Robust quantum switch with Rydberg excitations

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We develop an approach to realize a quantum switch for Rydberg excitation in atoms with Y-typed level configuration. We find that the steady population on two different Rydberg states can be reversibly exchanged in a controllable way by properly tuning the Rydberg-Rydberg interaction. Moreover, our numerical simulations verify that the switching scheme is robust against spontaneous decay, environmental disturbance, as well as the duration of operation on the interaction, and also a high switching efficiency is quite attainable, which makes it have potential applications in quantum information processing and other Rydberg-based quantum technologies.

I. INTRODUCTION

Switch is a device that is capable of switching some kind of signals (e.g., current, voltage, energy, heat et.al.) between different pathways. Classical switch plays a vital role in electronics and signal processing. Extending such a concept into the quantum regime where the role of pathways is played by quantum states leads to the production of various quantum switches, such as the switchable acoustic meta-materials [1], the current switch in quantum dots [2, 3], the superconducting switch [4], the fiber-optical switch [5] and so on. In particular, for achieving an all-optical quantum switch, one promising way is coupling the atoms to a microscopic high-finesses cavity [6-9], which can strongly enhance the light-atom interactions [10]. Such a quantum optical switch has many promising applications, ranging from quantum information processing to quantum metrology [11, 12].

Recently, Rydberg atoms have been manifested as an ideal candidate to study single-photon all-optical switches [13-17] and transistors [18-20], mainly due to the presence of interatomic interactions [21, 22]. The ultra-strong interaction between two Rydberg states gives rise to blockade effect, bringing on a strong enhancement for the light-atom interactions [23-25]. Moreover, the blockade effect can provide an efficient mechanism for controlling the quantum states of the atomic system itself. A simplest scheme can be carried out, for example in a two-atom system, it prohibits the excitation of the second atom when the first one has already been excited to the Rydberg state. That is, it allows to control one atom’s excitation or not via the status of the other [26, 28], achieving a switchable excitation between two atomic states.

In the present work we propose a new scheme of quantum switch based on two Rydberg atoms of same Y-typed four-level configurations [29]. The special level configuration has two different Rydberg states: one is weakly coupled to the intermediate state and the other is strongly coupled. This enables two different excitation pathways labeled as “OFF” and “ON” by us [see Fig. I(c)], which can be efficiently exchanged via the control of intrastate interaction of the strongly-coupled Rydberg state. The interstate interaction between different Rydberg states, as main disturbance for the status switch, is greatly suppressed by employing the feature of nS Rydberg states that the strength of van der Waals (vdWs) interaction is not affected by Zeeman effect [30]. The robustness of the switching scheme is confirmed by its low sensitivity to the other parameters of the system, such as the intra-state interaction of the weakly-coupled state, the decay rate of the intermediate state, and the duration time of the switching process. We present a detailed discussion of a realistic experimental implementation of the switch with 87Rb atoms and predict that the final switching efficiency will reach as high as 0.92.

II. MODEL DESCRIPTION

Our model consists of two identical Rydberg atoms in frozen-gas limit. As presented in Fig. I(a), each atom has a Y-typed level structure that the ground state |g⟩ is coupled to the middle state |m⟩ via a laser field with Rabi frequency Ωp and detuning Δ, and |m⟩ is further resonantly coupled to two different Rydberg states |s⟩ and |r⟩ with Rabi frequencies ω and Ω, respectively. The Hamiltonian for a single atom k reads (h = 1 everywhere)

$$H_k = \Delta \sigma_{mm}^{(k)} + (\Omega_p \sigma_{gm}^{(k)} + \Omega \sigma_{mr}^{(k)} + \omega \sigma_{ms}^{(k)}) + \text{H.c.},$$

where the atomic operators $\sigma_{\alpha\beta}^{(k)} = |\alpha_k\rangle \langle \beta_k|$, $\alpha, \beta \in \{g, m, s, r\}$.

