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Coherence measurements on Rydberg wave packets kicked by a half-cycle pulse

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A kick from a unipolar half-cycle pulse (HCP) can redistribute population and shift the relative phase between states in a radial Rydberg wave packet. We have measured the quantum coherence properties following the kick, and show that selected coherences can be destroyed by applying a HCP at specific times. Quantum mechanical simulations show that this is due to redistribution of the angular momentum in the presence of noise. These results have implications for the storage and retrieval of quantum information in the wave packet.

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Atoms can store and process data encoded in their quantum states [1–3]. We previously investigated the storage of information as a quantum phase in Rydberg wave packets, and its retrieval using half-cycle pulses (HCP's) [4–8]. The HCP produces multimode interference between the states, converting phase information into state populations [8].

More sophisticated quantum information processing involves multiple operations on the same data register. The phase information in the atom must then be retained after each operation. Even though the HCP interaction is unitary, technical noise problems that do not affect the populations may destroy the phase information, thus eliminating further processing capability. The loss of phase coherence in a Rydberg wave packet can be caused by several factors, such as background electrical noise, atomic collisions, and radiative decay. Here, we study the phase shifts and quantum coherence of a Rydberg wave packet following a weak HCP.

We use a wave packet holography technique developed earlier for wave packet sculpting [9], and apply it to HCP interactions. We excite a Rydberg wave packet in atomic cesium followed by an HCP at a specific time delay. A subsequent laser pulse excites a reference wave packet. Interference between the two wave packets is analyzed by state-selective field ionization (SSFI), and the results show the correlation between the populations in all pairs of states. We also view the same interference in the absence of the HCP, and thereby determine the change induced in the relative phases of the states.

Cesium atoms from an effusive source are excited from the 6*s* ground state to the 7*s* launch state by a two-photon transition using 1079 nm pulses from the focused output of a Ti:sapphire-pumped optical parametric amplifier. A Rydberg wave packet is then excited from 7*s* to $n=28,\ldots,32$, $\ell=1$. The excitation laser spectrum is shaped using an acousto-optic Fourier-plane filter [10], so that the phases of the states are initially equal. These phases evolve in time. After time τ, a weak THz HCP is applied with the same polarization as the two laser pulses. Details on the generation and detection of HCP's, as well as their interaction with Rydberg states and wave packets have been reported previously [11–16]. The HCP used in our experiment provides an impulse of 0.0014 a.u. (atomic units) to the Rydberg electron. The wave packet is then probed by superposing a reference wave packet on the same atoms. The reference is identical to the launch wave packet, but delayed up to 50 ps. In a typical run, we alternate collecting coherence data with the HCP on and off, to minimize the effects of laser drift or changes in the atomic beam.

There is a remarkable loss of coherence between some pairs of states when kicked with a HCP at specific times. These same states retain their coherence if they are kicked at later times (see Fig. 1). We also observe a τ-dependent shift in the phases of the correlations. These results imply that if we use a HCP as an operator on a wave packet, the choice of delay τ can make a significant difference in our ability to perform additional operations. To gain a better understanding of the physical processes that lead to these phase shifts and loss of coherence, we construct a model of a HCP that simulates the experimental conditions.

The states $\Psi_k(\vec{r},t)=\Psi_k(\vec{r})e^{-i\omega_k t}$ of the Rydberg wave packet have different energies $\hbar\omega_k$, so that the wave packet has a time dependence

$$\Psi(\vec{r},t) = \sum_k C_k \Psi_k(\vec{r}) e^{-i(\omega_k t - \phi_k)}. \qquad (1)$$

Here C_k and ϕ_k are the amplitude and phase, respectively, corresponding to $\Psi_k(\vec{r},t)$.

In a model where we simulate the HCP as an impulse of strength Q, we can write the HCP-kicked wave packet as $e^{iQz}\Psi(\vec{r},\tau)=e^{iQz}\Sigma_k C_{k0}\Psi_k(\vec{r})e^{-i(\omega_k\tau-\phi_{k0})}=\Sigma_k C_{k1}\Psi_k(\vec{r})e^{i\phi_{k1}}$.

