PHYSICAL REVIEW A VOLUME 21, NUMBER 1 JANUARY 1980

Energy analysis of the electrons ejected in the autoionization of the $Ba(6p_j20s_{1/2})_J$ states

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(Received 20 July 1979)

Analysis of the electrons ejected during the autoionization of the $Ba(6p_j20s_{1/2})_J$ states shows that for all but the $(6p_{3/2}20s_{1/2})_1$ state the electrons have ~2.5 eV of kinetic energy, implying autoionization to the ground $Ba^+6s_{1/2}$ state. However, in the autoionization of the anomalously wide $(6p_{3/2}20s_{1/2})_1$ state, roughly two-thirds of the electrons have an energy of 0.2 eV and one-third have an energy of 2.5 eV, implying that the anomalous width of the $6p_{3/2}20s_{1/2}$ state is due to autoionization to the excited $Ba^+6p_{1/2}$ state.

For many autoionizing states there exist several possible channels for autoionization; however, in most experiments it is difficult or impossible to determine the branching ratios for the different channels (or equivalently the final state of the resultant ion). With the recent interest in the development of short-wavelength lasers based on autoionization to excited ionic states[1] this problem has acquired a practical importance.

In a previous Letter,[2] we reported the observation of each of the four $Ba(6p_j20s_{1/2})_J$ levels in spite of the fact that, owing to autoionization, their widths are greater than their separations. Two very interesting features emerged in this work: the anomalous energy ordering of the J states as shown in Fig. 1 of Ref. 2 and the anomalous width of the $(6p_{3/2}20s_{1}/2)_1$ state, which has a width (FWHM) of 12 cm^{-1}, whereas the other three states have widths of 3 cm^{-1}. This led us to suggest that the excess width, 9 cm^{-1}, of the $(6p_{3/2}20s_{1/2})_1$ state might be due to a magnetic spin-other-orbit coupling of the two $J=1$ states, resulting in autoionization of the $(6p_{3/2}20s_{1/2})_1$ state to the $Ba^+6p_{1/2}$ state. Since this channel is not open to any of the other three states, such an explanation is appealing and completely consistent with the observations. However, we had no explicit evidence that the $(6p_{3/2}20s_{1/2})_1$ state autoionized to the $Ba^+6p_{1/2}$ state. Here we present explicit evidence that this is in fact the case.

The basic approach is the laser excitation of atoms in an atomic beam to the autoionizing $(6p_j20s_{1/2})_J$ states, followed by energy analysis of the ejected electrons. The relevant states for the laser excitation are shown in Fig. 1 of Ref. 2. By the appropriate choice of laser polarizations and wavelengths, we can populate separately each of the four $(6p_j20s_{1/2})_J$ states as described in detail previously.[2]

Energy analysis of the ejected electrons is a powerful technique for determining the final state of the ion, for conservation of momentum requires that virtually all the kinetic energy from autoionization go into the electron. Thus, if an atom in the $(6p_{3/2}20s_{1/2})_J$ state autoionizes to the $Ba^+6p_{1/2}$ state, the ejected electron will only have 0.2 eV of kinetic energy.

We have used a simple retarding-potential approach, shown in Fig. 1. The atomic beam passes midway between a grounded grid and a plate 1.12 cm apart, where it is excited by the lasers. The voltage on the plate is varied from +15 to −15 V to either retard or accelerate the electrons through the grid to the electron multiplier. The transmitting area of the grid is 2×3 cm, so the angular resolution is poor, leading to an energy resolution dependent on the energy of the ejected electron.

We scan the voltage on the plate and observe the

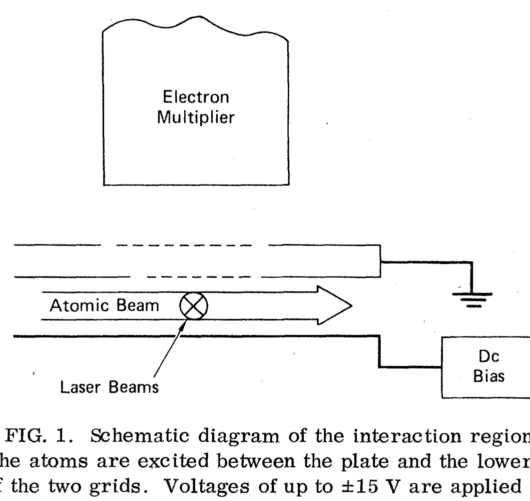

FIG. 1. Schematic diagram of the interaction region. The atoms are excited between the plate and the lower of the two grids. Voltages of up to ±15 V are applied to the plate to accelerate or retard the electrons' flight to the electron multiplier. The function of the upper grid is only to shield the interaction region from the +300 V on the face of the electron multiplier.

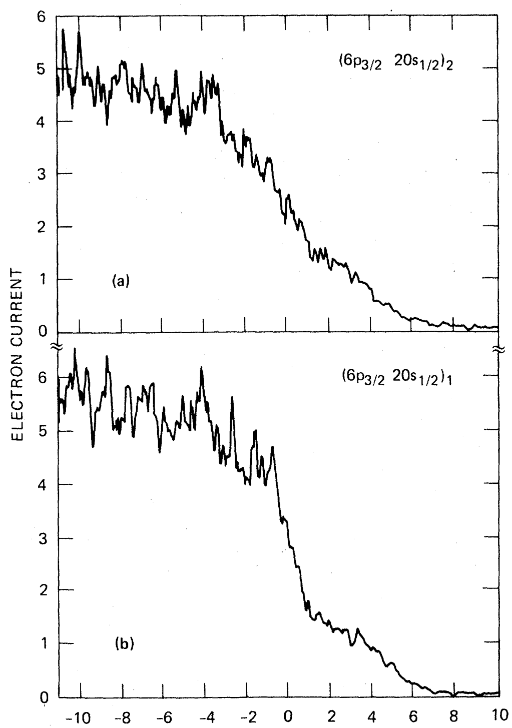

FIG. 2. Electron current vs retarding voltage: (a) for the $(6p_{3/2}20s_{1/2})_2$ state, showing one broad decrease in current, indicating ~2.5-eV electrons only; (b) for the $(6p_{3/2}20s_{1/2})_1$ state, showing a sharp decline superimposed upon the broad decline observed in (a), indicating both 0.2- and 2.5-eV electrons.

