Up-down asymmetry of the electrons ejected from barium $6p_{1/2}nk$ autoionizing states

Jirakan Nunkaew and T. F. Gallagher

Department of physics, University of Virginia, 382 McCormick Rd.

Charlottesville, VA 22904

Introduction

Electric dipole photoionization of atoms by light linearly polarized in the z direction usually leads to angular distributions of electrons which are symmetric in the z (up) and −z (down) directions. The up-down symmetry has its origin in the fact that the atoms are usually in a state of good parity, and electric dipole photoionization simply reverses the parity if an odd number of photons are absorbed and leaves it unchanged if an even number of photons are absorbed.

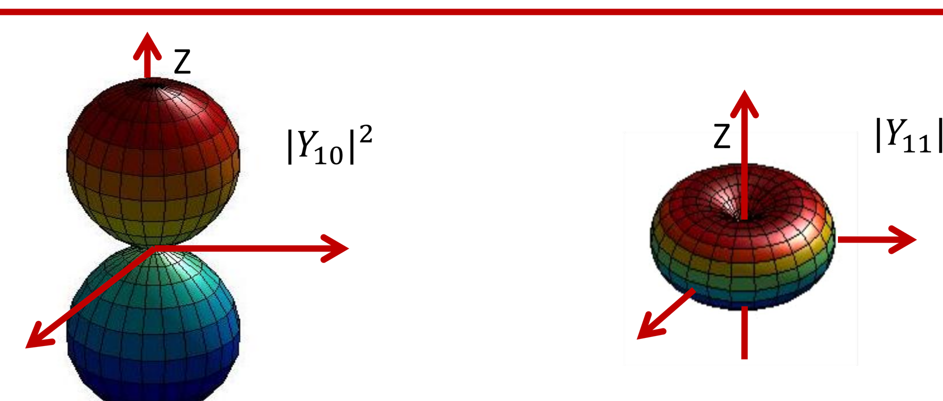

FIG. 1. Spherical harmonics are symmetric in the +z and −z directions.

The symmetry can be broken if the electrons are ejected from atomic states which do not have good parity, such as the Rydberg Stark states formed in the presence of an electric field. In a static field in the z direction, the Rydberg electron in a Stark state can be localized primarily on the +z or −z side of the atom [1]. Photoionization or autoionization of Stark states can be expected to result in superpositions of even- and odd-parity continua, with the result that the up-down symmetry of the electron ejection is broken.

