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The Interactions of Fast Molecular-Ion Beams with Matter

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The Argonne 4.5-MV Dynamitron accelerator is used to study the dissociation and other interactions of fast molecular ions incident upon thin (~100Å) foils and gaseous targets. Molecular-ion species employed thus far range from H_2^+ up to CO_2^+. A unique feature of the apparatus is that it permits exceptionally high-resolution (~0.005° and ~300 eV) measurements of the distributions in angle and energy for particles emerging downstream from the target.

The work has two major objectives: (a) a general study of the interactions of fast charged particles with matter, but with the emphasis on those aspects that take advantage of the unique features inherent in employing molecular-ion beams (e.g., the feature that each molecular ion incident upon a solid target forms a tight cluster of atomic ions that remain correlated in space and time as they progress through the target) and (b) a study of the structures of the molecular ions that constitute the incident beams. These two aspects of the work are mutually interdependent. In order to derive structure information about a given molecular ion, one needs to know details about the way the dissociation fragments collectively interact with the target in which the dissociation occurs. Similarly, a knowledge of the structure of the incident molecular ions is important in understanding the physics of their interactions with the target.

We report briefly on the following topics that have constituted the main thrust of our work over the past year:

(1) Contribution of Field-Ionized Rydberg Atoms to Convoy Electron Spectra

In an effort to explain some puzzling features of molecular-ion dissociation experiments which had suggested the production of large numbers of high Rydberg atoms in fast beams, we tried to determine the extent to which the presence of significant numbers of such atoms could be affecting observations of cusp electrons. We have demonstrated large yields of high Rydberg atoms formed in foil-excited fast ion beams.

We have further studied the systematics of this phenomenon with various ion beams (both atomic and molecular), targets, beam energies, and experimental geometries. Quite recently, we extended these measurements to include highly energetic heavy-ion beams. Using the Argonne Tandem-Linac heavy-ion accelerator, we studied the field-ionization of high Rydberg (n > 300) sulphur ions produced by beam-foil excitation of a 125-MeV sulphur beam. That experiment conclusively demonstrated a very high yield of such atoms as had been suspected from previous studies of the delayed x-ray emission of these fast heavy ions.

(2) Microwave Field Ionization of Fast Rydberg Atoms

In an attempt to determine the quantum-state populations for beam-foil excited high Rydberg atoms, we collaborated with a group from Yale University in studying the microwave ionization of such atoms. This experimental geometry separates the ionizing field from the analyzing field, allowing us to vary the former to much higher values than we had been able to achieve before. With a microwave power of 18.4 watts, we achieved a maximum electric field of about 2.8 kV/cm, sufficient to ionize hydrogen atoms as low as n = 24 (see Fig. 1). Analysis of the data to date seems to indicate that the n-population is consistent with a simple OBK-type last-layer capture process. It is hoped that the detailed information about the distributions of kinetic energies of the electrons which we observe will yield a better understanding of the microwave ionization process.

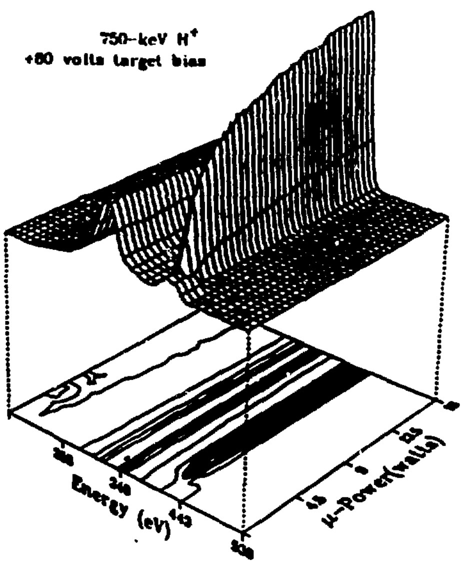

Figure 1: A joint distribution of 0° electrons showing energy spectra for various levels of microwave power (watts). The lower-energy peak, unaffected by microwave power, is caused by convoy electrons. The higher-energy peak, which grows with power, is produced by field-ionization of Rydberg atoms in the microwave cavity. At low power, there is an additional contribution from atoms ionizing in the spectrometer field (170 v/cm).

(3) Coherent Stark States in Foil-Excited Fast Rydberg Atoms

We also studied the field-ionization of fast Rydberg atoms in a variety of static field geometries. One finding is that transverse electric fields are more effective in ionizing such atoms than are longitudinal fields. This is a strong indication of high alignment in the excitations, suggesting an electron density in these states which is oblate with respect to the beam direction. A very surprising finding was the observation of oscillations in the ionization yield when a longitudinal electric field, starting at the target, is varied in magnitude. These oscillations are regularly spaced, with a period which varies with the beam energy. We have demonstrated that these observations imply coherent excitation of a few Stark levels near the unshifted center of the Stark manifold. The observed modulations are extremely sensitive to the amplitudes of the coherently excited states. This phenomenon offers a new and potentially powerful technique for studying excitation mechanisms that produce high Rydberg states of fast projectiles as they exit solids.

(4) Equilibration Lengths of K-Vacancy Production in Solids

Measurements on the angular distributions of fast ions traversing foils have shown a pronounced dependence of the multiple-scattering widths upon the charge state of the emerging ions. We have successfully explained these results in terms of the large scattering angles achieved by those ions that bear K-vacancies. A quantitative model has been developed which demonstrates how the "memory" of K-vacancy producing collisions gives rise to large multiple-scattering widths in spite of apparent charge-state equilibration. The K-shell capture and loss cross sections are an important input to this model. Because these cross sections are largely unknown, we conducted a series of experiments to determine the K-shell charge-exchange equilibration lengths for fast ions in foils. By measuring the yield of KLL Auger electrons from 0.4- and 2.7-MeV N^+ ions exiting solid carbon targets, we demonstrated that indeed the K-equilibration lengths are longer than had been previously assumed, confirming our model of the multiple scattering data.

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