



## Nondispersing Bohr Wave Packets

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(Received 30 September 2008; published 9 March 2009)

Long-lived, nondispersing circular, or Bohr, wave packets are produced starting from Li Rydberg atoms by exposing them first to a linearly polarized microwave field at the orbital frequency, 17.6 GHz at principal quantum number  $n = 72$ , which locks the electron's motion into an approximately linear orbit in which the electron oscillates in phase with the microwave field. The microwave polarization is changed to circular polarization slowly compared to the orbital frequency, and the electron's motion follows, resulting in a nondispersing Bohr wave packet.

DOI: [10.1103/PhysRevLett.102.103001](https://doi.org/10.1103/PhysRevLett.102.103001)

PACS numbers: 32.80.Rm, 32.80.Ee, 32.80.Qk

The most intuitive picture of an atom is classical, one in which the electron moves about the ion in a circular Bohr orbit. Although it may not be obvious how to reconcile this simple picture with the quantum mechanical description of an atom, given in terms of time-independent wave functions of energy eigenstates, the resolution of this apparent paradox was provided by Schrödinger [1]. He showed that for the harmonic oscillator that wave packets, with localized probability distributions which move as a classical particle does, can be constructed from coherent superpositions of the time-independent spatial wave functions of different energy eigenstates.

Wave packets remained theoretical constructs until the advent of mode-locked lasers, which have pulses short enough to provide adequate frequency bandwidth to produce coherent superpositions of several Rydberg states [2–4]. Rydberg states, those of high principal quantum number  $n$ , have small binding energies,  $Ry/n^2$ , where  $Ry$  is the Rydberg constant. More important, the energy spacing between adjacent  $n$  levels is  $2 Ry/n^3$ , which changes slowly with  $n$ . Thus, the Rydberg levels are approximately evenly spaced, and the orbital, or Kepler motion of the electron in a wave packet with an average principal quantum number  $\bar{n}$  occurs at the Kepler frequency  $f_K = 2 Ry/h\bar{n}^3$ , where  $2 Ry/h = 6.58 \times 10^{15}$  Hz. For  $\bar{n} = 72$ ,  $f_K = 17.6$  GHz. In Ref. [4], the Rydberg wave packets made were radial wave packets in which coherent superpositions of typically five  $np$  states were created, and the radial probability distribution breathed in and out at  $f_K$ , while maintaining  $p$  character [4]. More complex excitation schemes combining laser excitation with short unipolar pulses, often termed half-cycle pulses (HCP) [5–7], have been used to generate angularly localized wave packets in which the electron oscillates in an approximately linear or circular orbit [8,9].

As pointed out by Lorentz, the initial localization of the wave packet persists only for the harmonic oscillator, with its evenly spaced energy levels [10]. If, as in the Rydberg states, the levels are not evenly spaced the initially local-

ized wave packet becomes dispersed in space, typically after five or ten orbits [11]. With a finite number of states, the spatial localization can revive, but eventually, decoherence destroys the localization, with the result that at most tens of orbits are observed, and the typical lifetime of a Rydberg wave packet is 100 ps [12]. Bialynicki-Birula *et al.* suggested that it should be possible to create a long-lived nondispersing circular wave packet by adding a weak circularly polarized field at the Kepler frequency to phase-lock the motion of the Rydberg electron [13]. Adding a magnetic field and using a linearly instead of circularly polarized field have also been proposed [14,15]. To date, nondispersing wave packets (NWP) have only been made with linearly polarized microwaves [16–18] and trains of HCPs [19], resulting in wave packets in which the motion of the electron is roughly linear [20], more like a mass oscillating on a spring than an electron in a Bohr orbit.

Here we report a straightforward and robust way of making nondispersing Bohr wave packets (NBWP). The essence of the method is to create a nondispersing, approximately linearly oscillating wave packet phase-locked to a linearly polarized microwave (MW) field and then slowly change the MW polarization from linear to circular. We chose this approach based on the observation that the electron's motion in a NWP in a linearly polarized MW-field remains phase locked either after a 40% change in the MW frequency [17], or turning the MW field off and then on again [21], the latter investigation suggested by Hänsch [22].