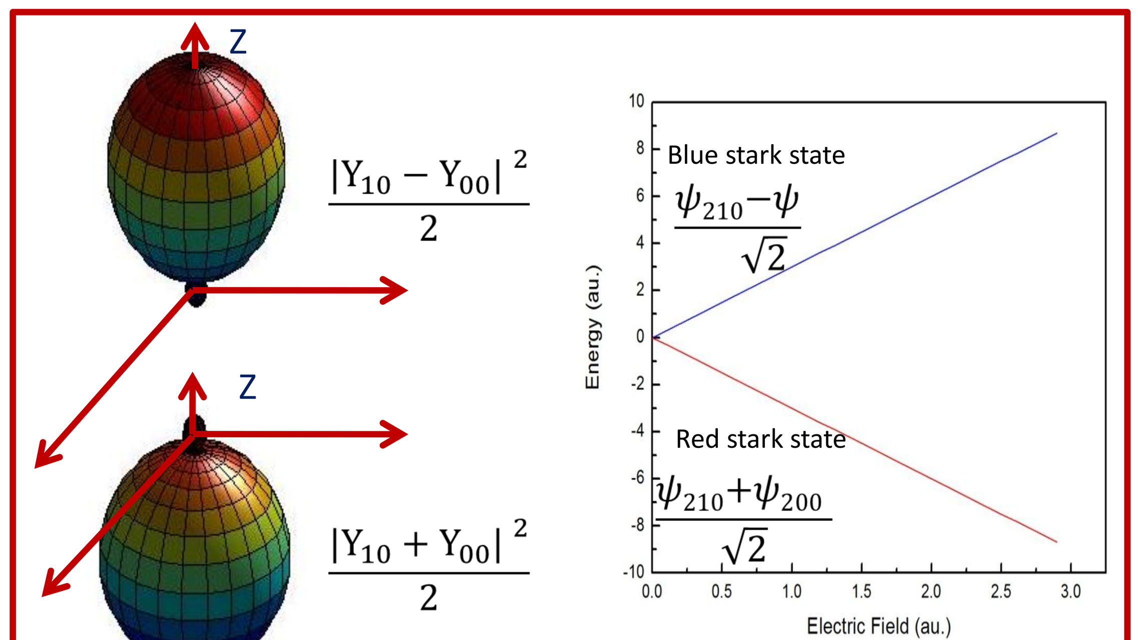

FIG. 2. The blue and red stark state are localized on the +z and −z side of the atom, respectively.

As a simple example, we show in Fig. 3 the classical trajectory of an electron initially in an ℓ = 3 orbit aligned along the −z axis which autoionizes as it passes near the core and leaves the atom in the −z direction. In a zero-field ℓ state, electron orbits along the +z and −z axes are equally likely, resulting in no up-down asymmetry of the ejected electrons. However, if the electron's orbit is on the −z side of the atom, as in Fig. 3 or in a Stark state, the electron is ejected preferentially in the −z direction.

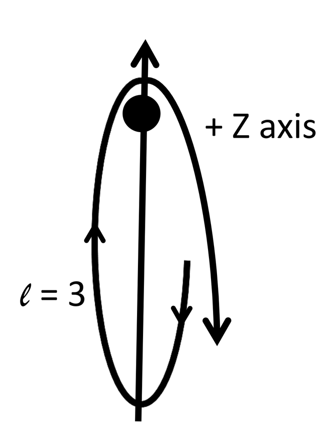

FIG. 3. The classical trajectory of an electron initially in an ℓ = 3 orbit aligned along the −z axis which autoionizes as it passes near the core and leaves the atom in the −z direction.

While the existence of the up-down asymmetry in the photoionization and autoionization of atomic states which do not have a well-defined parity, such as the Stark states, seems obvious, it has not, to our knowledge, been observed. The impediment to its observation is that to form the Stark states generally requires such strong fields that it is impossible to determine the direction in which the electrons have been ejected from the atoms.

Experimental Approach

Laser excitation scheme is shown in Fig. 4. (a). All the laser pulses are 5-ns long and are fired in static field as shown in Fig.5. In Fig. 5, the first 3 μs of the field ramp, a microwave field resonant with the 6s(n + 3)d to 6snk transition at the field E_R < E_0 is present, and as the field ramp passes through E_R, the atoms undergo adiabatic rapid passage from the 6s(n + 3)d state to the 6snk state.