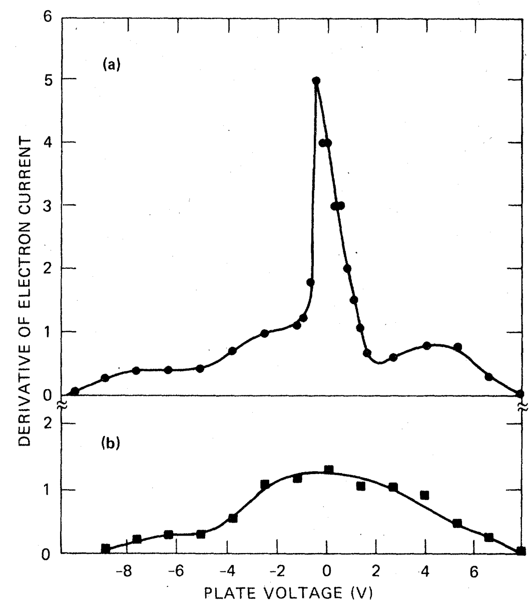

FIG. 3. Derivatives of Figs. 2(a) and 2(b) with respect to plate voltage: (a) for the $(6p_{3/2}20s_{1/2})_1$ state, showing clearly the broad and narrow features, indicating the presence of both 2.5- and 0.2-eV electrons; (b) for the $(6p_{3/2}20s_{1/2})_2$ state, showing one broad peak, indicating only 2.5-eV electrons.

electron signal. If, for example, the electrons are ejected with 2.5 eV of kinetic energy, we see a maximum plateau signal with −5 V (or a more negative voltage) on the plate which slowly decreases to zero at +5 V on the plate. Similarly, the signal from the 0.2-eV electrons will decrease from its plateau value starting at −0.5 V and reach zero at +0.5 V. In other words, the width of the drop in signal tells us the energy of the ejected electrons. While this is not the most elegant form of energy analysis, it is certainly adequate to distinguish between 0.2- and 2.5-eV electrons. It does not, however, permit us to discriminate between 2.5- and 1.7-eV electrons, which would be the result of autoionization to the Ba^+5d states. Thus, although we refer here only to autoionization to the 6s state of Ba^+, it is possible that autoionization the 5d states also occurs. However, on the basis of angular momentum considerations, this seems unlikely, but, in any event, it has no bearing upon the central result: that the Ba $(6p_{3/2}20s_{1/2})_1$ state does autoionize to the $Ba^+6p_{1/2}$ state, yielding 0.2-eV electrons.

The results of the experiments are shown in Fig. 2. In Fig. 2(a) we show a voltage scan for the $(6p_{3/2}20s_{1/2})_2$ state which shows a continuous decrease in signal from ~ −5 to +5 V, indicating that all the ejected electrons have ~2.5 eV of kinetic energy. When we repeat the measurement for the $(6p_{3/2}20s_{1/2})_1$ state, we see the curve of Fig. 2(b), with one component ~10 V wide and one component ~1 V wide, corresponding to the ejection of both 2.5- and 0.2-eV electrons. The $(6p_{1/2}20s_{1/2})_J$ states give signals similar to Fig. 2(a) implying that only ~2.3-eV electrons are ejected.

The scans of Fig. 2 are really integral signals, in the sense that the signal at any voltage represents those electrons which will be detected at that or a smaller retarding field. Thus it is helpful to display the derivative of the scans of Fig. 2 with respect to the retarding voltage.

The derivative plots are shown in Fig. 3. The widths of the observed peaks give the energies of the ejected electrons, and the areas under them give the branching ratios. The $(6p_{3/2}20s_{1/2})_2$ state leads to one feature 10 V wide shown in Fig. 3(b), indicative of only 2.5-eV electrons. The $(6p_{3/2}20s_{1/2})_1$ state has two clear features 1 and 10V wide, indicating 0.2- and 2.5-eV electrons, as shown by Fig. 3(a). Furthermore, in Fig. 3(b), about two-thirds of the total signal comes from the 0.2-eV electrons. If the excess width of the $(6p_{3/2}20s_{1/2})_1$ state is due totally to ionization to the $Ba^+6p_{1/2}$ state, we would expect the 0.2-eV electrons to compromise three-quarters of the total signal, in reasonable agreement with our measurement of two-thirds. Thus we conclude that the excess width of the $Ba(6p_{3/2}20s_{1/2})_1$ state is in fact due to autoionization to the $Ba^+6p_{1/2}$ state, as originally suggested.[2] Whether or not the details of the mechanism we suggested are correct remains an open question. We hope that this experimental verification of what was before only a suggestion will stimulate further thought.

ACKNOWLEDGMENT

We would like to acknowledge stimulating communications with R. Morgenstern in the course of this work. This work has been supported by the U. S. Department of Energy, Office of Basic Energy Sciences.

[1]S. E. Harris (private communication).
[2]W. E. Cooke and T. F. Gallagher, Phys. Rev. Lett. 41, 1648 (1978).