Autoionization of a quasicontinuum: Population trapping, self-trapping, and stabilization

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Three distinct phenomena are found to affect the autoionization of a quasicontinuum. For certain initial superpositions of the states within the quasicontinuum, the autoionization may be inhibited by quantum interference and the population may be trapped. For those initial superpositions that do decay, a self-trapping effect can be observed which causes the superposition to evolve into a trapped state. The self-trapping is due to a redistribution of the population within the quasicontinuum via Raman-like transitions driven by the channel interaction with the continuum acting as the intermediate state. The physical system of a two-electron atom is studied. There the autoionizing continuum is created by an isolated core excitation that embeds a range of highly excited Rydberg states into the continuum. Another mechanism appears, in this system, that affects the autoionization. When the channel interaction is strong compared to the strength of the core excitation a stabilizing effect occurs which slows the autoionization. Analytical models examine these effects in a system with degenerate quasicontinua. Perfect population trapping, self-trapping, and stabilization are all clearly displayed by this system. Numerical models of nondegenerate quasicontinua show that the stabilization process is virtually unchanged by the lifting of the degeneracy. These models also show that, in general, the trapping effects largely disappear. However, a synchronization of the free evolution of the quasicontinuum states with Rabi oscillation of the core excitation returns them to significant roles in the decay process. A wide variety of nondecaying states can be created. Competition between these mechanisms is explored and the impact of these phenomena on experiments is considered. [S1050-2947(98)09608-5]

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I. INTRODUCTION

Structure embedded in a continuum has long excited scientific interest [1]. The classic problem of a single state autoionizing to a continuum is well understood both experimentally [2,3] and theoretically [4–6]. Recently, the richer problem of the interaction between many states (quasicontinuum or QC) and a continuum has received a great deal of experimental and theoretical attention. One fascinating aspect of the problem is the effect of establishing a well-defined phase relationship or coherence between the states of the QC. The central question is what processes govern the decay and, for this work, how does a coherence within the QC effect that decay.

There are two general classes of effects which inhibit the process of decay. The first is an interference between multiple pathways that leads to a long-term trapping of the population in a particular state (or states). A simple example of this is a ''dark state'' in which interference between a superposition of ground states inhibits the excitation of an excited state [7]. The second class can be described as a stabilization and is characterized by a reduction in a decay rate as the strength of the interaction is increased. The physical mechanisms for stabilization are of various origins, but are linked to a significant change in the system as the strength of the interaction is increased (examples range from power broadening to the spatial alteration of the ground state by strong optical fields).

Such phenomena have been actively explored in the process of above-threshold ionization [8]. An example of particular interest for this paper may be found in Ref. [9]. There trapping and stabilization effects are found in the strong-field photoionization of a Rydberg atom quasicontinuum. In that case, when the ionization process becomes sufficiently strong population may be recaptured from the continuum and so slow the ionization rate. Here, we show that it is possible for an intrinsic interaction of the atom (autoionization) to lead to similar phenomena. In addition, the nature of the interaction leads to some unique features such as a self-trapping behavior of the QC.

Initially, we will use a model in which a degenerate QC is coupled to a continuum. The analytical solution of this model provides intuition for exploring the physical problem of the autoionization of Rydberg electrons in a two-electron atom. Precisely, the physical problem examines a superposition of Rydberg states that is coupled to an autoionizing collection of states through an isolated core excitation (ICE) [10] process in a two-electron atom. In ICE, one of the valence electrons is promoted to a highly excited state (or Rydberg state). The remaining core electron is driven so that it oscillates between its ground state and its first excited state. The states of this core electron are much like the states of the singly ionized atom or like that of a single-electron atom. However, the correlation between the two electrons leads to a coupling between the inner electron states and the Rydberg states. This coupling effectively embeds the Rydberg states into the continuum. Such two-electron systems have been the subject of a wide variety of studies [11,12]. Here we are particularly interested in this process when the highly excited state is a coherent superposition of many Rydberg states. Such a state can display strong classical characteristics, e.g., a classically oscillating localized wave packet [13–16]. These are commonly known as radially localized wave packets.

Some of the earliest work investigating ICE and coherent superpositions of Rydberg states was performed by Wang and Cooke [17–19]. When the core electron is driven by a strong field the correlations between these two electrons leads to a wealth of phenomena. Studies of this situation [20–24] found that the autoionization process and the laser induced structure was strongly modified (particularly, when the Rabi frequency for the core transition is equivalent to and synchronized to the classical orbital frequency or Rydberg frequency of the radial wave packet). The insight [21] for the synchronization comes from the following physical picture. The wave packet's motion is timed such that it is localized away from the core when the core is in the excited state. The lack of overlap between the wave packet and the excited core limits the autoionization. Half a period (Rydberg or Rabi) later when the wave packet is near the core, the core electron is in the ground state and again there is little autoionization. In addition to this suppression of the autoionization, the process can also shape the wave function of the Rydberg electron into a nondispersing wave packet.

