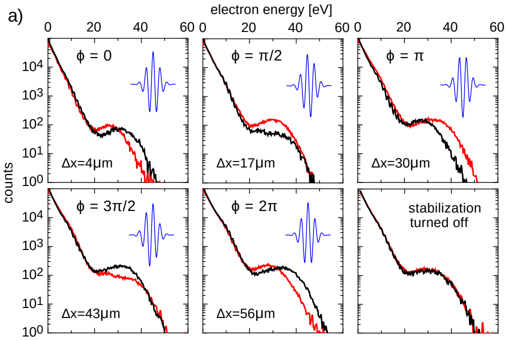
Quantum optics with tailored single optical cycles

G. G. Paulus
Dept. of Physics, Texas A&M University, College Station, TX 77843

In recent years technologies were developed to generate pulses shorter than 5 fs and consisting of less than two optical cycles in full-width at half maximum (few-cycle pulses). The (quite often extremely) nonlinear interaction of such pulses with matter renders important only one or a fraction of one optical cycle. In recent months it became possible to stabilize the phase of the carrier with respect to the pulse envelope ("absolute" phase) for powerful few-cycle pulses. Almost at the same time the absolute phase has been measured and controlled thus tailoring the temporal evolution of single optical cycles. First experiments investigating photoionization were performed and showed a wealth of information inaccessible so far.



Here we point out that the significance of these experiments might reach far beyond the measurement of the absolute phase in introducing single-cycle quantum optics. The limited amount of data taken for the purpose of phase measurement already reveals several novel effects providing e.g. information about characteristic times in the ionization process and possibly the role of atomic structure.

Particularly eye-catching phase effects are observed at high electron energies. The present understanding of the origin of these electrons (which is supported by the new results) implies that they are generated in a very small fraction of an optical cycle. The electrons with energy between 40 and 45 eV are created in a time span of less than 100 as. To our knowledge this is one of the most precise temporal informations ever gained about electronic transitions.
More time information can be obtained by evaluating the phase-dependent contrast of peak structure in the spectra. Depending on the absolute phase, photoelectrons of certain energy may be created in one or in two optical cycles. In the latter case, interference of the outgoing wavepackets leads to peak structure. This effect can also be interpreted as a manifestation of phase-dependent presence or absence of *which-way* information. In contrast to long pulses, the peak separation not necessarily corresponds to the center wavelength of the laser.
There is a third intriguing effect in photoionization with few-cycle laser pulses: The phase dependence of low- and high-energy electrons is different. This seems to provide information on the influence of atomic structure. It appears to be the first time that such information can be obtained experimentally for strong-field laser atom interaction in a systematic way.

Reading the experiment in the opposite direction, one arrives at the conclusion that control of the CE phase provides means to steer photoionization, i.e. to direct photoelectrons in a desired direction. In fact, we have observed ratios of emission in opposite directions approaching 10 in certain spectral regions. The experiment thus can be regarded as the prototype of a new kind of coherent control.

Reference: G. G. Paulus, F. Lindner, H. Walther, A. Baltuska, E. Goulielmakis, M. Lezius, F. Krausz, accepted at *Phys. Rev. Lett.*.