The properties of the interaction between atoms are dependent on the Rydberg states we chose. For nS Rydberg states, in the absence of electrostatic field the interaction is dominant by the second-order dipole-dipole interaction (i.e. vdWs interaction) [31]. It can be further classified as (i) the intrastate interaction $V_{ss(rr)} = V_{0, ss(rr)} |s\rangle \langle r| + |r\rangle \langle s|$, with the strength $V_{0, ss(rr)} = C_6^{ss(r)} / R^6$, which present if both atoms settle in a same Rydberg state |s⟩ or |r⟩, (ii) the interstate interaction $V_{sr} = V_{0, sr} (|s\rangle \langle r| + |r\rangle \langle s|)$ for atoms in different Rydberg states with $V_{0, sr} = C_6^{sr} / R^6$. Here R represents

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the separation of atoms, $C_{\alpha \beta}^{\sigma, r, s}$, are the interaction coefficients, and $|\alpha \beta\rangle \equiv |\alpha \rangle_1 \otimes |\beta \rangle_2$ are the two-atom states. Then the total Hamiltonian $\mathcal{H}$ is obtained from

$$\mathcal{H} = \mathcal{H}_1 + \mathcal{H}_2 + \mathcal{V}_{ss} + \mathcal{V}_{rr} + \mathcal{V}_{sr}.$$  \tag{2}

For a single atom, there exist two different pathways for excitation, I: $|g\rangle \rightarrow |m\rangle \rightarrow |r\rangle$ and II: $|g\rangle \rightarrow |m\rangle \rightarrow |s\rangle$. We consider the condition $\Omega > \omega$ so state $|r\rangle$ is the strongly-coupled state and the excitation pathway I is preferred, while $|s\rangle$ is the weakly-coupled state and the pathway II is less taken. Considering the long lifetime of states $|s\rangle$ and $|r\rangle$, their spontaneous decays $\gamma_s$ and $\gamma_r$ are far less than the decay $\Gamma$ for state $|m\rangle$. For simplicity, we first assume $\Omega_p = \Omega$, $\Delta = 0$ and $\gamma_s = \gamma_r = \gamma$. As shown in Fig. 1(c), if $\Omega \gg \omega$, it is easy to envision that there is a steady state that almost 1/2 population transfers from $|g\rangle$ to $|r\rangle$ through pathway I with no population on $|m\rangle$ or $|s\rangle$, which is labeled as “OFF” state. However, we will show that considerable population would counter-intuitively transfer into the weakly-coupled state $|s\rangle$ through pathway II once the interaction $\mathcal{V}_{0,rr} \neq 0$. This process is found to be fully irrespective of the exact interaction strength $\mathcal{V}_{0,ss}$ and can serve as a controllable switch between the two status “OFF” and “ON” corresponding to different Rydberg excitations.

III. SINGLE-ATOM CASE

We begin with the status “OFF” which can be analyzed in single-atom frame due to the absence of Rydberg interaction. The analytical expression for steady state can be obtained by solving the master equation $\dot{\rho}_k = -i [\mathcal{H}_k, \rho_k] + \mathcal{L}_k[\rho_k]$ ($k = 1, 2$) with $\rho_k$ and $\mathcal{H}_k$ the single-atom density matrix and Hamiltonian, respectively. Here the Lindblad superoperator $\mathcal{L}_k[\rho]$ is given by

$$\mathcal{L}_k[\rho] = \Gamma \left( \sigma_{gm}^{(k)} \rho_k \sigma_{mg}^{(k)} \right) + \gamma \left( \sigma_{gs}^{(k)} \rho_k \sigma_{sg}^{(k)} - \frac{\sigma_{gs}^{(k)} \rho_k \sigma_{sg}^{(k)}}{2} \right) + \gamma \left( \sigma_{gr}^{(k)} \rho_k \sigma_{rg}^{(k)} - \frac{\sigma_{gr}^{(k)} \rho_k \sigma_{rg}^{(k)}}{2} \right),$$  \tag{3}

