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Relative charge transfer cross section from Rb(4d)

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Relative charge transfer cross section measurements for the excited state Rb(4d) with 7 keV Na+ is reported. The specific channels reported are Na+ + Rb(4d3/2) → Na(nl) + Rb+, where the dominant transfer cross sections channels were nl = 3d and 4s. Using a combination of a magneto-optical trap and recoil ion momentum spectroscopy (MOTRIMS methodology), the cross sections were measured relative to the previously studied Na+ + Rb(5s, 5p) systems at the same collision energy.

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During ion atom collisions, processes such as ionization, charge transfer, or excitation can occur. These processes may strongly depend upon the collision energies. At higher energies excitation and ionization are more probable processes, whereas at low energies charge transfer is the dominant process. Several decades ago, a considerable amount of charge transfer cross section studies involving alkali ions and atoms [1] have already been done experimentally as well as theoretically. However, these studies were carried out on ground state targets. In the relatively few studies on excited targets, most of these have been on simple, i.e., one-photon excitation, systems. Furthermore, only rarely have the final states of the charge transfer products for these systems been determined.

Charge transfer cross section measurements are vital for extracting information from many new experiments, for example the measurement of population dynamics in a magneto optical trap, coherent excitation schemes, and molecule formation in cold collisions between excited collision partners [2,3]. It is also essential for the development of new theoretical models for more complicated but realistic systems. Scattering experiments, differential in initial and final states, are therefore crucial for the verification and future predictions of theory.

In the present work, a scattering experiment between neutral, excited atoms and singly charged alkali ions has been carried out at low collision energy. Making these measurements is the first step in a series of experiments that include stimulated Raman adiabatic passage (STIRAP) and laser induced population dynamics [3].

The methodology used in this experiment is referred as MOTRIMS; details of the apparatus can be found elsewhere [4]. Briefly, it consists of the combination of a magneto-optical trap (MOT) and the well known RIMS (recoil ion momentum spectroscopy) methods [5–7]. MOT technology enables the atoms to be cooled down to the hundreds of micro Kelvin scale, reducing the momentum spread of the target by a factor of about thirty compared to other RIMS techniques. The RIMS methodology consists of electrostatically extracting recoil ions created in ionization collisions and measuring their three dimensional momentum vector through time of flight and 2D position sensitive detector (PSD) techniques.

A salient feature of MOTRIMS is the high resolution in Q value, i.e., the difference in energy between initial and final states of the collision partners. The Q value is directly deduced from the component of momentum lying along the collision axis. Data are extracted ion by ion in “event mode” [4] with better than 2 nsec temporal resolution [5].

FIG. 1. (Color online) Typical plot of Q value vs laser timing. The captured from Rb(4d) is seen when Stokes is on.

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FIG. 2. Typical plot of $Q$ value vs counts. The peak labeled 1 is capture from Rb(5s) of the target to the Na(3p) of the projectile, $\langle 5s \rightarrow 3p \rangle$. Peaks 2–5 are $(4d \rightarrow 3d)$, $(4d \rightarrow 4s)$, $(5p \rightarrow 3p)$, and $\langle 5s \rightarrow 3s \rangle$, respectively.

Specifically, the target under investigation is $^{87}$Rb, trapped and cooled to $\sim 130$ $\mu$K using two 780 nm diode lasers. The “master” laser is tuned to the red of the $5S_{1/2}, F = 2$ to $5P_{3/2}$, $F = 3$ transition, while the “repump” is tuned to the $5S_{1/2}, F = 1$ to $5P_{3/2}$, $F = 2$ transition. A third laser, at 1529 nm, is used to further excite the target to the desired Rb$^{+}$ state. This “Stokes” laser is tuned into resonance by using an acousto-optical modulator (AOM), which also chops the Stokes laser with a 25% on and 75% off duty cycle, having an on time of 1.25 $\mu$sec. The 7 keV Na$^+$ beam, with a typical current of 150 pA, is directed through the cloud of target atoms. Following a charge transfer collision the neutral Na atom hits a 2D-PSD starting a time-digital converter (TDC). This is the time of flight information from which the $Q$ value is deduced. A time-amplitude converter (TAC) was started by a signal synchronized to the AOM, and stopped by the detection of a neutral projectile. The TAC output was sent to the analog-digital converter (ADC) of the data acquisition system which provides a signal related to the laser status at the time of collision. A plot of laser timing (TAC output) versus $Q$ value is shown in Fig. 1.

As it has already been demonstrated [2], chopping of the Stokes laser is essential for the relative cross section measurements. During the Stokes “on” time a fraction of the atoms is in the 4$d$ state. Hence, charge transfer takes place from each of 5$s$, 5$p$, and 4$d$ states of the target when the Stokes is on, as shown in Fig. 2. The area under a peak is proportional to the product of the capture cross section, $\sigma$, and, $n$, the number of atoms in the target state. That is, $A \propto \sigma n$, where the constant of proportionality contains acquisition time and geometric factors. Because the total number of trapped atoms is constant during the 5 $\mu$sec measurement period, a comparison of capture rate with the Stokes laser on and off gives the relative cross section for capture from Rb(4$d$) via [2]

$\frac{\sigma_2}{\sigma_1} = -\Delta A_k \left( \sum_{i=1}^{k-1} \Delta A_i \frac{\sigma_i}{\sigma_f} \right)^{-1}$  \hspace{1cm} (2)

Here $\Delta A_k$ refers to the difference in areas under the $k$th $Q$-value peak when the Stokes laser is turned on and off. The term $\sigma_i/\sigma_f$ is sequentially determined for all $i \leq k$ by interactively using the above equation.

In the present work, the subscripts 1, 2, 3 refer to Rb(5$s$), Rb(5$p$), and Rb(4$d$), respectively. The ratio $\sigma_p/\sigma_s$ has already been measured. It has the value 11.29±0.66 which was found to be in excellent agreement with theory [8]. For the 3-level system under discussion here, the above equation can be written more intuitively as

$$\frac{\sigma_d}{\sigma_s} = -\frac{\Delta A_d}{\Delta A_s + \Delta A_p \frac{\sigma_i}{\sigma_f}}.$$  \hspace{1cm} (2)

Hence, measuring the differences $\Delta A_d$, $\Delta A_p$, and $\Delta A_s$, as the Stokes laser is chopped, directly gives the relative cross section for capture from the 4$d$ state without ever measuring the fraction of atoms excited into that or any other state.

From the $Q$-value spectrum in Fig. 2 it is evident that Na(3$d$) and Na(4$s$) are the dominant product states after charge transfer from Rb(4$d$). Measured cross sections for these channels relative to the ground state are given in Table I. The error estimate includes the published uncertainty in $\sigma_p/\sigma_s$. The dominant systematic error is due to the background subtraction before fitting the peaks to Gaussians.

The data have not been compared with theory as, to our knowledge, no theoretical work is available in the literature. In summary, we have measured the relative cross sections for charge transfer from excited Rb(4$d$) in collision with Na$^+$, differential in final state. In the future, the cross section measurements will be extended to Rydberg states.

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