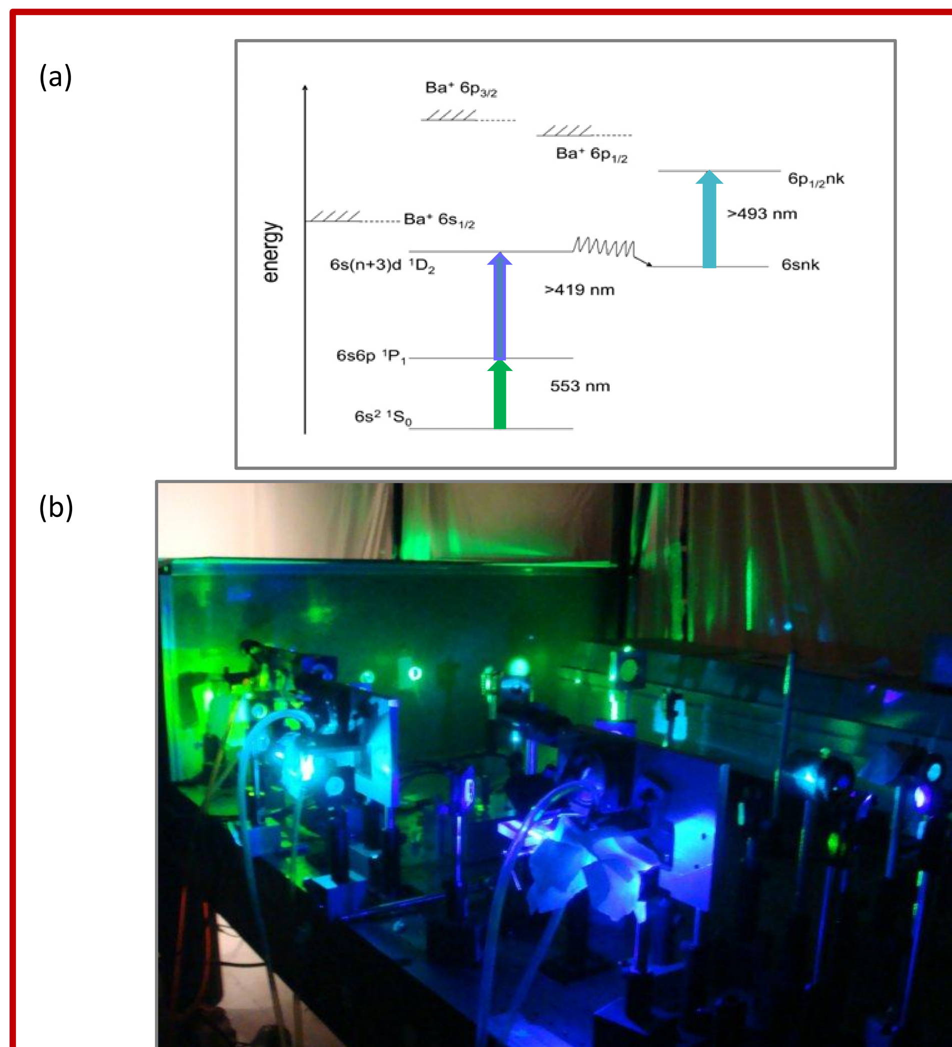

FIG. 4. (a) Energy levels and (b) lasers used in the experiment.

At a chosen time, and therefore field, after the microwave pulse, atoms in the 6snk state are excited to the autoionizing $6p_{1/2}$nk state by a third laser pulse at a wavelength of~493 nm. This excitation, the isolated core excitation (ICE), is one in which the ion core is excited while the outer nk electron remains a spectator [2]. The $6p_{1/2}$nk atoms autoionize rapidly, during the third laser pulse, and the electrons resulting from autoionization are forced through a 1-cm diameter hole in the top plate and fly to the 1.8-cm diameter microchannel plate (MCP) detector 3.2 cm above the top plate as shown in Fig. 6.

