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Quantum optics meets attosecond science

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Generating high harmonics or attosecond pulses of light is normally thought of as a classical process, but a theoretical study has now shown how the process could be driven by quantum light.

Quantum optics deals with the discrete nature of light – the photon. For quantum technologies, usually that means a few photons. For example, if one knows how many photons there are in a light pulse, then the resulting pulse is not in a classical state. However, to the surprise of many of us working on the interaction of intense light with matter, researchers have developed bright quantum sources[1]. Immediately, the question arises of whether it is possible to apply these sources to produce high harmonics or attosecond pulses, and if so, whether there would be a qualitative difference. This is the subject of a theoretical study published in *Nature Physics* by Alexey Gorlach and colleagues that every physicist should read[2].

High-harmonic and attosecond pulse generation is normally thought of as a classical phenomenon. Like conventional nonlinear optics, extreme nonlinear optics is usually described as arising from classical light interacting with quantum matter. However, instead of using the nonlinear behaviour of bound electrons (as in conventional nonlinear optics), extreme nonlinear optics uses continuum electrons. In fact, it is the large energy gained by the continuum electron that has allowed high-energy harmonics or attosecond pulses to be produced. However, to gain high energy, continuum electrons must be driven by many photons, so one would not think that high-harmonic generation is the natural place in which to look for novel quantum effects. Gorlach and colleagues have shown that this is wrong.

It was not that researchers working on the interaction of intense light with matter did not understand that the energy of the recollision electron was key to extending the harmonics. They have tried many possible combinations of classical light pulses to create the ‘perfect wave’[3]. Although the idea was to extend the harmonic spectrum to higher energies, more recently this effort was abandoned in favour of more straightforward scaling with the wavelength of the driving laser pulse. At present, this allows harmonics extending to more than 1.3 kiloelectronvolts, driven by 3.9-micrometre light interacting with helium[4]. But there may be a different way.

For their calculation, Gorlach and colleagues used a bright squeezed vacuum[1]. All physicists know that the vacuum is never truly empty. Therefore, an amplifier can amplify the vacuum, providing a route to a bright vacuum. If the amplification is phase-sensitive, specific phases of the vacuum fluctuations are favoured. That is, a parametric amplifier squeezes the vacuum as it is amplified, producing a bright squeezed vacuum – intense quantum light, a form of light that had not previously been considered for the ‘perfect wave’.

Once the driving laser beam is established, high-harmonic generation is a rather straightforward process. An intense pulse irradiates an atomic or molecular gas[4], a transparent solid[5] or even a metal[6], and the interaction creates high harmonics of the fundamental light. The maximum energy of the radiation has a precise cut-off photon energy. For atoms, the cut-off energy can be derived from classical physics[7]. To make harmonics a quantum source, all that is necessary is to replace classical light with a quantum source.

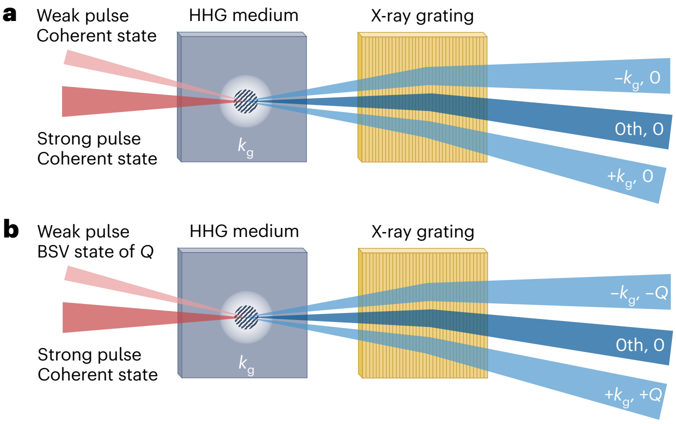

Fig. 1 | Perturbative control of the recollision while generating high-harmonic radiations. a, Conventional noncollinear two-beam configuration of the wave-mixing nonlinear optics in high-harmonic spectroscopy, involving a wavenumber k_g. **b**, Potential experiment employing a quantum beam – for example, a bright squeezed vacuum (BSV) – as a perturbation, where Q indicates that the bright squeezed vacuum perturbing pulse and the diffracted high harmonics have quantum statistics. HHG, high-harmonic generation.

But an even lower-energy alternative exists. If it is difficult to create sufficiently intense quantum radiation, one can perturb the recollision electron trajectories created by classical light with a quantum beam of the same wavelength (or a multiple thereof) overlapping the classical beam in the nonlinear medium at an angle[8]. Conservation of momentum requires that the net number of photons contributed from each beam can be identified. In this setup, the perturbing beam need not be intense.

The two-beam perturbed trajectory method (not analysed in the paper) will produce a classical beam for the net-zero quantum photon direction. As sketched in Fig. 1, this classical beam can serve as a reference for a deflected beam that will have quantum properties. It is possible to arrange for the two beams to interfere[9].

But one must be able to interpret experimental results, and this is where the theoretical analysis of Gorlach and colleagues comes in. They compared the behaviour of the high-harmonic spectrum generated with both a bright squeezed vacuum beam and a classical beam of the same intensity. Treating the single-beam case, they predicted a dramatic difference. The spectrum that they calculated for a bright squeezed vacuum is so distinct that it is qualitatively observable in any experiment. Using standard parameters for irradiating a hydrogen-like atomic gas, Gorlach and colleagues predicted that the cut-off will be extended by a factor of about five.

Although there have been precursors[10], in our opinion the paper by Gorlach and colleagues effectively marks the beginning of a new subfield of high-intensity quantum optics. Short-wavelength and X-ray quantum optics will arise from transparent materials and metals and also from atomic and molecular gases. One can study the quantum response of all subfields of high-field physics including tunnel ionization, above-threshold-ionization electrons and electrons emitted from metal tips. All can be powered by both quantum or classical light or combinations of each. We anticipate that X-rays up to kiloelectronvolt energies and energetic electrons will be able to carry quantum statistics. These new and varied quantum sources will greatly expand the impact and applications of quantum optics.

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Competing interests

The authors declare no competing interests.