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 an 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.

Atoms can store and process data encoded in their quantum states $|1\rangle, |2\rangle, |3\rangle$. We previously investigated the storage of information as quantum phase in Rydberg wave packets, and its retrieval using half-cycle pulses (HCP’s) $|4\rangle, |5\rangle, |6\rangle, |7\rangle$. The HCP produces multi-mode interference between the states, converting phase information into state populations $|8\rangle$.

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 phase information, thus eliminating further processing capability. 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 $|9\rangle$, but not previously applied 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 $6s$ ground state to the $7s$ 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 $7s$ to $n = 28, \ldots, 32$, $\ell = 1$. The excitation laser spectrum is shaped using an acousto-optic Fourier-plane filter $|10\rangle$, so that the phases of the states are initially equal. These phases evolve in time. After time $\tau$, 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 $|11\rangle, |12\rangle, |13\rangle, |14\rangle, |15\rangle$. 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 $50$ psec. 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 an HCP at specific times. These same states retain their coherence if they are kicked at later times (see Fig. $11\rangle$. We also observe a $\tau$-dependent shift in the phases of the correlations. These results imply that if we use an HCP as an operator on a wave packet, the choice of delay $\tau$ 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 constructed an impulse model of an 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:

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

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

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

$$\sum_k \Psi_k(\vec{r})e^{-i\omega_k t} \left( C_{k1} e^{i\phi_{k1}} + C_{k2} e^{-i((\omega_g - \omega_k)\tau - \phi_{k2})} \right)$$ \hspace{1cm} (2)

where $\omega_g$ is the energy of the launch state. The populations in the states of the combined wave packet vary with the delay $\tau$ as

$$P_k(\tau) = C_{k1}^2 + C_{k2}^2 + 2C_{k1}C_{k2} \cos(\phi_{k1} - \phi_{k2} - (\omega_k - \omega_g)\tau)$$

$$= (C_{k1}^2 + C_{k2}^2) \left[ 1 + C_k' \cos(\phi_{k1} - \phi_{k2} - (\omega_k - \omega_g)\tau) \right]$$ \hspace{1cm} (3)

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

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

$$r_{jk}(\tau) = \frac{P_{jk} - P_{jk}'}{\sigma_j \sigma_k}$$  \hspace{1cm} (4)

where

$$\sigma_j \sigma_k = \sqrt{P_{j}^2 - P_{jk}^2} \cdot \sqrt{P_{k}^2 - P_{jk}'^2}$$  \hspace{1cm} (5)

Using Eqn(5) and averaging over multiple optical cycles, we can expand the terms of the numerator in Eqn(4):

$$\frac{P_{jk} - P_{jk}'}{\sigma_j \sigma_k} = \frac{(C_{j1}^2 + C_{j2}^2)(C_{k1}^2 + C_{k2}^2)}{(1 + \frac{C_j C_k}{2} \cos((\varphi_{j1} - \varphi_{k1}) - (\varphi_{j2} - \varphi_{k2}) - (\omega_j - \omega_k)\tau)} \right)$$

$$\Rightarrow P_{jk} - P_{jk}' = 2C_{j1}C_{j2}C_{k1}C_{k2} \cos((\varphi_{j1} - \varphi_{k1}) - (\varphi_{j2} - \varphi_{k2}) - (\omega_j - \omega_k)\tau)$$  \hspace{1cm} (6)

The denominator in Eqn(4) can be expressed as

$$\sigma_j \sigma_k = 2C_{j1}C_{j2}C_{k1}C_{k2}$$  \hspace{1cm} (7)

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

$$r_{jk}(\tau) = \cos((\varphi_{j1} - \varphi_{k1}) - (\varphi_{j2} - \varphi_{k2}) - (\omega_j - \omega_k)\tau)$$ \hspace{1cm} (8)

The presence of any background noise in the measurements modifies the correlations as

$$r_{jk}(\tau)_{meas} = \sqrt{\left(1 - \frac{\sigma_{N_j}^2}{\sigma_{j,meas}^2}\right) \left(1 - \frac{\sigma_{N_k}^2}{\sigma_{k,meas}^2}\right)} r_{jk}(\tau)$$ \hspace{1cm} (9)

where $\sigma_{N_j}$ 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. 4. 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. Fig. 3 shows the remaining p-state population following an 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 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.

Previous work by Ahn et. al \cite{9, 10, 11} has demonstrated the possibility of information storage in the phase relationship between states in a Rydberg wave packet and its
retrieval by an HCP. The current work demonstrates that we can use an HCP of programmable strength and delay as an operator for manipulating the stored information.

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FIG. 4: Phase change comparison: The change in 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).

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