In this paper, analytic and numerical solutions for a continuum interacting with both degenerate and nondegenerate, embedded quasicontinua are described. They extend the conclusions of the previous theoretical works and provide new insight into the interplay of stabilization and population trapping in this system. They also point out the limitations of the physical picture as the self-trapping process leads to an entangled state of the core electron and the Rydberg electron. Section II studies analytically two situations for the degenerate system. First, it examines a single autoionizing QC and then it adds a coupling to a bound QC. The first situation highlights the trapping phenomena while the second highlights the stabilization process. Section III explores the same situations numerically for a nondegenerate system. The results indicate that, in general, the trapping phenomena play only a minor, transitory role for a nondegenerate QC. However, the synchronization of the free evolution to the Rabi oscillation of the core electron can largely restore the trapping phenomena to a dominant role. Intuition gained from the analytical models suggested that there exists a variety of nondecaying states and nondispersing wave packets. Two examples are given. If the initial superposition corresponds to just a single state excited or if it corresponds to a Schrödinger-cat wave packet state [25] an appropriate Rabi frequency may be chosen that leads to their evolution into a nonautoionizing state. Section IV uses the conclusions of Secs. II and III to explore the feasibility of observing the various phenomena in the physical system of a two-electron atom.

II. A DEGENERATE QUASICONTINUUM AUTOIONIZING TO A CONTINUUM—ANALYTIC SOLUTION

The case of a degenerate quasicontinuum decaying to a continuum serves as the starting point. Figure 1(a) depicts the interaction of a degenerate QC (the states within this QC are labeled η) with a continuum. The channel interaction drives the autoionization process coupling the QC to the continuum. It is described by a matrix element $R_{\eta\varepsilon}$ connecting the η series to the continuum. Schrödinger's equations of motion for the amplitudes of the states of this system may be written

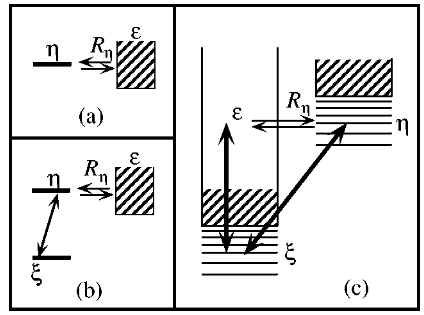

FIG. 1. Energy level diagram describing the coupling of a quasicontinuum to a continuum. In (a) the quasicontinuum is degenerate. In (b) the autoionizing quasicontinuum is coupled to a bound quasicontinuum by a cw isolated core excitation. A two-electron atom is modeled in (c) in which the bound quasicontinuum is excited by a short pulse. Again, the bound quasicontinuum is coupled to an autoionizing quasicontinuum by a cw isolated core excitation.

$$i\dot{a}_\eta(t)=E_\eta a_\eta+\int_\varepsilon d\varepsilon R_{\eta\varepsilon}c_\varepsilon, \tag{2.1}$$

$$i\dot{c}_\varepsilon(t)=E_\varepsilon c_\varepsilon+\sum_\eta R_{\eta\varepsilon}a_\eta, \tag{2.2}$$

where E_η and E_ε are the energies of the QC states and the continuum states, respectively. Note that in the degenerate case all E_η are equal.

These equations can be transformed to the interaction picture. If we also make use of the Markov approximation [1] to eliminate the continuum, then we can write the following differential equations for the discrete states:

$$\dot{A}_\eta(t)=-\pi R_\eta\sum_{\eta'}R_{\eta'}A_{\eta'}, \tag{2.3}$$

where $a_\eta=A_\eta\exp(-iE_\eta t)$. We have also assumed that the continuum is flat so that $R_{\eta\varepsilon}$ is independent of ε and so write $R_{\eta\varepsilon}=R_\eta$.

The solution of Eq. (2.3) is accomplished in two steps. First, a new differential equation is formed for the sum, $\Sigma_\eta A_\eta R_\eta$, by multiplying both sides of Eq. (2.3) by R_η and introducing a sum on η to both sides. The solution of this equation is simply $\Sigma_\eta A_\eta R_\eta=Q_0e^{-\Gamma t}$, where the constant $Q_0=\Sigma_\eta A_\eta(0)R_\eta$ contains the initial conditions of the states in the quasicontinuum. The autoionization coupling appears in the constant $\Gamma=\pi\Sigma_\eta R_\eta^2$. This solution for the sum now acts as a driving term in Eq. (2.3) and the exact solution of this equation is

$$A_\eta(t)=A_\eta(0)+\frac{\pi R_\eta Q_0}{\Gamma}(e^{-\Gamma t}-1). \tag{2.4}$$

In the simple case of a single state embedded in the continuum, the above solution reduces to the well-known solution, $A_\eta(t)=A_\eta(0)\exp(-\pi R_\eta^2 t)$. The population of the state decays exponentially into the continuum [4].

Next, consider the phenomenon of population trapping. If there are a number of states in the QC then the initial amplitudes of the states play a key role. The quantity $Q_0=\Sigma_\eta A_\eta(0)R_\eta$ determines whether the decay is inhibited or enhanced. Clearly, if Q_0 is zero, the population is trapped forever in the QC. The simplest trapping example occurs when there are only two states in the QC. In that case, the initial state has the familiar asymmetric form of a ''dark state''similar to those found in the laser excitation of a Λ system [7]. Specifically, if the R_η are all identical, the amplitudes of the states are equal in magnitude but opposite in sign. For a QC with many states, any superposition of states that yields a $Q_0=0$ is a trapped or a nonautoionizing state.