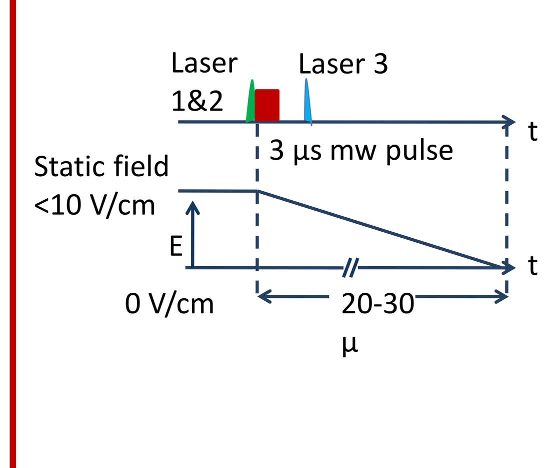

Fig. 5. Timing sequence used in this experiment

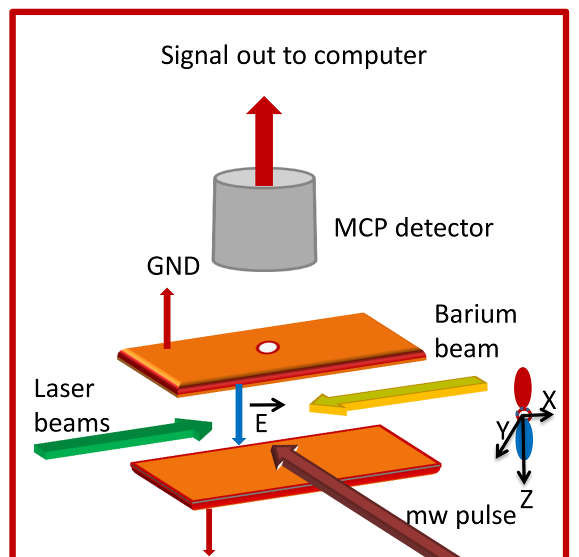

Fig. 6. The apparatus inside the vacuum chamber.

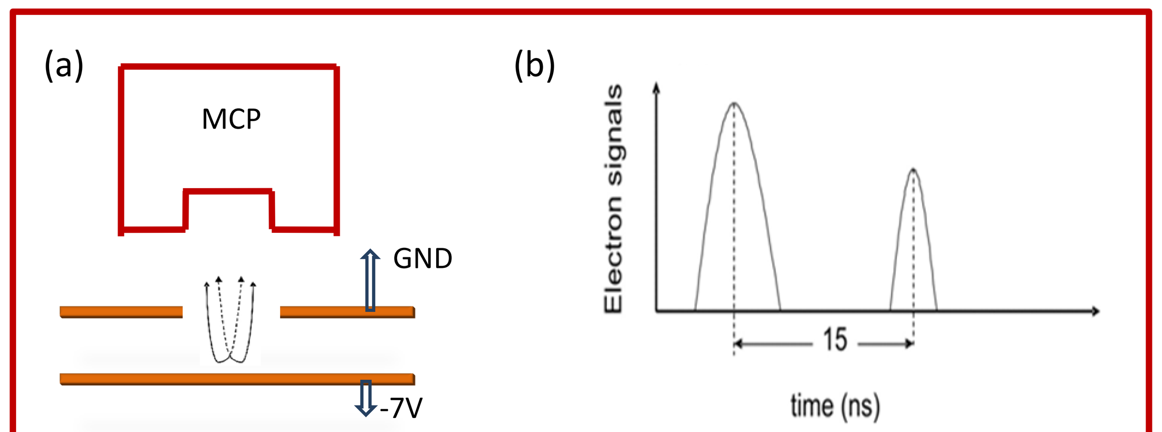

FIG. 7. (a) Arrangement for detecting the angular distribution of electrons ejected from Stark states. Trajectories are shown for electrons ejected at the same angle relative to the positive and negative z axes. (b) Expected time-resolved electron signals. The earlier signal is due to electrons ejected upward to the detector, and the later signal is due to electrons ejected away from the detector.

Experimental Results and Discussion

We have observed the ejected electrons from Ba $6p_{1/2}$nk states of n = 28 and 29, 5≤ k ≤n − 1 in electric fields. For both n, k = 15 and 16 are in the middle of the Stark manifold as shown in Fig. 8. These states have small Stark shifts, and the wave function of the Rydberg electron is up-down symmetric. States of k < 15 are red states, and the wave functions are localized on the upward side of the atom, while states of k > 16 are blue states, and the wave functions are localized on the downward side of the atom.