which describes the effect of spontaneous decays from states $|m\rangle$, $|s\rangle$, and $|r\rangle$. In the following calculations, we use $\Omega \equiv (\Omega^{-1})$ as the frequency (time) unit, leading to normalized parameters as $\Omega_p \rightarrow \Omega_p / \Omega$, $\omega \rightarrow \omega / \Omega$, $\Gamma \rightarrow \Gamma / \Omega$, $\gamma \rightarrow \gamma / \Omega$, $\Delta \rightarrow \Delta / \Omega$, $\mathcal{V}_{0,rr} \rightarrow \mathcal{V}_{0,rr} / \Omega$, $\mathcal{V}_{0,rr} \rightarrow \mathcal{V}_{0,rr} / \Omega$, and $t \rightarrow \Omega t$. Then the steady population of $|r\rangle$ is

$$P_r = \frac{1}{4(1+\omega^2)^{-1/2} + (1+\gamma)} \left[ 4 + 4(\omega + \gamma) \right]$$

and of $|s\rangle$ is $P_s = \omega^2 P_r$. In the limit of $\omega \ll 1$, Eq. 11 reduces to $P_r \rightarrow 1/2$ and $P_s \rightarrow 0$, coinciding with our previous predictions about the status “OFF”. In Fig. 2 we plot $P_r$ and $P_s$ as functions of $\omega$, which shows that $P_r$ decays and $P_s$ grows up as $\omega$ increases and they become equal at $\omega = 1$. For further increased $\omega$, both of them decrease but at different rates. The monotonous decrease of $P_r$ is easy to understand, while the variation of $P_s$ is ascribed to the electromagnetically induced transparency (EIT) effect in pathway II. A unique feature of the effect is that the excitation probability decreases as enhancing the coupling laser strength [32].
FIG. 2. (Color online) For the single-atom case, the steady probabilities of Rydberg state $|r\rangle$ (blue solid) and $|s\rangle$ (red dashed) are plotted as functions of $\omega$ with the decays $\gamma = 0.001$ and $\Gamma = 1.0$. All frequencies are scaled by $\Omega$.

IV. TWO-ATOM CASE

Turning to the picture of two interacting atoms, if the initial state is $|gg\rangle$ the total Hamiltonian $\mathcal{H}$ can be expanded by the ten symmetric two-atom bases only, $\{|gg\rangle, |mm\rangle, |rr\rangle, |gm\rangle_+, |gs\rangle_+, |gr\rangle_+, |ms\rangle_+, |mr\rangle_+, |sr\rangle_+\}$ where $|\alpha\beta\rangle_+ = (|\alpha\beta\rangle \pm \beta|\alpha\rangle)/\sqrt{2}$, with the asymmetric states $|\alpha\beta\rangle_-$ safely ignored [33]. The coupling strategy and strength among them are presented in Fig. 4(b). In the absence of all Rydberg interaction, the population transfer is mainly following the approach $|gg\rangle \rightarrow |gm\rangle_+ \rightarrow |gr\rangle_+ \rightarrow |mr\rangle_+ \rightarrow |rr\rangle$ (red arrows) due to the stronger coupling strengths $(\propto \Omega)$. Finally, the long-lived states $|gg\rangle, |gr\rangle_+$ and $|rr\rangle$ are stably populated. Less population is found to accumulate in middle states $|gm\rangle_+$ and $|mr\rangle_+$ for their short lifetimes, and in $|mm\rangle$ and $|gs\rangle_+$ for large decay rate $\Gamma$ and small coupling strength $\omega$, respectively. The steady populations are $P_{gr+} \approx 0.5$ and $P_{gs+} \approx 0$ which is same as the status “OFF” analyzed in the single-atom case. Note that $P_{gg} + P_{rr} = 1 - P_{gr+} \approx 0.5$. Once the intrastate interaction $V_{0,rr}$ is nonzero, giving rise to an energy shift on state $|rr\rangle$, the transition from $|mr\rangle_+$ to $|rr\rangle$ will be affected. If the condition for strong blockade, $V_{0,rr} > \sqrt{2}$, is satisfied [24], the transition to the doubly Rydberg excited state will be fully suppressed. Instead, the population moves towards $|sr\rangle_+$ when the interstate interaction $V_{0,ss} = 0$, which leads to the second transition pathway $|mr\rangle_+ \rightarrow |sr\rangle_+ \rightarrow |ms\rangle_+ \rightarrow |gs\rangle_+$ (blue arrows). Finally the steady populations are $P_{gr+} \approx 0$ and $P_{gs+} \approx 0.5$, corresponding to the status “ON” for our quantum switch. $P_{gr+}$ is also dominantly occupied besides $P_{gs+}$ and $P_{gg} \approx 0$.