For an initial distribution that results in a nonzero Q_0, a portion of the population may still be trapped. A compact result is found for the steady-state solution of Eq. (2.4) if all of the coupling coefficients for these states, R_η, are assumed to be identical:

$$A_\eta(\infty)=A_\eta(0)-\frac{1}{N}\sum_\eta A_\eta(0). \tag{2.5}$$

A case of particular interest is when only a single state is initially populated in the QC. Then the total steady-state population in the QC is given by $\Sigma_\eta|A_\eta(\infty)|^2=1-1/N$. For example, consider a three-state QC in which only one of them is populated. The steady-state solution predicts that 2/3 of the population is trapped. The associated final superposition state has amplitudes that yield a zero value for Q_0. Therefore the final population trapping results from the evolution of the QC into a nonautoionizing superposition. It is the Raman-like transitions between the states of the QC via the channel interaction with the continuum that produces this self-trapping behavior.

It is possible for the entire population to leave this QC. If the initial superposition had identical amplitudes (i.e., for an N-state QC, $A_\eta(0)=1/\sqrt{N}$) then the trapping is inhibited and the steady-state population in the QC is zero. These examples highlight the key role played by the coherence initially established in the superposition. Depending upon the initial superposition state, the trapping of the population in this degenerate QC may vary from perfect to none.

A further question can be addressed by this analytical model. How quickly is the population of the quasicontinuum lost to the continuum in comparison to the decay of a single, isolated state? Again, for compactness, we assume that all the R_η are identical. Then the decay rate is N times faster for the degenerate QC compared to a single, isolated state, i.e., $\Gamma(N)=NR^2$. Of course, if $Q_0=0$ this enhanced decay rate is of little importance since the population is perfectly trapped. However, for nonzero Q_0, there is a rapid evolution to a trapped state. That is, there is a rapid drop to a new level of the population that is then maintained forever.

The addition of an interaction between this autoionizing QC and a bound QC brings this model a step closer to the physical problem that will be discussed in Sec. IV. The extension of the analytical model is depicted in Fig. 1(b), where a laser interaction couples a degenerate bound quasicontinuum to a degenerate autoionizing quasicontinuum. This coupling produces a Rabi oscillation between these two quasicontinua. The indices ξ and η are for the bound and autoionizing QC's, respectively. Any direct photoionization process from the bound QC is assumed to be weak and we ignore its effect. Now, the equations of motion for this system can be written

$$i\dot{a}_\eta=(E_p+E_\eta)a_\eta+\sum_\xi S_{\eta\xi}\cos(\omega t)a_\xi+\int_\varepsilon d\varepsilon R_{\eta\varepsilon}c_\varepsilon, \tag{2.6}$$

$$i\dot{b}_\xi=(E_s+E_\xi)b_\xi+\sum_\eta S_{\xi\eta}\cos(\omega t)a_\eta, \tag{2.7}$$

$$i\dot{c}_\varepsilon=(E_s+E_\varepsilon)c_\varepsilon+\sum_\eta R_{\eta\varepsilon}a_\eta. \tag{2.8}$$

The Schrödinger amplitudes are denoted a_η, b_ξ, and c_ε, corresponding to the autoionizing, the bound, and the continuum states, respectively. Each channel has its own ionization threshold and these are denoted E_s and E_p for the lower and upper channels, respectively.

Again, we enter the interaction picture and use the Markov approximation to eliminate the continuum. In addition, we also use the rotating wave approximation for the laser interaction. The resulting set of differential equations is

$$i\dot{A}_\eta=\sum_\xi \frac{S_{\eta\xi}}{2}e^{-i\Delta_{\eta\xi}t}B_\xi-i\pi R_\eta\sum_{\eta'} R_{\eta'}A_{\eta'}, \tag{2.9}$$

$$i\dot{B}_\eta=\sum_\xi \frac{S_{\eta\xi}}{2}e^{i\Delta_{\eta\xi}t}A_\eta, \tag{2.10}$$

where $\Delta_{\eta\xi}=(\omega-E_p+E_s)-(E_\eta-E_\xi)$. It is assumed that there are no shakeup processes so that the laser interaction between an η state and the corresponding ξ state can be written with a Kronecker delta function $S_{\eta\xi}=\Omega\delta_{\eta\xi}$. The notation is further simplified by keeping only a single index η. The analytic solution of this more complex system is also possible. The solution for the case of exact resonance, i.e., $\Delta_{\eta\xi}=0$, is particularly straightforward. The more general solution (nonzero detuning) is closely related to this special case and can be found by a substitution.

Since the right-hand sides of our differential equations are no longer explicitly time dependent, these equations may be solved in the same fashion as described in the simpler case above. Depending upon the relative size of Γ and Ω, the solution will have different dynamic behavior. For $\Omega>\Gamma$ we find

$$iA_\eta(t)=\left(B_\eta(0)-\frac{\pi R_\eta Q_0}{\Gamma}\right)\sin\left(\frac{\Omega t}{2}\right)+\frac{\pi R_\eta Q_0\Omega}{\sigma\Gamma}\sin\left(\frac{\sigma t}{2}\right)e^{-\Gamma t/2}, \tag{2.11}$$

$$iB_\eta(t)=\left(B_\eta(0)-\frac{\pi R_\eta Q_0}{\Gamma}\right)\cos\left(\frac{\Omega t}{2}\right)+\left[\frac{\pi R_\eta Q_0}{\Gamma}\cos\left(\frac{\sigma t}{2}\right)+\frac{\pi R_\eta Q_0}{\sigma}\sin\left(\frac{\sigma t}{2}\right)\right]e^{-\Gamma t/2}, \tag{2.12}$$

where $\Gamma=\pi\Sigma_\eta R_\eta^2$ and $\sigma=\sqrt{\Omega^2-\Gamma^2}$. The rightmost terms in Eqs. (2.11) and (2.12) are exponentially damped oscillatory terms. The solution for $\Omega\leqslant\Gamma$ is similar in form; however, the rightmost terms are now purely decay terms.