The superposition of two arbitrary wave packets excited from the same launch state and separated by a delay T can be expressed at time t after the arrival of the first wave packet as

$$\sum_k \Psi_k(\vec{r}) e^{-i\omega_k t}\left(C_{k1}e^{i\phi_{k1}} + C_{k2}e^{-i[(\omega_g-\omega_k)T-\phi_{k2}]}\right), \qquad (2)$$

where ω_g is the energy of the launch state. To analyze the current experiment, the first wave packet can be replaced by the HCP-kicked wave packet without loss of generality. The populations in the states of the combined wave packet vary with T as

$$\begin{aligned} P_k(T) &= C_{k1}^2 + C_{k2}^2 + 2C_{k1}C_{k2}\cos[\phi_{k1}-\phi_{k2}-(\omega_k-\omega_g)T] \\ &= (C_{k1}^2 + C_{k2}^2)\{1 + C_k' \cos[\phi_{k1}-\phi_{k2}-(\omega_k-\omega_g)T]\}, \end{aligned} \qquad (3)$$

where $C_k'=2C_{k1}C_{k2}/(C_{k1}^2+C_{k2}^2)$.

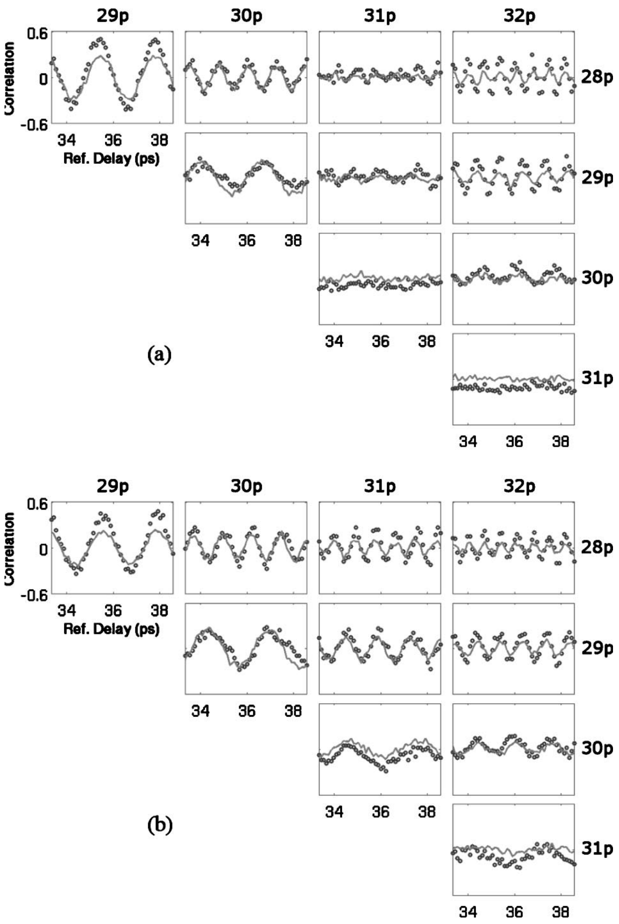

FIG. 1. Selective destruction of coherence: (a) The result of a correlation measurement with the HCP delayed 7.2 ps after the wave packet excitation. Note that the correlation of the 31*p* state with all other states vanishes while the rest of the states have a nonzero correlation with each other. The dark circles represent the experimental results while the thick gray line is obtained from our simulations. (b) A similar plot of correlations but with the HCP delayed 7.8 ps after wave packet excitation shows the 31*p* state having nonzero correlation with the other states. The results from the experiment and simulation at other HCP delays are available online as movies on EPAPS [17].

