset shows the filtered XUV pulse from the 100th iteration (red full line) compared with the input IR field (black dotted line).

Figure 2 shows the results obtained by implementing an iterative procedure. The harmonics yield produced by a strong IR pulse in a first HHG process is combined with the IR field and sent to second He target, and this process is repeated iteratively. The XUV delay is set to zero in each iteration, which means that the XUV pulse is added to the IR pulse as delayed as it comes out from the output of each interaction. We observe that the amplification of the yield becomes progressively centered at around 125 eV, and that the enhanced spectrum is roughly 50 eV wide at the 100th iteration. This shows that the spectral HHG region slightly above the cutoff is preferably enhanced, as in this region the harmonics yield is very low, and as a consequence the scattered spectral components in the cutoff region initially dominate the amplification.

We conclude that the observed scattering enhancement effect can be used to strongly amplify the yield in the HHG cutoff region, which sets the basis for a new coherent X-rays source. We are currently extending this study in order to estimate quantitative results for the particular experiments, which may include other interaction geometries and use different amplifying media.

References

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