$$iA_\eta(t)=\left(B_\eta(0)-\frac{\pi R_\eta Q_0}{\Gamma}\right)\sin\left(\frac{\Omega t}{2}\right)+\frac{\pi R_\eta \Omega Q_0}{2\Gamma\delta}(e^{\lambda_1 t}-e^{\lambda_2 t}), \tag{2.13}$$

$$iB_\eta(t)=\left(B_\eta(0)-\frac{\pi R_\eta Q_0}{\Gamma}\right)\cos\left(\frac{\Omega t}{2}\right)+\frac{\pi R_\eta Q_0}{2\delta}(e^{\lambda_1 t}-e^{\lambda_2 t})+\frac{\pi R_\eta Q_0}{2\Gamma}(e^{\lambda_1 t}+e^{\lambda_2 t}), \tag{2.14}$$

where $\delta=\sqrt{\Gamma^2-\Omega^2}$, $\lambda_1=-(\Gamma-\delta)/2$, and $\lambda_2=-(\Gamma+\delta)/2$.

The off-resonance solution $(\Delta_{\eta\xi}\neq 0)$ can be found in a straightforward manner by transforming to slowly rotating variables. That is, let $A_\xi(t)=C_\eta(t)e^{-i\Delta_{\eta\xi}t/2}$ and $B_\eta(t)=D_\eta(t)e^{i\Delta_{\eta\xi}t/2}$. Then the solutions for C_η and D_η are exactly the same as for A_η and B_η, respectively, except that the Ω^2 in σ and δ are replaced by $(\Omega^2-\Delta^2_{\eta\xi}-2\Gamma\Delta_{\eta\xi})$.

This extended model still displays a sensitive dependence upon the initial superposition. For example, the trapped population is the sum of the steady-state population in the two quasicontinua. If we make this sum, we find

$$\sum_\eta |A_\eta|^2+\sum_\eta |B_\eta|^2=\sum_\eta \left|B_\eta(0)-\frac{\pi R_\eta Q_0}{\Gamma}\right|^2. \tag{2.15}$$

This steady-state population is identical to that resulting from the simpler model described above. Therefore all the predictions regarding population trapping and the self-trapping behavior remain true for this extended model.

A new phenomenon does appear in the transient evolution of the population in the two QC's. If Q_0 is chosen to allow some decay, the final population in the QC is nonzero and is equal to $1-(\pi Q_0^2)/\Gamma$, as previously. However, the route taken to that steady state is dependent upon the strength of the channel interaction. Note that one of the decay constants in Eqs. (2.13) and (2.14), λ_1, is quite small for large Γ. Counterintuitively, the rate of autoionization decreases as the strength of the channel interaction increases beyond the Rabi frequency of the laser interaction.

Three examples of the short term evolution are shown in Fig. 2. In all of them, the Rabi frequency is held fixed and Γ is varied. The behavior falls into two distinct regimes and is reminiscent of the behavior of a damped, harmonic oscillator. One example lies in the underdamped regime, another in the overdamped regime, and the last at the border (critical damping). For $\Omega>\Gamma$, the short term evolution contains exponentially damped oscillatory terms. The combination of these damped oscillations leads to the stair step structure seen in Fig. 2. The stairlike structure seen here is of pure quantum origin. The time scale of the structure is related to the Rabi period, number of states involved and the strength of the channel interaction. In this underdamped regime, the decay rate of the population increases as Γ increases. However, as Γ increases beyond the threshold $\Omega=\Gamma$, the damped oscillations disappear and the decay rate now decreases as the Γ increases. Such a reduction in the decay rate with the increase of the strength of the interaction is commonly described as stabilization. It is similar in character to power broadening, the broadening of a resonance due to a strong laser interaction, except that in this case it is the intrinsic channel interaction that produces the effect.

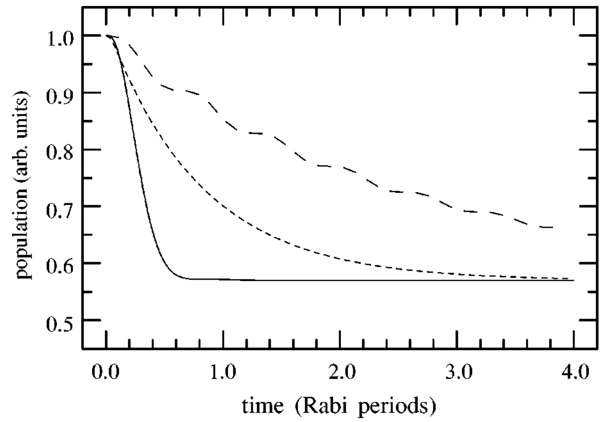

FIG. 2. Short term evolution of the population of a degenerate quasicontinuum. The long-dashed curve ($V_0=0.05$) is for the case of $\Omega>\Gamma$. The short-dashed curve ($V_0=0.5$) is for the case of $\Gamma>\Omega$. The case of $\Gamma=\Omega$ is the plain curve ($V_0=0.2$). Counterintuitively, as channel interaction strength Γ is increased beyond Ω the autoionization rate decreases.

