RICC Usage Report for Fiscal Year 2012

Project Title:

Atoms and molecules driven by relativistic laser fields

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1. Background and purpose of the project, relationship of the project with other projects.

With present table-top laser technology, it is possible to produce short pulses of electromagnetic radiation, with a peak electric field strong enough to accelerate an electron to close to the speed of light. Moreover, it is possible to control to a large extent different parameters of the pulse, such as pulse width, wavelength, carrier envelope phase and peak field intensity. If an atom or molecule is placed in such a laser pulse, a wealth of phenomena are induced due to the strong laser-matter interaction. One particularly interesting process that is induced by the laser field is called recollision: First, an atom is ionized by the field, and an electron is ejected. The electron is then accelerated by the oscillating electric field of the laser pulse in such a way that it returns close to the parent atom. If its kinetic energy at the time of recollision is high enough, this recollision may result in the ejection of another bound electron, so that the final state is a doubly ionized atom. This process yields spectra highly correlated in the final energies and angles of the ejected electrons.

Previous research on the recollision process in laser-driven atoms and molecules was mainly performed in the regime of non-relativistic laser-matter interaction. For 800 nm laser light, this implies that the laser field intensity is smaller than about 10^{17} W/cm^2. In the non-relativistic regime, the laser pulse can be modeled to a good approximation as an oscillating electric field. The purpose of the present project is to investigate theoretically if recollision can be induced also in relativistically intense laser fields, with intensities exceeding 10^{17} W/cm^2. Recollisions induced by ultra-intense laser fields are interesting since the maximal kinetic energy of the recolliding electron scales linearly with the laser intensity. A complication in the relativistic regime is that the influence of the magnetic field of the laser pulse can no longer be neglected, due to the high velocity of the electron.

2. Specific usage status of the system and calculation method.

As a first part of the project, we have conducted simulations of helium atoms and helium-like ions subjected to intense laser fields. Since these three-particle systems are not easy to simulate quantum mechanically, we performed classical, Monte-Carlo type simulations. In this kind of calculation, one first fixes a classical Hamiltonian which models the system under study. The classical equations of motion derived from this Hamiltonian, including the electric and magnetic force induced by the laser field are then integrated numerically for many different initial conditions. Physical observables such as ionization probabilities

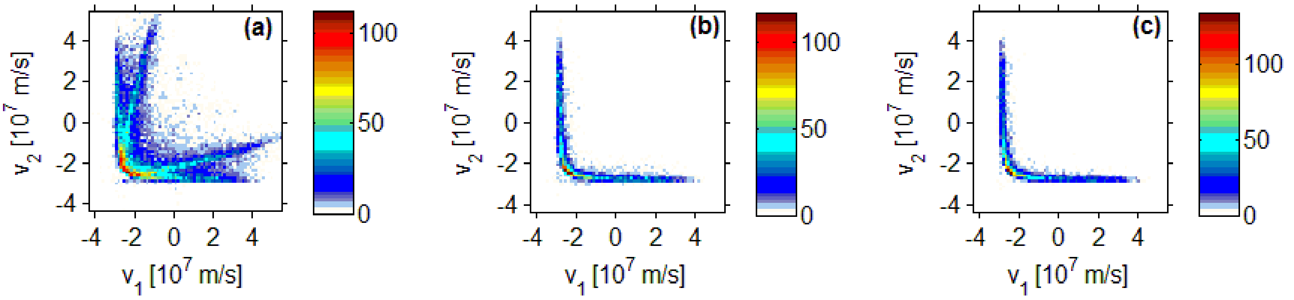

Figure 1. Distribution of the final electron velocities v_1, v_2 in the polarization direction. (a), non-relativistic without magnetic field; (b), non-relativistic with magnetic field; (c), Darwin approximation with magnetic field.

and energy spectra are then calculated as statistical averages over the trajectories. Monte-Carlo simulations are in general well suited for a computer cluster such as RICC, since each trajectory can be computed independently. In our case, typically 10^6 (sometimes up to 10^8) trajectories were run for each laser pulse parameter set.

3. Results.

To investigate the relativistic effects in the recollision ionization of helium and helium-like ions, we conducted simulations both including and excluding the force due to the magnetic field of the laser pulse. In addition, we also performed simulations based on the equations of motion derived from the Darwin Lagrangian and compared with the results obtained from the usual Newtonian equations of motion. The Darwin Lagrangian includes first-order magnetic field corrections in the electron-electron interaction potential.

We found that the magnetic field can have a large impact on both total ionization probabilities and final electron spectra, already at intensities as low as 10^{15} W/cm^2. The reason is that some classes of trajectories leading to recollision in absence of the magnetic field are strongly modified when the magnetic field is included. The electron is deflected by the $\mathbf{v}\times\mathbf{B}$ force, and misses the atomic core. We also found that including or excluding the Darwin corrections in the equations of motion did not have any statistically significant impact on the final spectra.

In Figure 1, we show an example of the final velocity distribution for electrons ejected from Li^+ exposed to an 800 nm, 10^{17} W/cm^2, linearly polarized three-cycle laser pulse. The color indicates the number of trajectories ending up in a particular velocity bin.

4. Conclusions.

We have studied relativistic effects in the recollision double ionization by relativistically intense laser pulses. It was found that the magnetic part of the Lorentz force can in general not be neglected when calculating total probabilities and electron ejection spectra. The use of the RICC facility was essential for this investigation, enabling the calculation of a large number of trajectories.

5. Schedule and prospect for the future.

During the next fiscal year, we plan to investigate another idea in recollision physics: Ejection of core electrons by recolliding electrons. If the intensity of the laser field is high enough, the kinetic energy of the recolliding electron can reach the keV level, allowing for tightly bound core electrons to be ejected. Moreover, this process is expected to be controllable with the carrier envelope phase of the laser pulse. We plan to conduct both classical trajectory simulations and simulations based on quantum mechanical wave equations.

Fiscal Year 2012 List of Publications Resulting from the Use of RICC

[Publication]

"Effect of the laser magnetic field on nonsequential double ionization of He, Li^{+}, and Be^{2+}", Erik Lötstedt and Katsumi Midorikawa, Physical Review A, vol. 87, issue 1, page 013426, published 24 January 2013.