Excitation of Light in Hydrogen and Helium by Hydrogen Ions*

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The light excited when protons or H_2^+ ions pass through hydrogen or helium with kinetic energies of 2000 ev has been observed. Contamination of the beam by stray particles has been eliminated by electrostatic deflection and magnetic mass separation. The light is almost entirely due to the Balmer spectrum. Relative cross sections for the excitation of H_α by protons and H_2^+ impinging on H_2 and He have been determined.

I. INTRODUCTION

THE excitation of light by *proton impact* is of interest for the comparison with excitation by *electron impact* and with the results of wave mechanics, and for the explanation of the aurora, whose primary excitation is due to a beam of ionized atomic hydrogen ejected by the sun. In the aurora[1] and in laboratory experiments in which protons of several hundred kev are shot into nitrogen[2] the emission of the Balmer spectrum indicates the presence of neutral atoms. Apparently charge exchange occurs, leading either directly to excited atoms or else to normal atoms which are excited by subsequent collisions.

Basic theoretical work on the cross sections for inelastic collisions between ions and neutral atoms has been confined to the interaction of protons with helium, because of the difficulty of the calculations for more complex colliding systems. Cross sections have been calculated for charge exchange collisions between protons and helium atoms in which the hydrogen atom is formed in the ground state[3] or the 2*s* state,[4] and for the excitation of the $2\,^1P$ state of helium.[3] Theoretically, triplet states of helium should not be excited at all, because of the rule of spin conservation. These calculations are for energies of a few hundred to a few thousand electron volts. On the other hand, for high-energy protons passing through helium, Bransden, Dalgarno, and King[5] developed a theory based on a modified Born approximation.

In recent experiments Stedeford and Hasted[6] measured the charge exchange between protons of 0.1 to 40 kev and various gaseous atoms and confirmed the general predictions expressed by the "adiabatic hypothesis" of Massey.[7] They found good agreement of their results with the theory just referred to in the energy range above 30 kev.

Experimental observation of the light excited by low-energy protons has been obstructed by the difficulty of eliminating stray particles contaminating the ion beam or by uncertainty regarding the identity of the ion exciting the observed light. Any particle, such as a neutral hydrogen atom or a molecular ion, having circumnuclear electrons is much more efficient than a bare proton in exciting gas atoms and in producing the Balmer spectrum. It is the difficulty in eliminating such stray particles from the beam which has hampered previous investigators.[8–10] The present paper is concerned with the light emitted by helium when bombarded by 2000-ev protons.

II. APPARATUS

The apparatus used in this experiment is shown schematically in Fig. 1. Hydrogen ions are formed in the ion source and are extracted with a kinetic energy of 2000 ev through a small canal into a high vacuum maintained in the main vacuum chamber. As they enter the chamber, the ions are made parallel by the first electrostatic lens and deflected by the first set of electrostatic deflection plates. A uniform magnetic field perpendicular to the plane of the figure is maintained in the magnetic deflection region; this field separates the ions in accordance with their mass. Ions of a certain mass, determined by the electrostatic deflection angle, return to the axis of the system so as to be

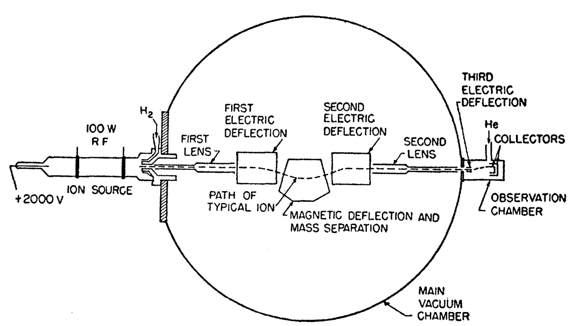

FIG. 1. Excitation of helium by H^+ or H_2^+.

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deflected by the second set of electrostatic deflection plates and focused by the second electrostatic lens onto the entrance aperture of the observation chamber, where the ion current is collected and measured by the collector electrodes. The path of ions of the selected mass is indicated by the heavy dashed line.

The gas to be studied is admitted to the observation chamber from a reservoir through a capillary leak, at a pressure measured by an ionization gauge. A window in the top of the observation chamber permits the observation of the light excited along the length of the beam by impacts of ions with gas molecules. Discrimination against stray light excited by neutrals is improved by bending the ion beam with the third set of deflection plates, within the observation chamber.

The ion source is of a type devised at Oak Ridge for use with a Cockcroft-Walton accelerator.[11] For this experiment, ions were extracted at 2000 v, which severely limited the ion current obtainable. A current of approximately 10 μa of protons, 5 μa of H_2^+, or 2 μa of H_3^+ could be collected in the observation chamber. The contamination of the proton beam by molecular ions was less than one part in 10^4; there is no evidence of any contamination of the proton beam by high-speed neutral particles ejected from the ion source.

Both hydrogen and helium were studied as target gases. The helium was admitted from the reservoir and maintained at a pressure of about 25 μ. Hydrogen was present as an undesired contaminant at a partial pressure of 0.6 μ, owing to diffusion through the aperture from the main vacuum chamber. Some observations were made with hydrogen alone in the observation chamber by turning off the helium supply.

II. RESULTS

In the observation chamber the ion beam was sufficiently well collimated to be observed as a line-source of light with a slitless spectrograph, in the manner of earlier observers.[8] The deflection plates within the observation chamber permitted discrimination between effects due to ions and those due to neutrals formed just inside or just outside the observation chamber. Just as the spectral lines formed in an ordinary spectrograph are images of the slit in light of various wavelengths, so in this apparatus the plate receives the various monochromatic images of the entire observation chamber at positions determined by the wavelength and dispersion. When both ions and neutral particles in the beam are responsible for the production of light, a characteristic forked trace is produced when voltage is applied to the deflection plates during an exposure.

Spectrograms were taken of 2000-ev H^+ and H_2^+ ions in hydrogen and in helium heavily contaminated by hydrogen, using a Kipp liquid prism spectrograph with an $f/2$ camera and Eastman 103a-F spectroscopic plates, prefogged for additional sensitivity with an apparatus constructed by Branscomb.[12] In these experiments, in which a proton or H_2^+ beam was shooting into He, hardly any excitation of He occurred. Instead, the Balmer spectrum was the predominant feature of the spectrograms. In one exposure the helium line, λ5876, was observed, excited by H_2^+, and on another plate there appeared a line attributed to the (0,1) band of the main system of N_2^+ excited by the proton beam.

TABLE I. Relative cross sections for the excitation of H_α by H^+ and H_2^+ colliding with He or H_2.

Ion \ Gas	He	H_2
H^+	1	30
H_2^+	60	60

By making several exposures of different durations on one plate, with various combinations of target gas and ion, it was possible to compare the exposure required to obtain the same photographic density from the light produced by different processes. Care had to be taken to correct for reciprocity law failure, for variation in beam current and gas pressure, and, in case helium was the target gas, for the presence of residual hydrogen. In this manner relative values were obtained for the cross sections for the excitation of the Balmer line H_α by protons and H_2^+ colliding with molecules of hydrogen and helium, as indicated in Table I. The uncertainty of these values is estimated to be a factor of three

In summary, fast protons passing through helium gas are much less effective in exciting the helium spectrum than they are in producing the Balmer spectrum in a charge-exchange process. H_2^+ ions of the same energy produce the Balmer spectrum with even greater intensity, apparently by a process of dissociative excitation. In addition they are responsible for weak excitation of He atoms.

The experimental work will be continued.

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