These analytic solutions allow an easy separation of the processes that effect the autoionization. The perfect trapping of the population is linked to the initially established coherent superposition, i.e., an initially prepared dark or nonautoionizing state. Similarly, the self-trapping phenomenon (redistribution of population by Raman-like transitions) leads to the evolution of an initially decaying state to a coherent superposition that is nondecaying. Once a nondecaying state is established or produced, the degeneracy of this system halts further evolution. On the other hand, the stabilization phenomenon is not dependent upon the coherence established in the superposition. It depends solely upon the relative sizes of Ω and Γ and is not tied to the degeneracy of the model system. How do these processes change when the degeneracy is lifted?

III. A NONDEGENERATE QUASICONTINUUM AUTOIONIZING TO A CONTINUUM—NUMERICAL SOLUTION

Figure 1(c) depicts the model of the nondegenerate quasicontinua of the physical problem. The bound QC is a nondegenerate set of Rydberg states of a two-electron atom. This bound QC may be coupled to a nondegenerate autoionizing QC, as above, by a cw isolated core excitation. First, proceeding as in the preceding section, we consider only the interaction between the autoionizing QC and the continuum. The primary result is that the initial superposition of the QC now freely evolves. In the degenerate case, only the interaction with the continuum could change this superposition. If the autoionization was suppressed by the population trapping (i.e., $Q_0=0$) this superposition did not ever change. However, in the present nondegenerate case, the free evolution will inhibit such population trapping since the trapping relies

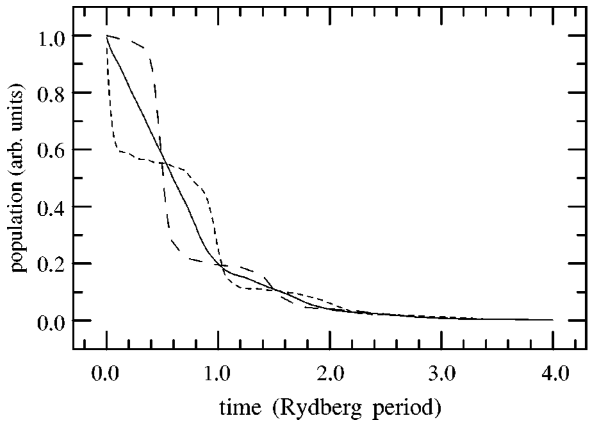

FIG. 3. Dependence of autoionization on initial superposition for a nondegenerate quasicontinuum. This figure compares the population of the quasicontinua obtained from an numerical analysis with those of the analytic solution for the degenerate case. The initial superposition that led to perfectly trapped population in the degenerate case now produces the long-dashed curve. The behaviors of all the initial superpositions are now similar. The $Q_0=0$ superposition (long dashes), the nonzero Q_0 superposition (short dashes), and a single state (solid line) all lead to a rapid decay of the population.

on maintaining a specific superposition state.

The amplitudes of the autoionizing QC (interaction picture) can be described in this nondegenerate situation by the equation

$$i\dot{A}_\eta = -i\pi R_\eta \sum_{\eta'} R_{\eta'} A_{\eta'} e^{-i(E_{\eta'}-E_\eta)t}, \tag{3.1}$$

where $E_\eta=-1/(2\eta^2)$. A natural time scale for the free evolution of the superposition is given by the fundamental energy difference $E_\eta - E_{\eta-1}$ and is commonly described as a Rydberg period, $\tau_R=2\pi\eta^3$. Figure 3 compares the results of this numerical analysis with those of the previous analytic solution. There is no choice of initial superposition that leads to perfectly trapped population. The initial superposition that led to perfect trapping (long dashes) can maintain it for only half a Rydberg period before a sharp drop in the population. In fact, the other cases of interest (a nonzero Q_0, and a single state) are also little like the degenerate solutions. Clearly, the choice of initial superposition does not have the same sensitivity in determining the decay of a nondegenerate autoionizing QC. However, the original behavior can be regained if the free evolution of the superposition can be compensated.

The semiclassical argument put forward by Hanson and Lambropoulos [21] showed that coupling the autoionizing QC to a bound QC can lead to a suppression of the autoionization. They explored the situation of initial superposition that corresponds to a well-localized radial wave packet and the Rabi frequency equal to Rydberg frequency. If the two oscillations are synchronized, as described in the Introduction, the autoionization is suppressed and a nondispersing wave packet is formed.

In the terms of this paper, synchronizing the Rabi period and the Rydberg period offers a means of compensating the free evolution of the states of the QC and so offers a means of restoring the trapping and self-trapping behaviors that were lost in the lifting of the degeneracy. The effect of the synchronization is to provide a time dependent phase term in the amplitudes A_η that nearly cancels the free evolution term that appears in Eq. (3.1). In the degenerate case, the quantity Q_0 defined the population trapping. In the nondegenerate case, the trapping can be regained as long as the evolution of the time dependent quantity $Q(t) = R_\eta \Sigma_{\eta'} R_{\eta'} A_{\eta'}(0) e^{-i(E_{\eta'}-E_\eta)t}$ can be compensated by the Rabi oscillations of the core excitation. In effect it is a transformation to a rotating frame that rotates at the rate of the free evolution of the quasicontinuum. The situation explored by Hanson and Lambropoulos [21] is not unique and the analysis presented here allows their insight to be generalized. The initial superposition need not be a well-localized radial wave packet. For example, any superposition that has a simple periodic free evolution can have suppressed autoionization by choosing a Rabi period that matches that period. This opens such intriguing questions as what happens to other wave packet states such as the nonclassical Schrödinger-cat state [25]. In fact, even if the initial superposition does not have a simple periodic evolution, the self-trapping behavior will shape it into a superposition that is a nondecaying state for the particular synchronization chosen. These superpositions may be either stationary states or nonstationary (wave packets) states of the combined Hamiltonian.