The essential idea of NBWP can be understood by considering an electron in a two-dimensional circular Bohr orbit around an ion in the  $x$ - $y$  plane (Fig. 1). The combination of the Coulomb and centrifugal potentials forms a circular potential trough in the  $x$ - $y$  plane, in which a classical electron with binding energy  $Ry/n^2$  circulates about the ion at the Kepler frequency  $f_K = 2 Ry/n^3$ .

If we add a circularly polarized MW field rotating in the  $x$ - $y$  plane at frequency  $f_K$ , the potential seen by the elec-

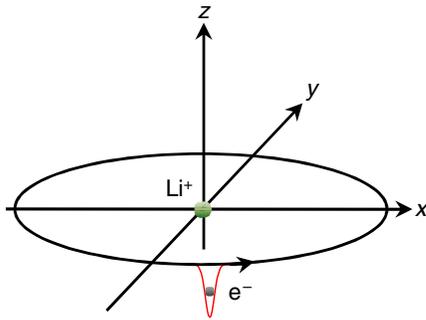


FIG. 1 (color online). Schematic diagram of the nondispersing Bohr wave packet showing the low point in the potential which rotates about the ion core.

tron is tilted with a low point which rotates about the  $z$  axis at  $f_K$ , as shown schematically in Fig. 1. In its lowest energy state the electron is localized at the low point, which rotates about the ion at  $f_K$ , and will remain there indefinitely.

In the experiment, Li atoms in a thermal beam in a vacuum chamber pass through a 17.564 GHz Fabry-Pérot MW cavity as shown in Fig. 2(a). The atoms are excited at the center of the cavity by three 5-ns laser pulses to  $np$  states of  $70 \leq n \leq 75$  via the route  $2s \rightarrow 2p \rightarrow 3s \rightarrow np$ . The dye lasers are pumped by the first of two Nd:YAG lasers running at a 20-Hz repetition rate. Subsequent to the laser excitation the atoms are exposed to a combination of  $x$ - and  $y$ -polarized MW pulses. One such combination is shown in Fig. 2(b). First a pulse is injected through the upper mirror of the cavity, producing a  $y$ -polarized MW field. If the Kepler frequency of the atom is within 500 MHz of the MW frequency, a 1 V/cm MW field converts the atoms in the  $np$  state to a NWP in which the electron's motion is approximately one dimensional and phase-locked to the oscillating field, as shown in Fig. 2(c). Then a second MW pulse is injected into the cavity through the lower mirror to produce a field polarized in the  $x$  direction, the phase of which is shifted by  $90^\circ$  from the  $y$ -polarized field. As the amplitude of the  $x$ -polarized field rises to match that of the  $y$ -polarized field the MW polarization changes from linear to circular. The electron's motion is locked to the field and evolves from a linear to a circular orbit, as shown in Fig. 2(c).

To detect that the Rydberg atom has been converted from an  $np$  eigenstate to a linearly oscillating wave packet and then to a circular wave packet we observe the time variation of the  $x$  or  $y$  momentum of the electron with a 1/2-ps HCP, which is short compared to the 56-ps period of the Kepler orbit and the MW-field cycle. The HCP can be polarized in either the  $x$  or  $y$  direction. Typically the amplitude of, for example, an  $x$ -polarized HCP is set to ionize those atoms in which the electron has  $x$  momentum  $p_x > 0$ . We detect the remaining Rydberg atoms not ionized by the HCP by applying a field-ionization pulse after the HCP, as shown by Fig. 2(b). A negative voltage pulse is applied to the lower cavity mirror to field ionize the atoms