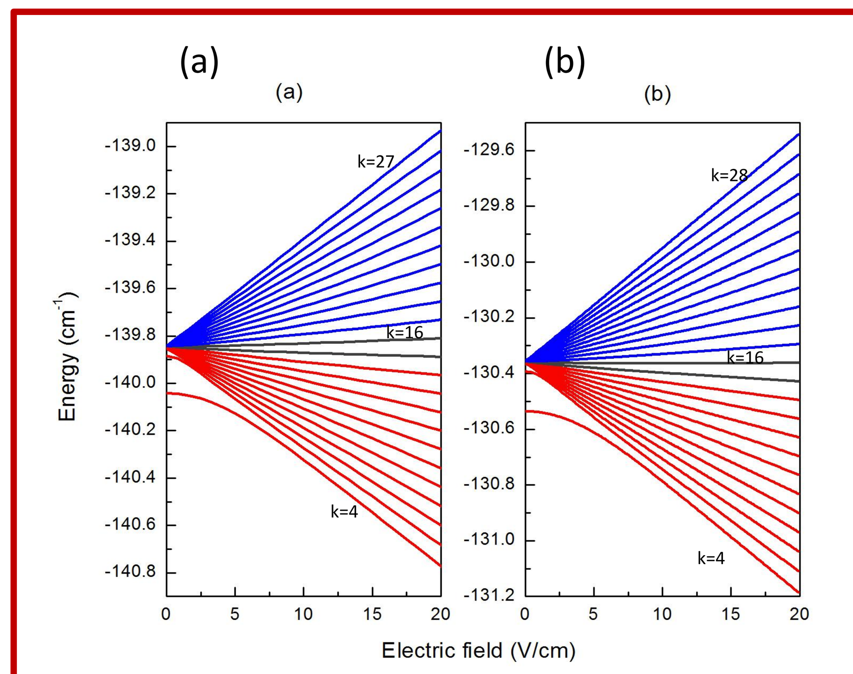

Fig. 8. Starkmap of (a) $6p_{1/2}28k$ and (b) $6p_{1/2}29k$

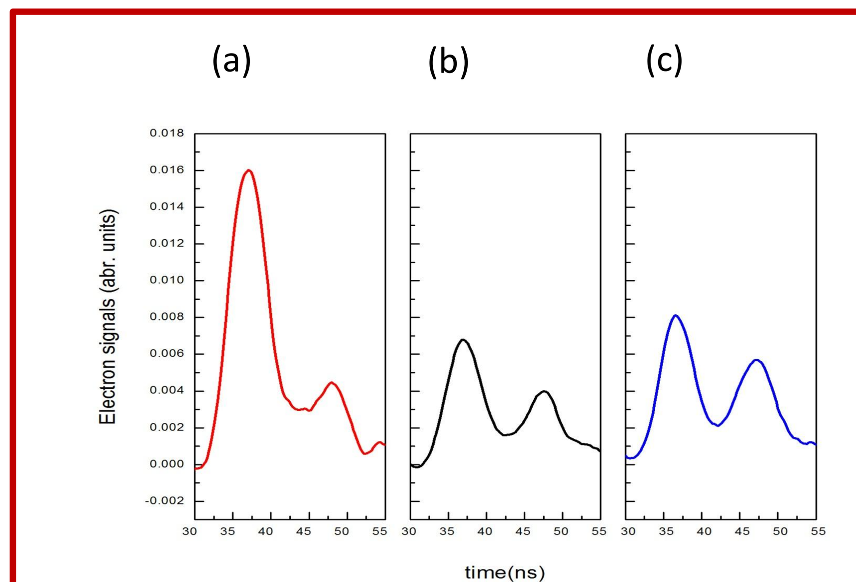

FIG. 9. Ejected electron signals from $6p_{1/2}28k$ (a) k = 5 (red), (b) k = 16 (intermediate), and (c) k = 21 (blue) autoionizing states as a function of time in |E| = 7.90 V/cm.

Fig. 9(a) k = 5 more electrons ejected in the upward direction are detected. Fig. 9(b) k = 16 the earlier electron signal is only slightly larger than the later one. Fig. 9(c) k = 21 the earlier and later signals are comparable in amplitude, but the time-integrated later signal is larger.

