Observation of two-photon potential scattering of Rydberg sodium atoms by a microwave field

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Scattering of Rydberg sodium atoms by a gradient potential of a microwave field has been observed experimentally for the first time. The field was at resonance with a two-photon transition between the 36*P* and 37*P* Rydberg states.

Interest in the ponderomotive effect of optical fields on heavy particles has increased sharply in recent years. There have been detailed studies of resonant radiation pressure, cooling, channeling, spatial trapping, atomic diffraction, interference, etc. (e.g., Refs. 1 and 2). The possibility of observing a scattering of highly excited atoms (Rydberg atoms) by a gradient potential was first raised in a previous paper[3] by the present authors. The potential would be formed by a standing millimeter-range electromagnetic wave. We showed that for Rydberg atoms (in contrast with ground-state atoms) a resonant potential due to a multiphoton interaction would be more effective. The scattering angle depends on the principal quantum number n of the lower level of the multiphoton transition of order i:

$$\theta \sim n^{5i-6}. \tag{1}$$

Experiments with Rydberg atoms are distinguished by a low probability for spontaneous transitions, which disrupt the coherence. At the same time, Rydberg atoms are exceedingly sensitive to electric fields and thermal radiation. Adding to the novelty of the situation is the large wavelength of the electromagnetic field, which is greater than the dimensions of the atomic beam.

These considerations make it a matter of particular interest to carry out a direct experiment to observe multiphoton potential scattering of Rydberg atoms.

Multiphoton transitions with $i=2$–4 from the 36*P* state of the sodium atom had been reliably observed in our previous studies (e.g., Ref. 4) on experimental apparatus for IR and microwave spectroscopy of Rydberg sodium atoms. Figure 1 shows the excitation spectrum of the two-photon transitions 36*P*–37*P* and 36*P*–36*F*, the three-photon transition 36*P*–38*S*, and the four-photon transition 36*P*–38*P*. This spectrum was recorded by scanning the frequency of the microwave source over the range 60–74 GHz. The width of the peaks is set by saturation and by the strong, field-induced broadening of all multiphoton resonances. After some refinements, the same apparatus could be used for a first experiment to observe a scattering of a beam of Rydberg sodium atoms in a layout like that described in Ref. 5.

As the working transition we selected the 36*P*–37*P* transition, the most intense two-photon transition, which we had studied in detail in Ref. 6. The 36*P* state was

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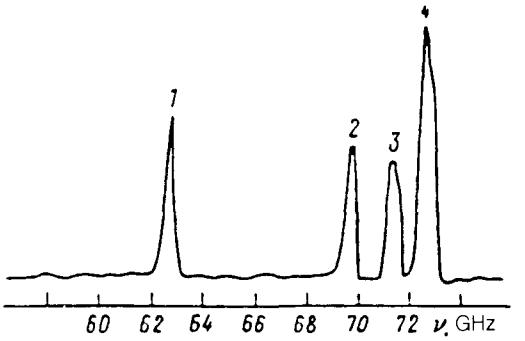

FIG. 1. Experimental spectrum of the excitation of multiphoton transitions from the $36P$ Rydberg state of the sodium atom caused by microwave radiation at an intensity of 4×10^{-4} W/cm^2. *1*—The $36P$–$36F$ two-photon transition; *2*—the $36P$–$38P$ four-photon transition; *3*—the $36P$–$38S$ three-photon transition; *4*—the $36P$–$37P$ two-photon transition.

selectively excited in the three-level scheme $3S$–$3P$–$4S$–$36P$ by the beams from three synchronized tunable pulsed lasers. These beams were focused into a vacuum chamber and were directed perpendicular to the thermal beam of sodium atoms ($T=500$ K). The millimeter-range radiation entered the chamber from the open end of a waveguide from a backward-wave-tube source tuned to the frequency $\nu=72.6$ GHz, which is at resonance with the $36P$–$37P$ two-photon transition. A spatially nonuniform field was produced by an interference of the incident microwave power with that reflected from the metal wall.