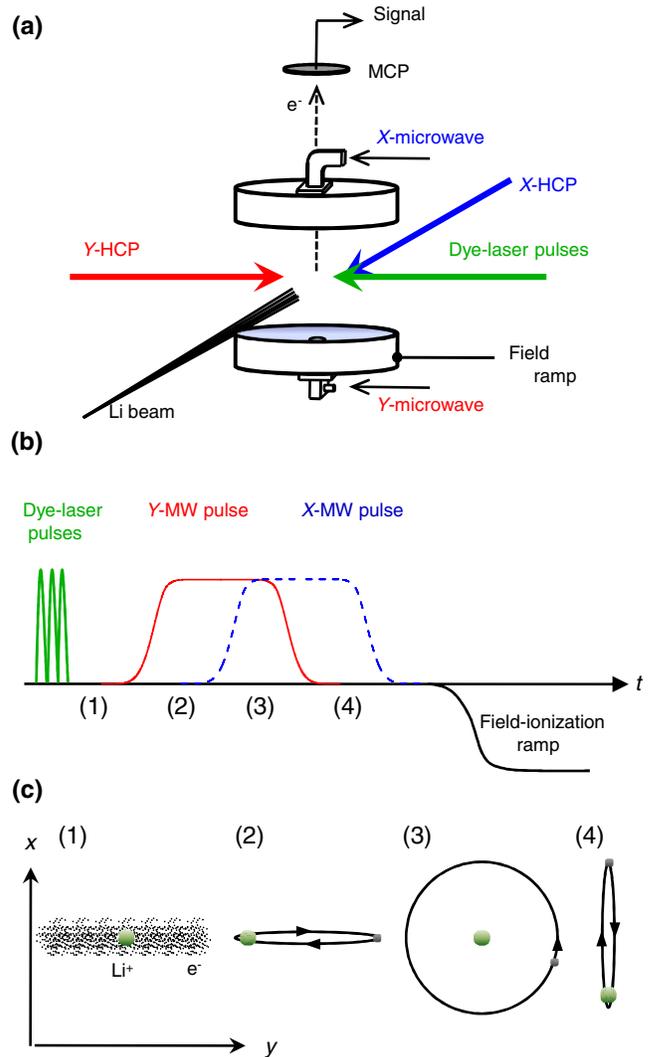


FIG. 2 (color online). Schematic diagram of the experiments. (a) The Li atomic beam passes through the center of the Fabry-Pérot MW cavity where it is excited by the dye-laser pulses. The  $x$ - and  $y$ -polarized MW fields are injected into the cavity through the mirrors, and a field-ionization pulse applied to the lower mirror ionizes the Rydberg atoms and ejects the resulting electrons for detection. (b) Timing diagram. After the dye-laser excitation a  $y$ -polarized MW pulse is injected into the cavity (—), then an overlapping  $90^\circ$ -phase shifted  $x$ -polarized pulse of the equal amplitude (- - -). Finally, a field-ionization pulse is applied to the lower mirror. The time-resolved momentum is sampled at times (1) to (4), when the MW field is zero,  $y$ -polarized, circularly polarized, and  $x$ -polarized, respectively. (c) The Rydberg electron orbits at times (1) to (4) showing the evolution from an eigenstate to  $y$ -polarized linear, then circular, and finally  $x$ -polarized linear wave packets.

and drive the resulting electrons through a hole in the upper cavity mirror to a dual microchannel-plate (MCP) detector [23]. The detector output is recorded with a gated integrator as the fine time delay of the HCP relative to the MW field is scanned. If the atom is in an energy eigenstate and

the electron's motion is not phase-locked to the MW field there is no variation in the signal, but if the atom has become a NWP there is a variation with the 56-ps period of the MW field [16,18].

The Fabry-Pérot cavity is composed of two 82-mm-diameter brass mirrors of 102-mm radius of curvature with an on axis separation of 25.6 or 42.7 mm. The cavity is operated at 17.564 GHz on the TE 002 or TE 004 mode, with a typical cavity  $Q$  of 3800 and a filling time of 35 ns. The source of the MW field is a Hewlett Packard 8350B/83550A sweep oscillator which is amplified by a MITEQ solid-state or Hughes traveling-wave-tube amplifier to a power of up to 300 mW.

The HCP is generated when an amplified 200 fs, 810 nm Ti:sapphire laser pulse strikes a biased GaAs wafer. The MW oscillator is phase locked to the 230th harmonic of the 76 MHz repetition rate of the mode-locked Ti:sapphire oscillator. The coarse timing of the HCP is set by the electronic delay of the second Nd:YAG laser, which pumps the Ti:sapphire amplifier, and the fine delay is varied with an optical delay line for the 810 nm pulse. The jitter between the HCP and the MW field is 5 ps.

