EXPERIMENTS ON ELECTRON-IMPACT EXCITATION AND IONIZATION OF IONS

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1. INTRODUCTION

The challenge of understanding the characteristics and behavior of the so-called fourth state of matter, the ionized plasma, requires quantitative information on both the structure and collisional properties of ions. The simple glow-discharge tube, the laboratory ion source, the controlled-thermonuclear fusion plasma, the ionosphere, the solar corona — they all share one common attribute — their microscopic and macroscopic properties are controlled to a large degree by inelastic collisions between electrons and ions. The delicate balance produced by the continual interchange of kinetic, radiative and potential energy determines the signature by which such a plasma communicates with its surroundings, namely the light it produces. For even the simplest of plasmas, the interpretation of the spectrum of radiation which is emitted requires detailed knowledge of both the electronic structure of the ionic species present, and of the collision processes by which these ions reach and leave the excited ionic states from which the radiation occurs. At higher particle densities, the transport of radiation within the plasma must also be taken into consideration.

The quantitative study of inelastic collisions between electrons and ions has been motivated for many years by the astrophysical community. The need for accurate collision cross sections has been dramatically intensified during the last decade by the worldwide emphasis on controlled-thermonuclear-fusion research, and its development as a potential energy source. The energetic radiation from highly ionized impurities in such high-temperature plasmas represents a serious mode of energy loss which has thus far prevented such devices from reaching the required ignition temperature (kT ≥ 10 keV) and confinement condition (nτ ≥ 10^{14} cm^{-3}s). The effect of impurity ions on plasma confinement is also poorly understood, and may perhaps even be beneficial under certain circumstances [1]. Accurate models for plasmas require reliable cross section data for electron-impact excitation, ionization and recombination of these impurity ions.

Since the pioneering intersecting-beams experiments of Dolder, Harrison and Thonemann [2] in 1961 on electron-impact ionization, and of Dance, Harrison and Smith [3] on electron-impact excitation in 1966, considerable progress has been made in electron-ion collisions, particularly...
in the case of ionization. This careful early work set a high standard for research in the field, and it is interesting to note that despite significant refinements in such areas as detectors, optical calibration standards, data acquisition, computer control and ion sources, the basic methodology of these experiments remains unaltered. Useful data have been produced by other techniques, such as monitoring spectral-line emission from magnetically confined plasmas [4], or by storing ions in a trap [5], but it is generally accepted that the colliding-beams method is capable of producing the most definitive basic data, since all the important parameters may be directly measured, and diagnostic checks performed. Such techniques form the subject of lectures to be presented at this Advanced Study Institute by P. Defrance and will therefore not be addressed here, except for purposes of categorization of experiments. Similarly, the theory of excitation and ionization of ions will be discussed in detail in the lectures of M. S. Pindzola and D. L. Moores and will not be addressed here per se.

The subjects of electron-impact excitation and ionization of ions have been comprehensively reviewed by D. H. Crandall [6] and E. Salzborn [7], respectively, at the preceding NATO Advanced Study Institute on this same topic, held at Baddeck, Canada, in 1981. Useful reviews have also been given at two other NATO Advanced Study Institutes on related themes by Dolder [8] on excitation and ionization of positive ions, and by Crandall [9] on collisions of electrons with multiply charged ions.

The present report will review some of the fundamental aspects and then focus on highlighting some of the important experimental results which have been produced during the interim period.

2. ELECTRON-IMPACT EXCITATION

2.1 Fundamentals

2.1.1 Threshold Behavior

The cross section for excitation of an ion by a free electron has the distinct characteristic of being finite, and often having its maximum value, at the threshold electron energy for the process. This threshold corresponds to the difference in energy between the initial and final ionic states. This is in contrast to that for excitation of a neutral atom, which rises from zero at threshold. The characteristic for ion excitation can only be accounted for quantum-mechanically and is a consequence of the Coulomb attraction between the electron and the ion. In this near-threshold region, resonances often play an important role in the excitation process and must be taken into account in accurate theoretical predictions of the cross section. At asymptotically high energies, perturbation methods generally give an accurate account of the cross section. Thus, ion excitation by electrons is most important in the energy region where theory is most difficult and least reliable. Accurate experimental data are needed near threshold to benchmark the calculations.

2.1.2 High-Energy Behavior

At high collision energies (i.e., above roughly ten times the excitation threshold), the energy-dependence of the cross section is well-defined and depends on the specific type of excitation process.