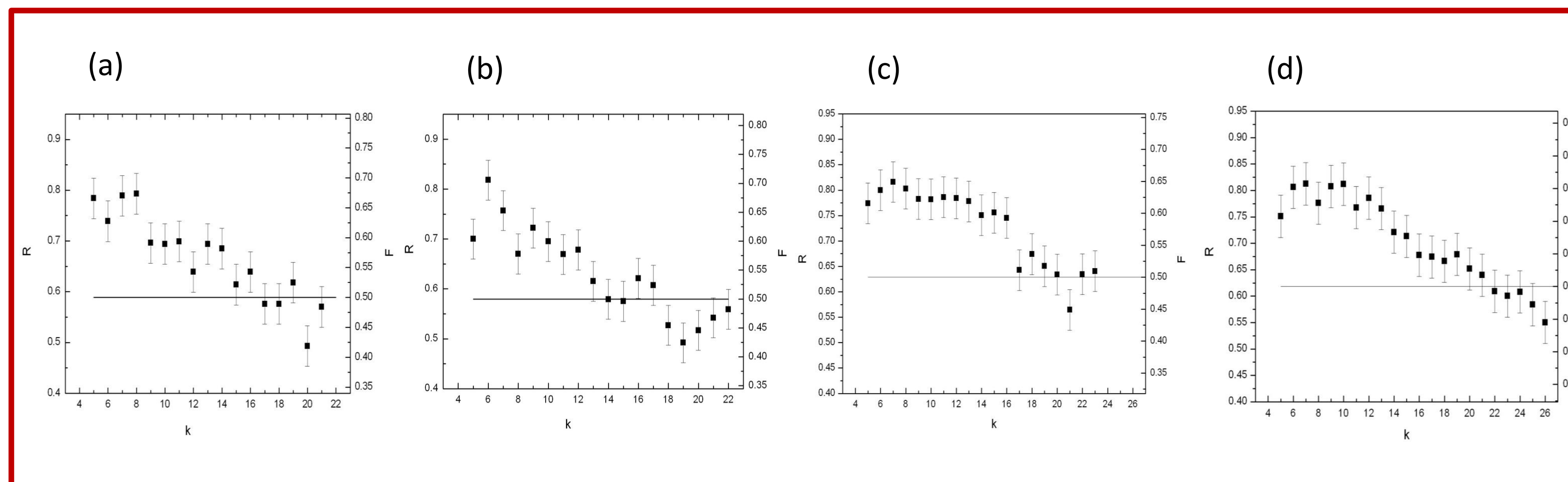

FIG. 10. R, the ratio of up to the total up and down time-integrated electron signals, as a function of k for (a) the $6p_{1/2}28k$ states in |E|=7.10 V/cm, (b) the $6p_{1/2}28k$ states in |E|=7.90 V/cm, (c) the $6p_{1/2}29k$ states in |E|=5.02 V/cm and (d) the $6p_{1/2}29k$ states in (a) |E|=5.43 V/cm. The line is the R value for up-down symmetric ejection of electrons from Ba $6p_{1/2}22s$ states as shown in Fig. 7. The values of R above (below) the lines indicate electron ejection in the up (down) direction. F is the fraction of the electrons ejected up.

In Figs. 10., the observed up-down asymmetry is not large. In higher ℓ states, the electron does not come as near the core due to the centrifugal potential, and the electron is no longer ejected with as strong a preference for the +z or −z direction. In our experiment, we have studied the Stark states which are composed of states of $\ell \geq 5$ for which there is less asymmetry in the direction of the ejected electron than the lower ℓ states.

From a quantum-mechanical point of view, the asymmetry arises from the interference between partial waves of even and odd. Autoionization rates of the Ba $6p_{1/2}n\ell$ states fall quickly with ℓ, so the interference terms cannot be too large. Calculating the probability of ejection in a specific direction, P(θ,ϕ), poses a theoretical challenge, and we hope these data will inspire a theorist to undertake it.

Conclusion

We have observed the up-down asymmetry in electrons ejected from an asymmetric atomic state, specifically from Ba $6p_{1/2}nk$ autoionizing Stark states. The red autoionizing states are more likely to eject the electrons in the upfield direction, while the blue autoionizing states are more likely to eject the electrons in the downfield direction.

Acknowledgments

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References

[1] T. F. Gallagher, Rydberg Atoms (Cambridge University Press, Cambridge, England, 1994).

[2] W. E. Cooke, *et al.* , Phys. Rev. Lett. 40, 178 (1978).