The above qualitative analysis have been verified by numerically solving the master equation of two atoms, $\dot{\rho} = -i[\mathcal{H}, \rho] + L_1[\rho] + L_2[\rho]$, in which $\rho$ is replaced by a two-atom density matrix. The steady populations $P_{gr+}$ and $P_{gs+}$ for states $|gr\rangle_+$ and $|gs\rangle_+$ are illustrated as functions of $\omega$ in Fig. 3 for three different cases: (i) $V_{0,rr} = V_{0,ss} = 0$ (the black dashed curve for $P_{gr+}$ and the blue solid curve for $P_{gs+}$), (ii) $V_{0,rr} = 1.0$ and $V_{0,ss} = 0$ (the black dashed curve with circles for $P_{gr+}$ and the blue solid curve with circles for $P_{gs+}$), and (iii) $V_{0,rr} = 1.0$ and $V_{0,ss} = 1.0$ (the black dashed curve with triangles for $P_{gr+}$ and the blue solid curve with triangles for $P_{gs+}$).

In case (i) we find $P_{gs+} \approx 0.5$ and $P_{gr+} \approx 0.0$ at $\omega \ll 1$ and they two become equal as $\omega$ increases to 1, same as in Fig. 2 obtained in the single-atom frame. When the intrastate interaction $V_{0,rr}$ is present, see the cases (ii) and (iii), there is a counterintuitive reversal of $P_{gr+}$ and $P_{gs+}$ at $\omega \approx 0.05$, indicating a large fraction of population transferred from $|gr\rangle_+$ to $|gs\rangle_+$. In the shadow region of $0.1 \lesssim \omega \lesssim 0.3$, $P_{gr+}$ and $P_{gs+}$ attain peak and off-peak values, respectively. Especially, by comparing cases (ii) and (iii) we find their variations are quite insensitive to the interaction strength $V_{0,ss}$ in this region, which is ideally suited for operating the quantum switch.

V. THE SWITCH EFFICIENCY

To investigate the performance of the quantum switch, we first define the switching efficiency as

$$\eta = \frac{P_{on}^{gr+}}{P_{off}^{gr+}},$$

where $P_{off}^{gr+}$ and $P_{on}^{gr+}$ are the steady population of $|gr\rangle_+$ in status “OFF” and of $|gs\rangle_+$ in status “ON”, respectively. The status is switched by turning up or down the interaction $V_{0,rr}$. For a ideal switch the population $P_{on}^{gr+} = P_{off}^{gr+} = 0.5$ and the efficiency $\eta = 1$. In Fig. 4(a-c) we show the dependence of $\eta$ on the interaction strength $V_{0,rr}$ under the different relative couplings $\omega$ ($\omega$ is already normalized by $\Omega$). For comparison, the steady populations $P_{gs+}$ (blue dashed) and $P_{gr+}$ (black dotted) are presented in the same frame. $\eta$ reaches a saturation value and no longer changes with $V_{0,rr}$ once $V_{0,rr} > \sqrt{2}$, satisfying the two-atom strong blockade condition [24]. This brings us a big advantage at selections of
so that the energy shift of \( \eta \) is observed to be enhanced with the increase of \( \omega \), which is attributed to the slight changes of \( P_{\text{off}} \) (green dot) and \( P_{\text{on}} \) (blue dashed curve). For instance, in the case of \( \omega = 0.3 \) the saturated \( \eta \) is observed to be enhanced with the increase of \( \omega \).