The divergence required of the atomic beam for these experiments, 5×10^{-3} rad, was set by two diaphragms 0.5 mm in diameter, one of which was near the beam source, while the other was 10 cm away from the first (Fig. 2). This second diaphragm served as the entrance aperture of the system for detecting the Rydberg atoms. The detection part of the apparatus was divided between two independent chambers. In the first chamber, the Rydberg states were excited, the interaction with the microwave

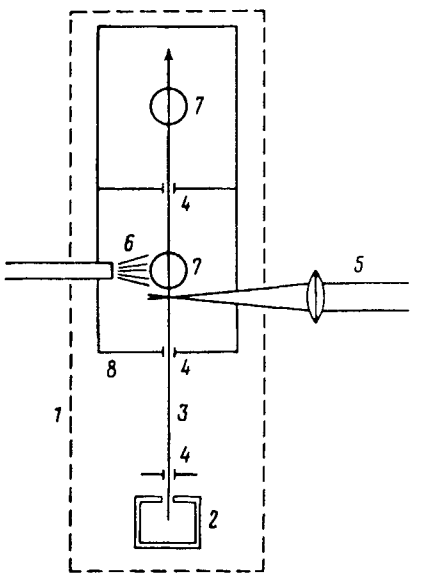

FIG. 2. Experimental layout. *1*—Vacuum chamber; *2*—beam source; *3*—beam of sodium atoms; *4*—diaphragms; *5*—laser radiation; *6*—microwave radiation; *7*—entrance windows of the channel electron multipliers; *8*—copper screen.

radiation occurred, and the tuning of the microwave frequency to the two-photon resonance was monitored by the method of selective field ionization. The electrons formed as a result of the ionization were detected by a channel electron multiplier, whose output signals were processed under pulse-counting conditions.

The atoms then passed through a third diaphragm, 0.5 mm in diameter, into the second chamber, where the total number of atoms in Rydberg states was determined by selective field ionization.

Both chambers were enclosed in copper shielding, cooled to 77 K in order to suppress the effect of thermal radiation on the lifetime of the Rydberg states. Under these conditions the lifetime of the $36P$ and $37P$ states was about 200 μs. The mean thermal velocity of the beam, which had a Maxwellian velocity distribution, was 600 m/s. The number of Rydberg atoms in the second chamber was detected at a delay of 70 μs with respect to the laser excitation pulse. Atoms with velocities from 680 to 800 m/s were detected. The total number of Rydberg atoms in the second chamber was measured with an accumulation time of 10 s, with subsequent statistical analysis and averaging. The electric field strength was selected to achieve complete ionization of the Rydberg atoms in all states.

It was found experimentally that an increase in the power of the microwave source leads to a decrease in the number of Rydberg atoms which enter the second chamber, because of a scattering of these atoms. According to our estimates in Ref. 3, the maximum scattering angle is given as a function of the microwave intensity I for the $36P$–$37P$ two-photon transition, for an interaction with the radiation lasting about 35 μs, by the relation

$$\theta \simeq 0.18I, \tag{2}$$

where I is expressed in W/cm^2. In our case the power density was about 20 mW/cm^2, so θ was no greater than 4×10^{-3}; this figure is comparable to the original divergence of the beam of sodium atoms. However, only an insignificant fraction of the atoms were scattered through this angle. Most of the atoms, as in experiments with atoms in the ground state,[5] should have been scattered through angles roughly an order of magnitude smaller, i.e., $\sim 5\times 10-4$ rad. Correspondingly, we should have observed a change in the signals governed by the ratio of this angle to the original divergence of the beam, i.e., $\sim 10\%$. This expectation was solidly confirmed by the experiment: The average value of the signal in the second chamber in the absence of microwave power was 12.4 ± 0.3, while that at the maximum microwave power was 10.1 ± 0.3. Each of these values is an average over 130 measurements. Upon increasing the size of the receiving diaphragm the control experiments showed that the effect disappeared, confirming that it is of a geometric nature. In further experimental studies of multiphoton potential scattering of Rydberg atoms, we suggest measuring the dependence of the scattering angle on the radiation intensity, measuring the scattering pattern of the beam atoms as a function of the gradient of the electromagnetic field, using multiphoton transitions of higher order and testing law (1), and determining the effect of electric fields and thermal radiation.

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