Including the ICE into the model leads to the following set of equations:

$$i\dot{A}_\eta = \frac{1}{2}\sum_\xi S_{\eta\xi} B_\xi e^{-i(\Delta+E_\xi-E_\eta)t} - i\pi R_\eta \sum_{\eta'} R_{\eta'} A_{\eta'} e^{-i(E_{\eta'}-E_\eta)t}, \tag{3.2}$$

$$i\dot{B}_\xi = \frac{1}{2}\sum_\eta S_{\eta\xi} A_\eta e^{i(\Delta+E_\xi-E_\eta)t}, \tag{3.3}$$

where A_η and B_ξ are, respectively, the autoionizing QC and bound QC probability amplitudes in the interaction picture. E_ξ and E_η are $E_i=-1/[2(n-\delta_i)^2]$ $(i=\xi,\ \eta)$. The δ_i allow the introduction of quantum defects. The optical frequencies are denoted ω for the cw laser field. $S_{\eta\xi} = D_{\eta\xi}\{2\sqrt{\eta\xi}\sin[\pi(\eta-\xi)]\}/[\pi(\eta^2-\xi^2)]$ is the Rabi frequency for the core excitation, determined by the matrix element of the dipole operator and the electric field amplitude of the light. The channel interaction coupling the upper series and the continuum is governed by $R_\eta = V_0/\eta^{3/2}$, where V_0 is the strength of the channel interaction and is a constant for a given atom and for a given core excitation of that atom. The detuning is $\Delta=\omega-(E_\eta-E_\xi)$.

These equations are again solved numerically. Figure 4 shows results for several different initial superposition states of the autoionizing QC. The Rabi period of the core laser transition is chosen equal to the Rydberg period. It is assumed that this ICE process is abruptly turned on at $t=0$ (this abrupt turn on will be discussed in the next section). The results for the well-localized wave packet repeat that of Ref. [21], i.e., the autoionization is suppressed and a nondis-

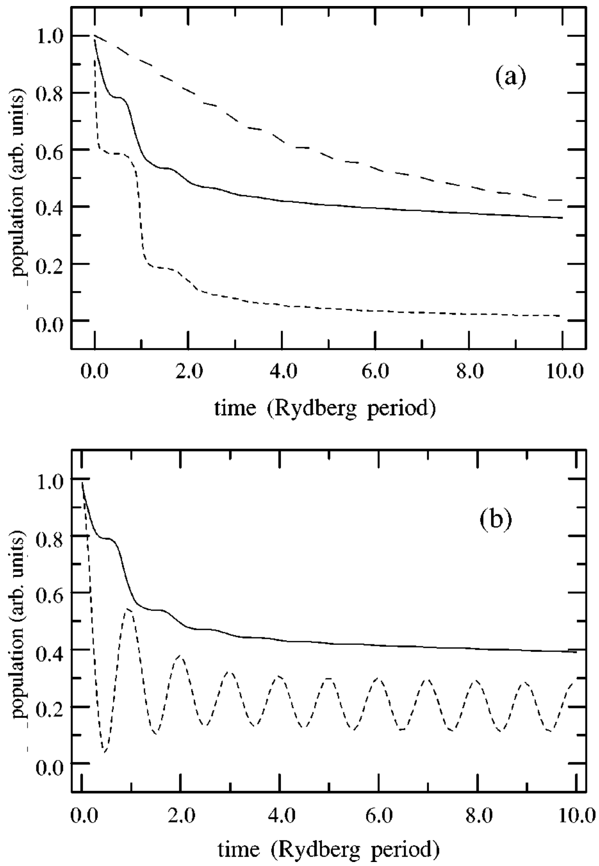

FIG. 4. Autoionization of a nondegenerate quasicontinuum coupled to a bound quasicontinuum by an ICE interaction. In (a) the total population of both continua are shown. The initial superposition states of the autoionizing QC described in Fig. 3 are considered here. The synchronization of the Rabi period of the core laser transition to the Rydberg period restores the trapping phenomena lost with the lifting of the degeneracy. The $Q_0=0$ superposition (long dashes) leads again to a well-trapped population, the nonzero Q_0 superposition (short dashes) decays rapidly but then is trapped, and the single state (solid line) also evolves to a trapped situation. In (b) the population in the autoionizing continuum (solid line) is shown along with the total population (dashed line) when the initial population in the quasicontinuum is in only one state. Note that there exists a nonzero steady-state population in the autoionizing continuum.

persing wave packet is formed. Note that the single state also evolves into a nondecaying state with significant population. It is the self-trapping that keeps the population from completely decaying to the continuum.