Except for \( V_{0,rr} \) and \( \omega \), we also explore the influence of other parameters on the switching scheme, including the spontaneous decay \( \Gamma \) of the middle state, and the Rabi frequency \( \Omega \). As shown in Fig. 5(c), the decrease of \( \eta \) is enhanced with the increase of \( \omega \) and \( V_{0,rr} \), which results in a decrease of excitations to the middle-state decay \( \Gamma \). Additionally, \( \omega = 0.2 \) and \( V_{0,rr} = 1.0 \). The steady-state population \( P_{\text{off}} \) and \( P_{\text{on}} \) as a function of the driving laser \( \Omega_p \) is shown in (d). All frequencies are scaled by \( \Omega \).

In addition to the parameters above, it should be stressed that the intermediate interaction \( V_{0,ss} \), strongly destroys the switching efficiency. As shown in Fig. 5(c), \( \eta \) rapidly decreases as long as \( |V_{0,ss}| \neq 0 \). That is because a nonzero \( V_{0,ss} \) will shift level \( |sr\rangle_s \) and hinder the transition from \( |mr\rangle_r \) to \( |sr\rangle_s \), see Fig. 1(b). Worse, the competition between transitions of \( |mr\rangle_r \rightarrow |rr\rangle_r \) and \( |mr\rangle_r \rightarrow |sr\rangle_s \) is most serious when \( V_{0,ss} = V_{0,rr} \), resulting in a near zero \( \eta \). So the suppression of \( V_{0,ss} \) is a crucial condition for our approach of quantum switching. It can be guaranteed if we choose two nS states with large difference in principle quantum numbers n as Rydberg states. In the absence of applied electrostatic fields, the intermediate interactions are negligible compared with the intrastate interactions, which has been confirmed theoretically \([34, 35]\) as well as experimentally \([36]\).

Finally, we consider a more general case \( \Omega_p \neq 0 \) (i.e. \( \Omega_p \neq \Omega \)). Since the common limit \( P_{\text{on}} = P_{\text{off}} = 0.5 \) is unable to maintain in this case, the definition of \( \eta \) is no longer rigorous. We then show \( P_{\text{off}} \) and \( P_{\text{on}} \) individually in Fig. 5(d). As the increase of \( \Omega_p \), \( P_{\text{off}} \) (black dashed) exhibits a clear reduction after reaching its maximum value \( 0.5 \) at \( \Omega_p = 1.0 \). Similar trends are observed in \( P_{\text{on}} \) (red solid) but the maximum 0.6 appears at \( \Omega_p \approx 0.6 \). The reductions are because that for a large \( \Omega_p \) the transition of \( |gm\rangle_r \rightarrow |mm\rangle \) is enhanced which results in a decrease of excitations to \( |gs\rangle_r \) and \( |gr\rangle_r \), see Fig. 1(b). Hence, we conclude that \( \Omega_p = 1.0 \) is an optimized value for our switching scheme, because the population of status “OFF” and “ON” are asymmetry for other values.

### VI. EXPERIMENTAL IMPLEMENTATION

After carefully researching the steady state of the switching system, we now turn to study the switching dynamics by numerically simulation with a series of practical experimental parameters. We assume two \(^{87}\text{Rb}\) atoms are respectively confined in two independent optical dipole traps whose separation \( R \) can be adjusted from 15\( \mu \text{m} \) to 4.0\( \mu \text{m} \) by changing the incidence angle of the optical beams in a duration \( \tau \) of the orders of several \( \mu \text{s} \). For the atomic states \( |g\rangle = |5s_{1/2}\rangle \), \( |m\rangle = |5p_{3/2}\rangle \), and Rydberg nS states \( |s\rangle = |47s\rangle \), \( |r\rangle = |65s\rangle \), the vdW intrastate interaction coefficients are \( C_6/2\pi = 50.4\text{GHz} \mu \text{m}^6 \) and \( C_8/2\pi = 1.0\text{GHz} \mu \text{m}^8 \).
and population and 8 mated values of interaction strength for status “ON” and the simulation are described in the main text.