The relative phase between pairs of states is measured using a covariance technique [9]. The correlation between the populations in various states in the wave packet is represented by

$$r_{jk}(T) = \left[\frac{\overline{P_jP_k} - \overline{P_j}\,\overline{P_k}}{\sigma_j\sigma_k}\right]_T, \tag{4}$$

where

$$\sigma_j\sigma_k = \sqrt{\overline{P_j^2} - \overline{P_j}^2}\sqrt{\overline{P_k^2} - \overline{P_k}^2}. \tag{5}$$

Using Eq. (3) and averaging over multiple optical cycles, we can expand the terms of the numerator in Eq. (4)

$$\overline{P_jP_k} = (C_{j1}^2 + C_{j2}^2)(C_{k1}^2 + C_{k2}^2)$$

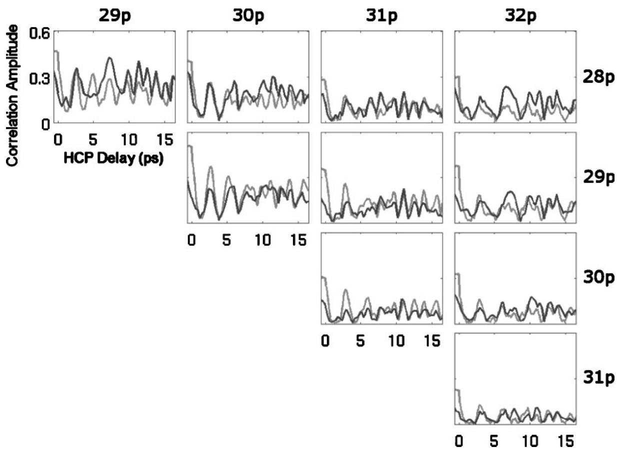

FIG. 2. Comparison of correlation amplitudes. The amplitude of the correlation measurements from the experiment are compared with the results of our simulations for a range of delays of the HCP following wave packet excitation. The dark line represents the experimental results while the thick gray line is a result of the simulations.

$$\overline{P_jP_k} = (C_{j1}^2 + C_{j2}^2)(C_{k1}^2 + C_{k2}^2)\left[1 + \frac{C'_jC'_k}{2}\cos[(\phi_{j1} - \phi_{k1}) - (\phi_{j2} - \phi_{k2}) - (\omega_j - \omega_k)T]\right]$$

$$\Rightarrow \overline{P_jP_k} - \overline{P_j}\,\overline{P_k} = 2C_{j1}C_{j2}C_{k1}C_{k2}\cos[(\phi_{j1} - \phi_{k1}) - (\phi_{j2} - \phi_{k2}) - (\omega_j - \omega_k)T]. \tag{6}$$

The denominator in Eq. (4) can be expressed as

$$\sigma_j\sigma_k = 2C_{j1}C_{j2}C_{k1}C_{k2}. \tag{7}$$

We can then write the expected correlation between the states of the wave packet,

$$r_{jk}(T) = \cos[(\phi_{j1} - \phi_{k1}) - (\phi_{j2} - \phi_{k2}) - (\omega_j - \omega_k)T]. \tag{8}$$

The presence of any correlations as

$$r_{jk}(T)_{meas} = \sqrt{\left(1 - \frac{\sigma_{N_j}^2}{\sigma_{j_{meas}}^2}\right)\left(1 - \frac{\sigma_{N_k}^2}{\sigma_{k_{meas}}^2}\right)}\, r_{jk}(T), \tag{9}$$

where σ_{N_j} represents the standard deviation of the noise present in the measurement of state j and $\sigma_{j_{meas}} = \sqrt{\sigma_j^2 + \sigma_{N_j}^2}$ represents the measured standard deviation for population identified as state j.

The simulations are in good agreement with our experimental results (see Fig. 1). The observed variation in the amplitude of the correlations is reproduced well by the simulation and is shown in Fig. 2. Our simulations suggest that the loss of coherence in the experiment is tied to the redistribution of *p* states into other angular momentum states by the HCP. Figure 3 shows the remaining *p*-state population following a HCP at various delays after the wave packet excitation and compares the correlation amplitude to the product of *p*-state amplitudes. The similarity in the two curves confirms that the correlation amplitude is determined

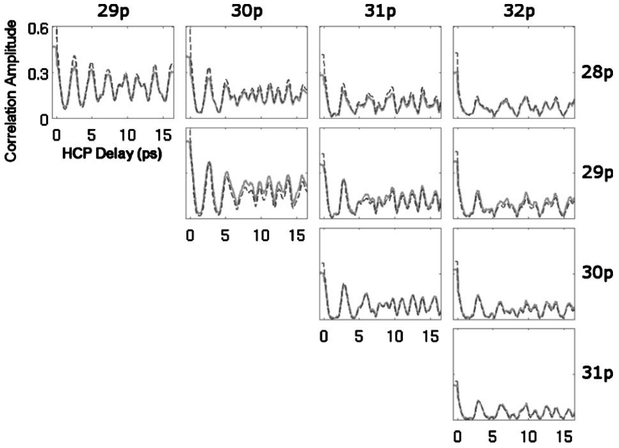

FIG. 3. *p*-state populations vs correlation amplitude. The product of the *p*-state amplitudes (dashed line) is plotted along with the correlation amplitude (solid gray line) for each pair of *p* states.

