Ionization of fast Rydberg atoms in a magnetic field

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Experimental results on the ionization of Rydberg atoms ($v/c \simeq 1.4\times 10^{-3}$) are reported. The atoms were prepared by laser light in a static magnetic field. The ions and electrons resulting from the ionization retain their kinetic energy. This circumstance is an important distinction from the ionization of Rydberg atoms in an ordinary electric field. © *1995 American Institute of Physics.*

An atom moving in a magnetic field alone or interacting with an electric field crossed with a magnetic field is an interesting and important entity in experimental and theoretical physics.[1,2] Such an atom may undergo ionization. This question was taken up in the early 1960s in connection with the possibility of injecting fast, highly excited hydrogen atoms into plasma confinement systems.[3] In those days, however, the use of laser light for selective preparation of Rydberg atoms was not a realistic possibility. Ionization of hydrogen atoms with a relativistic energy $v/c \simeq 0.84$ in a magnetic field was observed[4] at an accelerator in Los Alamos in the mid-1980s. The atoms were excited to states with principal quantum numbers $n = 4-10$ by a YAG laser beam.

In the present study we investigated the ionization of fast Rydberg helium atoms with $v/c \simeq 1.4\times 10^{-3}$, prepared beforehand by collinear laser light, in a static magnetic field. There is an important distinction between this type of ionization and the familiar ionization of Rydberg atoms in an ordinary electric field. In a static electric field, the force $eF = e[\mathbf{vB}]$ acting on a charged particle does not perform work. Accordingly, the kinetic energies of the ion and the electron are conserved after an ionization of this sort. In an ordinary electric field, the ions are formed at points with different potentials. There is therefore a scatter in the kinetic energies of these ions as they leave an ionizer of this sort.[5]

The experiments were carried out on an apparatus which allowed collinear laser photoionization of atoms in an accelerated beam.[6,7] Fast helium atoms with $v \simeq 4.3\times 10^5$ m/s were prepared by charge exchange of He^+ ions with potassium vapor. The helium ions were accelerated beforehand to a kinetic energy of 3.9 keV. The quasiresonant charge exchange resulted in an effective filling of high-lying metastable states of helium.

The He atom was excited into a Rydberg state by the light from two pulsed dye lasers in a $2^3S \to 3\,^3P \to n\,^3S$ [or $n\,^3D$] scheme ($19 \leqslant n \leqslant 50$). The width of the laser light spectrum was approximately 0.4 cm^{-1}. This excitation was carried out in a region shielded from external electric fields. The magnetic field in this region was determined by the geomagnetic field and the residual field of the apparatus ($B_{\mathrm{res}} \simeq 1$ G).

Since the residual magnetic field in the excitation region partially lifts the selection

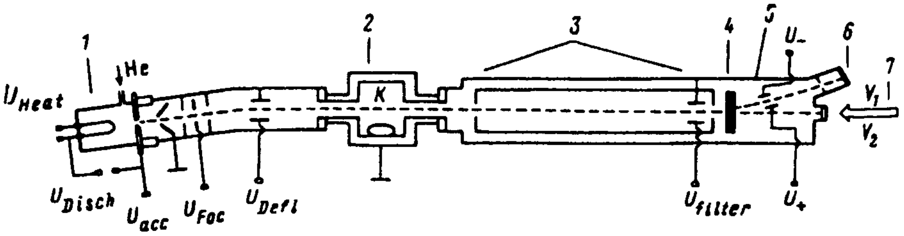

FIG. 1. Experimental apparatus. 1—Ion source; 2—charge-exchange chamber with potassium vapor; 3—region of laser excitation; 4—permanent-magnet ionizer of fast Rydberg atoms; 5—deflector; 6—ion detector (electron multiplier); 7—collinear laser light.

rule in terms of l for a fast atom, several low-lying Stark sublevels with $l>2$ can be excited along with the n^3D state by the laser light of the second stage, tuned to the atomic transition $3^3P\rightarrow n^3D$. The n^3S states for which the quantum defect is sufficiently high were excited in a strictly selective manner.

The fast Rydberg atoms which were prepared were ionized in the field of a permanent magnet with an effective length of 20 mm and a maximum field $B\simeq0.35$ T. This field corresponds to a Lorentz field $F\simeq1.5$ kV/cm. The ions which were produced were detected by an electron multiplier; the ions were deflected through a fixed angle to this multiplier. The distribution of the magnetic field in the ionizer was held constant during the experiments. Accordingly, to achieve further deflection of the ions formed during ionization of the Rydberg atoms to the slit of the ion detector, we used additional deflection in the electric field of a deflector placed between the ionizer and the detector (Fig. 1). The electric potentials U_- and U_+ $(U_+=-U_-)$ which had to be applied to this deflector depended on the main quantum number n, because Rydberg atoms with different values of n are ionized in different regions of the ionizer and thus deflected through different angles in the ionizer field.

In the experiments we observed photoion signals for Rydberg states with $n>22$. Figure 2 shows some recordings of the photoion signal. We see that there are two peaks in a plot of the photoion signal versus the voltage U_+ in the case of excitation of the n^3D states. In the case of excitation of the n^3S states, the signal has single peak, which coincides with the position of the first peak of the n^3D states.

Similar curves of the photoion signal were found in the same apparatus in the ionization of fast Rydberg helium atoms in an electric field transverse with respect to the beam axis.[8] The presence of two peaks is attributed to adiabatic and diabatic mechanisms for the ionization of a many-electron atom in a case in which states with an orbital-angular-momentum projection $|m|=0,1,2$ can be filled.[8,9] In the case of excitation of n^3S levels, only states with $|m|=0$ can be filled. Accordingly, the ionization goes predominantly by the adiabatic mechanism.[8,9]

An atom moving in a magnetic field is subjected to this magnetic field crossed with the Lorentz electric field. In first-order perturbation theory, the effect of these fields is determined by the linear Stark frequency $\Omega_S=1.5nF$ (a.u.) and the Larmor frequency $\Omega_L=0.5B$ (a.u.).[2] Under our conditions, the ratio of the two frequencies at $n=27$ is

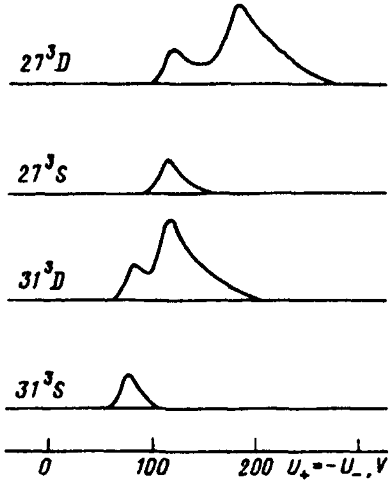

FIG. 2. Photoion signal versus the voltage on the deflector, $U_+=-U_-$, during laser excitation of various Rydberg states of the helium atom.

$\Omega_S/\Omega_L \simeq 16$. This circumstance apparently explains why the distributions of the photoion signals found in the different layouts for field ionization are similar.

In summary, it has been shown experimentally that a magnetic field can be utilized to detect fast Rydberg atoms in the method of collinear laser photoionization. There are two possibilities for reducing the collisional background,[7,8] which is a serious limitation. First, one might carry out an additional mass separation of the ion beam at the exit from an ionizer of this sort. This possibility is very pertinent to the detection and spectroscopy of very rare isotopes. Second, it might be wise to measure the energy of the ions at the exit from the ionizer, since atomic collisions occur as a result of a decrease in the kinetic energy.

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