where \( V_{0,rr}^{on} \) and \( V_{0,rr}^{off} \) take the previously estimated values of interaction strength for status “ON” and “OFF”, respectively. \( \tau \) is the switching duration characterizing the changing speed of the interaction, and \( t_0^+ \) and \( t_0^- \) are the critical switching moments of \( V_{0,rr}^{off} \rightarrow V_{0,rr}^{on} \) and \( V_{0,rr}^{on} \rightarrow V_{0,rr}^{off} \), respectively. As shown in Fig. 6(a), the larger the \( \tau \) is, the slower and smoother the switching operation between \( V_{0,rr}^{on} \) and \( V_{0,rr}^{off} \) is. The total duration of the switching cycle is 100\( \mu s \) which is less than the lifetime of the Rydberg states. As discussed before, the excitation is independent on the interaction \( V_{0,ss} \), so for simplicity we assume it has a similar tendency of change with \( V_{0,rr} \) here.

The dynamical evolution of the population \( P_{gr+} \) and \( P_{gs+} \), in response to the variation of interaction \( V_{0,rr}^{on} \), are obtained by numerically solving the master equation and displayed in Fig. 6(b). Two conversions are clearly present at \( t_0^+ = 20 \mu s \) and \( t_0^- = 40 \mu s \). When \( 0 < t < t_0^+ \) the status “OFF” with the situation \( P_{gr+}^{off} \gg P_{gs+}^{off} \) is maintained. A fast exchange of the population occurs around \( t_0^+ \) due to the switch and the spontaneous decay rates are \( \Gamma/2\pi = 6.1 \text{MHz} \), \( \gamma_s/2\pi = 7 \text{kHz} \), and \( \gamma_r/2\pi = 3 \text{kHz} \) (the effective lifetime is approximately 140\( \mu s \) and 320\( \mu s \) for \( |47s\rangle \) and \( |65s\rangle \), respectively, at 50 \( \mu K \) \cite{38}). In our switching operation, the initial separation is \( R = 15 \mu m \), leading to the interaction strength \( V_{0,rr}^{off}/2\pi = 0.004 \text{MHz} \) and \( V_{0,ss}^{off}/2\pi = 8 \times 10^{-5} \text{MHz} \). When \( R \) is reduced to 4.0\( \mu m \), the interactions are enhanced to \( V_{0,rr}^{on}/2\pi = 12.3 \text{MHz} \) and \( V_{0,ss}^{on}/2\pi = 0.24 \text{MHz} \). For Rydberg states \( |47s\rangle \) and \( |65s\rangle \), we have \( C_0^s \gg C_0^r \gg C_{gs}^r \) due to the large difference in principle quantum numbers of the two Rydberg states \cite{39}, so that the interstate interaction \( V_{0,rr} \) is largely suppressed and can be safely neglected. The Rabi frequencies, \( \Omega/2\pi = 10 \text{MHz} \) and \( \omega/2\pi = 2 \text{MHz} \), are typical of current experiments.

FIG. 6. (Color online) (a) Time dependence of interaction \( V_{0,rr}(t) \) in the switching process for different optical switching durations \( \tau = 1.0 \mu s \) (black solid), 5.0\( \mu s \) (blue dash-dotted) and 8.0\( \mu s \) (red dashed); (b) The dynamical evolution of the population \( P_{gr+} \) and \( P_{gs+} \) under the sequence of \( V_{0,rr}(t) \) in a normal and a reverse order. The parameters adopted in the simulation are described in the main text.