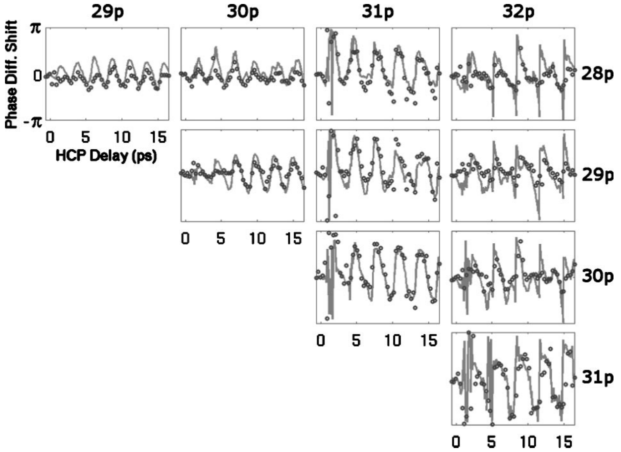

FIG. 4. Phase change comparison. The change in the relative phase of the correlation as a function of HCP delay as measured in experiment (black circles) is compared with the phase of the correlations obtained from our simulation (solid gray line).

largely by the population remaining in the *p* states. The peaks in the correlation amplitudes correspond to times when the electron is close to the core, while the dips occur when the electron is far from the core. This is consistent with the classical notion that the maximal angular momentum transfer occurs when the impulse is exerted far from the core.

The loss of coherence when angular momentum is transferred out of the *p* states is almost entirely attributable to the background noise that is always present in the measurement. In the absence of any noise, the correlation amplitudes are always unity. The effect of noise is introduced in the simulation as random fluctuations in the signal level detected for each state. The correlation amplitudes in the simulation match the experimental results well when we introduce shot-to-shot fluctuations of 100% rms, which is consistent with our observations. This suggests a remarkable robustness of the correlation method to retrieve useful information in the presence of large signal fluctuations.

The HCP-induced state redistribution changes the relative phases in the wave packet. The measured phase changes are plotted in Fig. 4 together with the corresponding results from simulations. All the major features in the data are reproduced by the simulations. The agreement is poorest when the amplitude of the correlations is small, at times when the wave packet is near the outer turning point of its orbit.

These correlation measurements show that a Rydberg wave packet can maintain its coherence following excitation by a HCP. The good agreement with simulations shows that the HCP can induce controllable phase shifts between components of the wave packet, which can be measured subsequently using interference with a reference wave packet. Finally, we have found that the HCP can selectively alter the angular momentum of individual states in the wave packet, while preserving the angular momentum and maintaining overall coherence among the rest of the states. The modulations in the amplitude and phase of the measured correlations as a function of the delay of the HCP can be used to characterize the effect of any HCP operator acting on phase information stored in the Rydberg atom data register. In the current experimental setup, we can vary the delay of the HCP or shape the laser pulse for excitation of the first wave packet to obtain a desired change in the phase of the different states. However, independent control of each phase will require the use of multiple HCP's or shaped THz pulses.

Previous work by Ahn *et al.* [6–8] has demonstrated the possibility of information storage in the phase relationship between states in a Rydberg wave packet and its retrieval by a HCP. The current work demonstrates that we can use a HCP of programmable strength and delay as an operator for manipulating the stored information.

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[17] See EPAPS Document No. E-PLRAAN-71-052502 for movies representing a complete set of results from the experiment and the simulation. A direct link to this document may be found in the online article's HTML reference section. The document may also be reached via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html) or from ftp.aip.org in the directory /epaps/. See the EPAPS homepage for more information.