I. INTRODUCTION

The two electron atom Helium is the simplest system where effects of electron-electron interactions can be studied. This atom therefore is a fundamental resource for the understanding of electron correlation in various physical processes. Ultra-short pulses offer the possibility to theoretically as well as experimentally access the time-scale of correlated electronic motion in atomic systems. Recently, large advances both on the experimental side as well in the availability of computer methods and resources have taken place. Within this project, theoretical studies on helium and other atoms are performed, with special focus on experimental proposals and studies relevant to experimentally available data. In this progress report, we show results from a joint theoretical-experimental study on two-colour driving of atoms (Sect. II) and discuss controlling population transfer between doubly excited states using chirped laser pulses (Sect. III).

II. TRACING THE ATOMIC POTENTIAL USING TWO-COLOUR LASER FIELDS

The influence the exact shape of the effective binding potential has on photoionization by strong laser fields has recently attracted much interest [1–8]. Using a fundamental infrared field together with its second harmonic at comparable strength is an ideal candidate for studying potential effects since they are predicted to be dependent on the relative phase of the two colours [9]. In our studies we combine angularly resolved measurements of photoionization with numerical solutions of the time-dependent Schrödinger equation [10]. We show examples of the asymmetry as a function of the relative phase $\phi_{12}$ between the two colours in Fig. 1. Clear differences between the different

![Graph showing asymmetry as a function of $\phi_{12}$ for different potentials and laser wavelengths.](image)

**FIG. 1**: Asymmetry $A = (P_L - P_R)/(P_L + P_R)$ with $P_{L,R}$ the probability for electron emission to the left or right along the laser polarization axis. **Left panel**: Asymmetry $A$ for hydrogen, helium, and a short-range model potential. **Right panel**: The results for helium resolved in $k_\rho$. The wavelengths of the two colours are 800nm and 400nm.
potentials can be seen (left panel). While the figure displays theoretical values, very similar curves have been obtained experimentally. The gross structure of the curves can be understood using arguments based on classical trajectories, see Fig. 2. Photoionization in this wavelength/ intensity regime can approximately be described as the release of one electron due to quasistatistical tunneling close to the maxima of the absolute value of the field (black line) followed by a subsequent classical time evolution. The final momentum for short-range potentials is given by the vector potential (integral of field, dashed red line). For $\phi_{12} = 0$ zero asymmetry is expected for short-range potentials (blue line) while a large change in asymmetry due to potential effects is expected (green line) since the potential bend all trajectories in the same direction. For $\phi_{12} = \pi/2$ maximum asymmetry is expected for short-range potentials while potential effects on the asymmetry are expected to be small since two trajectories born within one cycle of the field bend in opposite directions. Any corrections are due to that one of the two trajectories directly leave the nucleus while the other one passes the nucleus once. Already the total asymmetry (Fig. 1) therefore gives valuable information on potential effects on electrons directly leaving the nucleus as well as on those rescattered once.

![Diagram](image)

FIG. 2: Illustration of potential effects using classical trajectories for (a) $\phi_{12} = 0$ and (b) $\phi_{12} = \pi/2$.

More information can be obtained by considering the left-right asymmetry for electrons emitted with a certain momentum $k_\rho$ perpendicular to the laser polarization axis (right panel in Fig. 1). For short-range potentials, these values are almost independent of $k_\rho$ and given by the curve in the left panel. For long-range potentials, a strong dependence on $k_\rho$ is observed. The difference to the short-range results is the largest for $k_\rho \to 0$ and decreases with increasing $k_\rho$. This can be understood in classical terms – the larger $k_\rho$ is, the faster the trajectory leaves the region where potential effects can substantially influence the trajectory. The same is true if increasing the intensity of the laser field, since here the average time the electron is close to the nucleus decreases.

Our studies show that in two-colour photoionization, the intensity and relative phase act as two “knobs” by which the strength of the influence from the atomic potential can be tuned. Additionally, by discriminating in $k_\rho$ one can select electrons which have been more or less affected by the potential. To throughout-fully investigate the dependence of photoionization on the different parameters we need to simulate the interaction of a huge number of different fields with atoms. The same is true when aiming for agreement with the experimental data, since here the exact shape of the field is not known and additionally an incoherent average over different field strengths must be accounted for. A single line in Fig. 1 takes about 10,000 CPU hours on the Applikationsserver Strömungsdynamik und Finite Elemente or on the Opteron cluster Phoenix.
III. SHAPING OF WAVE PACKETS IN HELIUM

The left-right asymmetry in the previous section is also an example of coherent control by means of shaped laser fields: depending on the exact shape of the field, we can control in which direction the electron leaves the atom. Our studies on coherent control will continue in further directions, one of which is to steer population transfer in helium. We plan to optimize population transfer from the 1s1s ground state to doubly excited states (DES) as well as transfer between different ones of the highly correlated DES. The control schemes will be based on recent proposals involving model simulations within a restricted Hilbert space consisting of the relevant states only. Since the DES are decaying, the model Hamiltonian is non-hermitian. For a certain value of the field parameters, there exists an exceptional point, i.e. the complex eigenvalues of the model Hamiltonian coalesce [11]. Control opportunities can be realized by letting the intensity and frequency of the laser field move around the exceptional point [12]. One example within the model is shown in Fig. 3. Here, after the pulse is over, almost 100% of the non-decayed population has been transferred from the 2s2p to the 2s3d state in helium.

Since the initial state is rapidly decaying, a substantial fraction of the probability is lost before the transfer to the longer-lived second DES is complete. The optimization goal is therefore to make the transfer as fast as possible. Here, both the adiabaticity in the model states may get lost and the model assumptions get questionable. Therefore, simulations to validate the model results with fully correlated helium simulations are necessary. Such simulations using our newly developed methods for solving the time-dependent Schrödinger equation for two-electron atoms are in progress. Similarities and differences between the model and the simulations will be investigated. Within this project part, the ICP5 or the Phoenix are ideal for mid-size simulations, where only population transfer and total ionization rates are studied.

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