To simulate the variation of the interaction under control, we introduce a time-dependent pulse sequence of \( \gamma_{0,rr} \) for a complete switching cycle consisting of three status: OFF, ON, and OFF,

\[
\gamma_{0,rr} = \frac{\gamma_{on}^{on} - \gamma_{on}^{off}}{4} \left[ 1 + \tanh \left( \frac{t - t_0^+}{\tau} \right) \right] \times \left[ 1 - \tanh \left( \frac{t - t_0^-}{\tau} \right) \right] \tag{6}
\]

where \( \gamma_{0,rr}^{on} \) and \( \gamma_{0,rr}^{off} \) take the previously estimated values of interaction strength for status “ON” and “OFF”, respectively, \( \tau \) is the switching duration characterizing the changing speed of the interaction, and \( t_0^+ \) and \( t_0^- \) are the critical switching moments of \( \gamma_{0,rr}^{off} \rightarrow \gamma_{0,rr}^{on} \) and \( \gamma_{0,rr}^{on} \rightarrow \gamma_{0,rr}^{off} \), respectively. As shown in Fig. 6(a), the larger the \( \tau \) is, the slower and smoother the switching operation between \( \gamma_{0,rr}^{on} \) and \( \gamma_{0,rr}^{off} \) is. The total duration of the switching cycle is 100\( \mu s \) which is less than the lifetime of the Rydberg states. As discussed before, the excitation is independent on the interaction \( \gamma_{0,ss} \), so for simplicity we assume it has a similar tendency of change with \( \gamma_{0,rr} \) here.
ing time $t_{\text{cyc}} = 100\mu s$.

VII. APPLICATIONS AND CONCLUSIONS

The quantum switch we present here based on the controllable strong interaction between two Rydberg atoms, but different from the single-photon transistor with Rydberg blockade [18], it enables an efficient and compact transition between two symmetric singly Rydberg excited states $|gr\rangle_+^+$ and $|gs\rangle_+^+$. With appropriate applications and developments, this will broaden exciting perspectives on quantum information processing with Rydberg atoms. For example, owing to its long lifetime and entanglement [41], the singly excited states can become an excellent carrier of quantum information. Then the reversible and swift switch of these states is a requisite operation for implementation of information transfer and quantum computation. Especially, the considerable separation ($\sim 10\mu m$) between two Rydberg atoms in our design allows local operations on one of them individually, served with our switching on two-atom states, various quantum logic gates are hopefully realizable [11–14]. Besides, the Rydberg atomic pair-state interferometer has been experimentally realized [43] recently. A high-precision quantum switch between different Rydberg excitations can enrich its measurement objects and develop the application of Rydberg atoms in quantum metrology.

Finally, Rydberg dressing has been proposed to realize a number of interesting phases in ultra-cold gases, such as rotons and solitons [46, 47]. An extension of our switch in a many-atom case will allow more complex structure of Rydberg dressing, which makes it possible to simulate various and exotic spin-dependent phases by Rydberg atoms [48].

To conclude, our work presents a robust and experimentally feasible scheme of quantum switch, implemented in a system of two interacting Rydberg atoms. Each atom has a $Y$-typed level structure with two highly-excited Rydberg states. We show that which Rydberg state to be excited can be simply and effectively controlled by opening or closing the intrastate interaction of the strongly-coupled Rydberg state. After systematically investigating the steady state and the dynamics of the system in a numerical way, we verify the robustness of the scheme by presenting its insensitivity to the self-interaction of the weakly-coupled Rydberg state, the decay of intermediate state, and the duration time for switching. Our method is suitable for two Rydberg $nS$ states in which the interstate exchange interaction between them can be totally suppressed by considering two $nS$ states with large different principle quantum numbers. More possibilities for the implementation with other energy levels may work, e.g. by applying an external electrostatic field [49]. We show a numerical simulation of switch operation in $^{87}$Rb atoms under realistic experimental conditions and find the switch efficiency approaching as high as 0.92. A many-atom case maybe treated as a good extension to the current scheme in the future, requiring more attentions to complex energy levels and transitions. We also plan to develop the applications of such particular switch in the fields of quantum information processing and other quantum devices.

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