In Fig. 3 we show the transformation of Li atoms in the  $72p$  eigenstate into a wave packet oscillating linearly in the  $y$  direction, then to a circularly polarized Bohr wave packet, and finally to a wave packet oscillating linearly in the  $x$  direction, as shown schematically in Fig. 2(c). The MW field amplitudes of the  $x$ - and  $y$ -polarized fields are  $\sim 1$  V/cm, far smaller than the typical atomic field,  $\propto 1/n^4$ , felt by the Rydberg electron, 191 V/cm for  $n = 72$ . Specifically, we show the result of exposing atoms initially excited to the  $72p$  state in zero field to the MW pulse shown in Fig. 2(b), a MW field initially polarized in the  $y$  direction, then circularly polarized, and finally polarized in the  $x$  direction.

We expose the atoms to  $x$ - and  $y$ -polarized HCPs at the four different times indicated in Fig. 2(b). The ionization produced by the HCP is detected as the fine delay of the HCP relative to the MW field is slowly scanned over many laser shots. If the HCP arrives before the MW pulse (1), we see no variation in the signal as the delay of the HCP is scanned for either polarization, as expected; the atoms are in the  $72p$  state, an eigenstate. If the HCP arrives at (2), when only the  $y$ -polarized field is present, we observe the signals shown in Figs. 3(a) and 3(b). A strong modulation is observed with the  $y$ -polarized HCP but essentially none with the  $x$ -polarized HCP, as expected for a phase-locked wave packet oscillating in the  $y$  direction. We attribute the very weak modulation of Fig. 3(b) to a slight misalignment of the MW and HCP polarizations. If the HCP arrives at (3), when the field is circularly polarized, we observe the signals of Figs. 3(c) and 3(d). Modulation in the signal is seen for both polarizations, with a relative phase shift between them of  $90^\circ$ , as expected for a nondispersing circularly polarized Bohr wave packet. It is also apparent