The entanglement of these nondecaying states can be seen by examining the population in the autoionizing QC. Figure 4(b) compares the total population to the population within the autoionizing continuum for the single state case. Initially, the population undergoes Rabi oscillations between the bound and autoionizing QC's. However, after several Rydberg periods not all the population returns to the bound QC and eventually a steady-state population is established in the autoionizing QC. Such a steady-state population in the autoionizing continuum cannot easily be understood with the physical picture that provided the insight for synchronizing the Rabi oscillations and the evolution of the wave packet. It is not sufficient for a nondecaying state to correspond to a

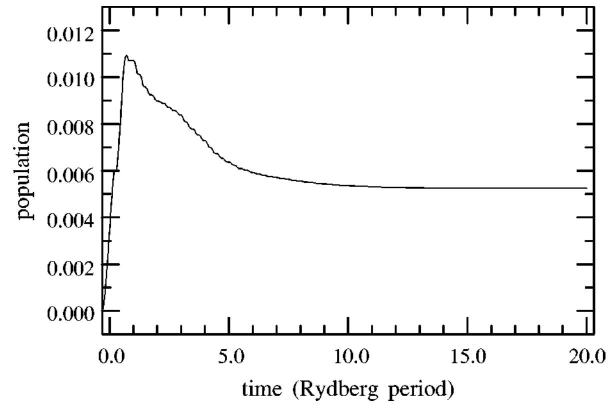

FIG. 5. Autoionization of a Schrödinger-cat state. The Rabi frequency Ω is equal to twice the Rydberg frequency. The total population of the two quasicontinua is shown. The superposition evolves into an essentially nondecaying state that is an eigenstate of the entire system. A channel interaction strength of $V_0=0.2$ was used for this simulation and the quantum defect was taken to be 0.1.

wave packet that is in the right place at the right time. That is, since there is significant steady-state population in the autoionizing QC there must be a time that the Rydberg wave packet approaches the core while the core is excited. The state does not autoionize at this time due to quantum interference between the states of the QC. It is the entanglement that results from the synchronized ICE that makes this possible. An analysis of the probability density of the wave function of this nondecaying state (at times longer than 10 Rydberg periods) shows that it oscillates at Rydberg frequency with no change of shape and with only a slow loss of amplitude. This indicates that it is nondispersing wave packet or equivalently a coherent superposition state of the complete system (atom, field, and channel interaction).

Other synchronizations are possible. Consider the free evolution of a Schrödinger-cat state. It occurs at twice the Rydberg frequency. Therefore the necessary synchronization requires a Rabi frequency equal to twice the Rydberg frequency. The creation of the cat state is modeled by a two-pulse excitation from the ground state to the bound QC. The first and second pulses are separated by approximately one-half of a Rydberg period. Two classical wave packets are excited and they are distinguishable by a small additional optical phase delay. In this case the optical phase shift between the two pulses was π. The ICE interaction is turned on abruptly at 1.0 Rydberg period after the first excitation pulse. Figure 5 shows the suppression of autoionization that occurs when a Schrödinger-cat state is the initial superposition.

The stabilization phenomenon is largely unchanged for this nondegenerate system. In Fig. 6, we explore the stabilization phenomenon by varying the channel interaction strength V_0, and so varying Γ. The initial superposition consists of a single populated state. We have chosen the Rabi frequency Ω equal to the Rydberg frequency. The ICE is turned on abruptly at $t=0$ and the single state evolves into a nondecaying state. However, the manner in which this evolution takes place is strongly dependent upon the strength of the channel interaction. As in Fig. 2 there are two distinct regions of behavior. When $\Gamma<\Omega$ the rate of decay is small. When we increase Γ the decay occurs more rapidly until Γ exceeds Ω. At this point the decay rate begins to decrease.

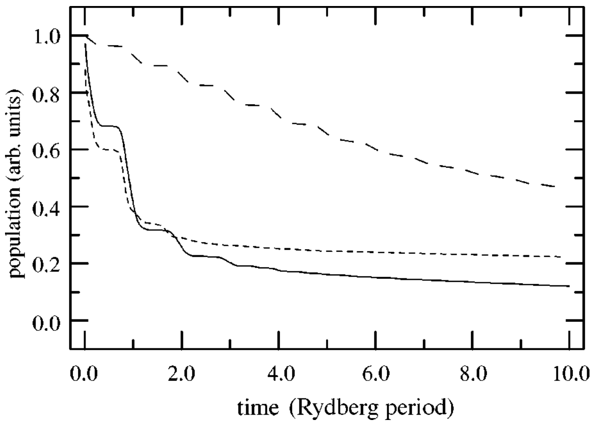

FIG. 6. Stabilization of the autoionization process by large channel interaction strengths for a nondegenerate quasicontinuum. Initially, only a single state is populated in the quasicontinuum. The ICE interaction is turned on abruptly at $t=0$. The Rabi frequency Ω is equal to the Rydberg frequency and they are synchronized to suppress the autoionization. The total population of the two continua is shown. The long-dashed curve ($V_0=0.05$) is for the case of $\Omega>\Gamma$. The short-dashed curve ($V_0=0.5$) is for the case of $\Gamma>\Omega$. The case of $\Gamma=\Omega$ is the plain curve ($V_0=0.2$). As before, when the channel interaction strength Γ is increased beyond Ω the autoionization rate decreases.

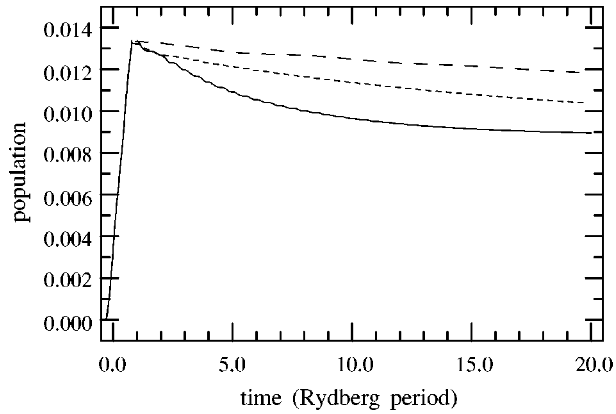

FIG. 7. Stabilization of the autoionization of a two-electron atom. A Schrödinger-cat state is excited in the presence of the ICE laser. The Rabi frequency Ω is equal to the Rydberg frequency. The total population of the two continua is shown. The long-dashed curve ($V_0=0.05$) is for the case of $\Omega>\Gamma$. The short-dashed curve ($V_0=0.5$) is for the case of $\Gamma>\Omega$. The case of $\Gamma=\Omega$ is the plain curve ($V_0=0.2$). As before, when the channel interaction strength Γ is increased beyond Ω the autoionization rate decreases. A quantum defect of 0.1 was used in this simulation.

This is exactly the behavior found in the degenerate case. Note that a strong channel interaction, in this case, enhances the ability of the self-trapping effect to form a nondecaying state.

This section has shown that, in general, a nondegenerate, autoionizing QC cannot trap population forever. However, synchronization of the oscillations of the core electron with the free evolution of the QC superposition allows the electron-electron correlations to restore the trapping phenomena. This section also showed that there were many possible initial superpositions and associated synchronizations that could lead to a trapping of the population. Similarly, many different types of nondecaying states can be generated by the self-trapping process. For example, even an initially prepared single state will evolve into a nondecaying state. In addition, the stabilization process that stems from the channel interaction modifies the rate at which such states evolve. In the next section, we will examine the experimental implications of these predictions.

IV. EXPERIMENTAL IMPLICATIONS

Here, we explore one method of exciting the initial superposition of states within the QC. We assume that the ICE laser is on for all times and that a pulsed excitation populates the bound QC from the ground state. By choosing an appropriately chirped pulse [26] or a multiple pulse sequence [27] a wide range of initial superpositions can be formed. The question is how are these superpositions modified by the presence of the ICE laser during the pulsed excitation?

It is straightforward to include this pulsed excitation of the Rydberg states in our model and numerically solve the resulting equations. As an example, we consider the case of the Schrödinger-cat state. The excitation of a Schrödinger-cat state is achieved by a two-pulse excitation, as described in the preceding section. Here, there is no abrupt turn on of the laser driving the ICE interaction. It is on for all times. The Rabi frequency of this ICE is twice the Rydberg frequency. In Fig. 7 we show that the nondecaying states still develop and that the stabilization phenomenon still appears in this physical system. There is some loss of the population during the excitation, but ultimately a nondecaying state evolves.

An analysis of the wave function of the nondecaying state ($V_0=0.2$, solid line) at time later than 20 Rydberg periods shows that it changes little with time. This indicates that it has evolved into a stationary state of the Hamiltonian of the complete system.

What are realistic values for the parameter Γ? Γ may be changed by either changing the atomic system or by exciting different core states for a particular atom. Both offer experimental difficulties. However, it is fortunate that for alkaline earth atoms the values of the channel interaction strength fall in the region of interest. For barium, the states $6p_{3/2}nd$ have a value of $V_0=0.13$ [28] and for calcium, the states $4p_{3/2}nd$ have a value of $V_0=0.25$ [29].

The experimental requirements are well within present day technology. Calcium is a particularly attractive system due to availability of lasers (titanium sapphire) at the necessary wavelengths to drive the various processes. The large intensities needed for the cw ICE interaction can be obtained either via enhancement cavities or through the use of long pulsed lasers synchronized to the short pulses used to excite the various initial superpositions.

V. CONCLUDING REMARKS

This paper has shown that three processes (population trapping, self-trapping, and stabilization) affect the decay of an autoionizing quasicontinuum to a continuum. The population trapping stems from the possibility of destructive interference between the pathways to the continuum. The self-trapping refers to the tendency of the superposition to evolve to a nondecaying or trapped superposition through Raman-like interactions via the continuum. However, in general, a nondegenerate, autoionizing QC cannot trap population. Electron-electron correlations (specifically an ICE) can be used to create a coupling that can restore the phenomenon of population trapping. The synchronization of the Rabi oscillation associate with that coupling and the free evolution of the superposition makes this possible. This paper generalized that synchronization idea and showed that there were many possible initial superpositions and associated Rabi frequencies that could lead to a trapping of the population. The self-trapping process leads to the formation of nondecaying states. This paper showed that a wide variety of such states could be formed. These nondecaying states range from being stationary states of the complete system (atom, field, and channel interaction) to being superpositions of such states that evolve with time, i.e., nondispersing wave packets. In an experimentally realizable example, it was demonstrated that an initially excited Schrödinger-cat wave packet evolved into a nondecaying state (in that case, a stationary state).

Finally, the introduction of the ICE also opened up another process that can affect the decay of the QC, i.e., stabilization. The ability of the self-trapping process to shape the superposition into nondecaying and nondispersing forms is affected by this stabilization process. Strong channel interactions can change the rate at which these form.

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