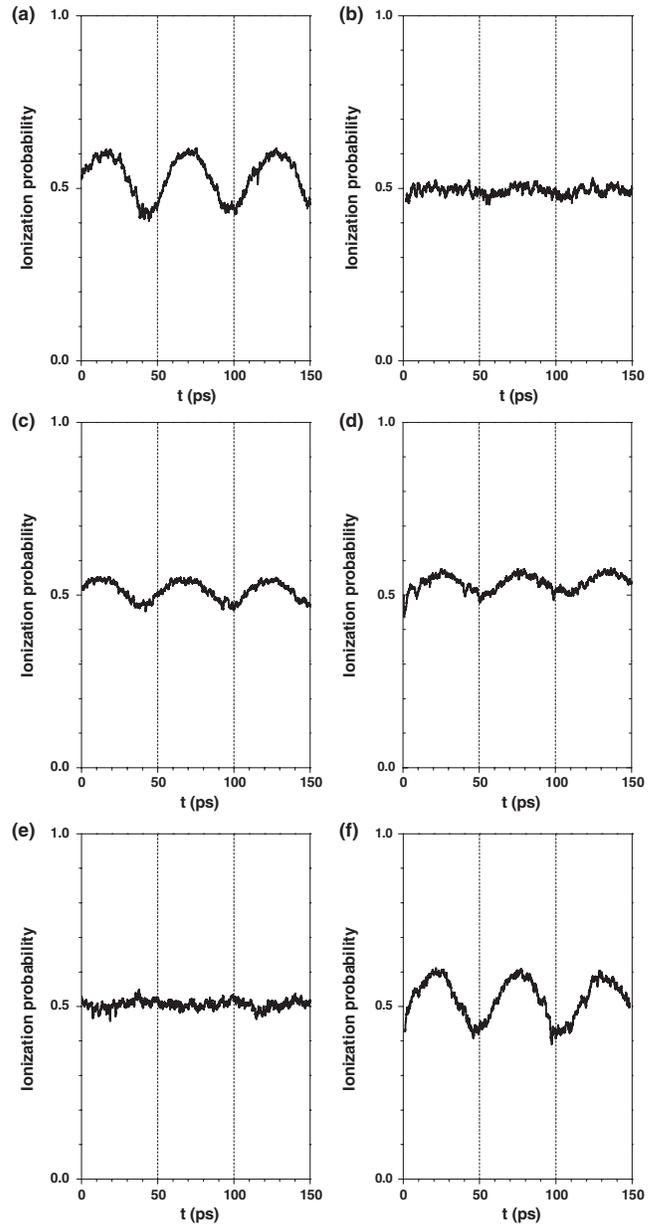


FIG. 3. Signals observed when atoms are exposed to  $y$ - and  $x$ -polarized HCPs and the fine time delay is scanned at the 4 times at the times of (2), (3), and (4) of Fig. 2(b). At time (2), with a  $y$ -polarized MW field (a)  $y$ -polarized HCP shows motion in the  $y$  direction, but (b) obtained with an  $x$ -polarized HCP shows no motion. At time (3), with a circular polarization, (c)  $y$ -polarized HCP and (d)  $x$ -polarized HCP both show motion, with a phase shift. At time (4),  $x$ -polarized MW field, (e)  $y$ -polarized HCP shows no  $y$  motion, but (f) the  $x$ -polarized HCP shows  $x$  motion.

that the modulations of both signals are smaller than the  $y$ -polarized signal of Fig. 3(a) by approximately  $\sqrt{2}$ , which is consistent with the fact that the peak momenta in the  $x$  and  $y$  directions are reduced by  $\sqrt{2}$ . Finally, if the HCP arrives at (4) a clear modulation is observed in the signal

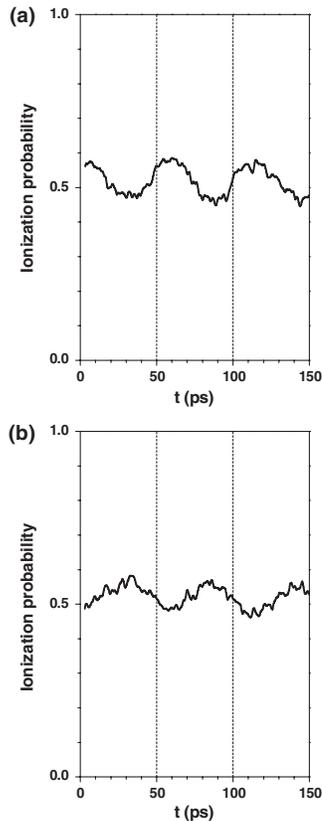


FIG. 4. Signals observed in right- and left-circularly polarized fields, time (3) of Fig. 2(b), when scanning the fine delay of the  $x$ -polarized HCP. (a)  $x$ -polarized MW field phase shifted by  $90^\circ$ . (b)  $x$ -polarized field phase shifted by  $-90^\circ$ .

from the  $x$ -polarized HCP, as shown by Fig. 3(f), but not the  $y$ -polarized HCP, as shown by Fig. 3(e), indicating that there is now a NWP oscillating in the  $x$  direction. The polarization of the NWP has been changed from linear to circular to the orthogonal linear polarization by performing the same transformation on the MW field to which the wave packet is phase locked.

A circularly polarized wave packet can have left or right circular polarization, and in Fig. 4 we show the result of turning on the  $x$ -polarized field of Fig. 2(b) with phase shifts of  $\pm 90^\circ$ . As shown, when the atoms are exposed to an  $x$ -polarized HCP at (3) of Fig. 2(b) the modulation exhibits a  $180^\circ$ -phase shift, while the modulation from the  $y$ -polarized HCP is unchanged, as expected for left- and right-hand circularly polarized wave packets.

In conclusion, we report the first observation of NBWP. The technique we have used is relatively simple and robust, and it is possible to make long-lived wave packets which

can be used in other experiments. For example, one can imagine using the synchronized electron motion as the basis of phase sensitive detection. More generally, this work shows that it is straightforward to take advantage of the fact that a NWP is phase-locked to the MW field to manipulate the wave packet using the polarization, amplitude, and frequency of the MW field.

It is a pleasure to thank B. C. Gallagher, E. A. Bollwerk, and R. R. Jones for helpful comments. This work has been supported by the NSF Grant PHY-0555491.

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