CONF 870701--10

Introductory Review: Physics of Electron Slowing-Down Processes*

CONF-870701--10

DE88 002918

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BACKGROUND

In any material subjected to any ionizing radiation there appear numerous electrons, which frequently play a dominant role in the initial stage of radiation action. Under γ-ray or x-ray irradiation, electrons are produced through the Compton effect, the photoelectric effect, and the Auger effect. Under irradiation with charged particles, secondary electrons are abundantly generated. In general those electrons have kinetic energies distributed over a wide range, characterized with a continuous spectrum with some discrete lines.

The energetic electrons travel through the material, collide with atoms and molecules, thereby give up a part of kinetic energies to them, and thus slow down. Often, an electron collision results in the ionization of an atom or molecule, and thus new secondary electrons emerge; they join in the slowing-down process. It has long been recognized that the energetic electrons are the major agent for the production of ions, excited states, dissociation fragments, and other reactive species that lead to the initiation of chemical effects, when in turn lead to biological effects. Among the initial species there are also subexcitation electrons, viz., those electrons which

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*Work supported by the U.S. Department of Energy, Office of Health and Environmental Research, under Contract W-31-109-Eng-38.

have kinetic energies lower than the threshold of electronic excitation of the major component of the material. The subexcitation electrons slow down at a modest rate, by giving up energies to translation, rotation, and vibration of molecules. Eventually they are thermalized or localized (by electron capture or solvation). Full description of the electron slowing-down process (or electron degradation process) is a key subject in radiation physics. [See Platzman (1967), Inokuti, (1983), and Gunther and Schulz (1983) for further discussion.] Knowledge of this subject is fundamental both to dosimetry and to microscopic analysis of mechanisms of radiation effects. Indeed, microdosimetry, track-structure theory, and other modeling studies familiar to radiation research all refer to electron slowing-down processes, at varying degrees of depth and detail.

SELECTED TOPICS

The present Symposium treats several selected topics from the physics of electron slowing-down processes. From a vast range of possibilities, I have selected those topics which are new in physics and do not seem to have been fully incorporated into the general culture of the radiation-research community. There topics are in part theoretical and in part experimental, should convey a sense of rich physics involved, and should also stimulate radiation researchers to think about many possibilities of applications.

Dillon's lecture concerns with a new development in the electron degradation theory. The well-known theory of Spencer and Fano (1954) provides a general framework for calculating the energy distribution of all the electrons (in all generations) present in a material under stationary irradiation. The energy distribution is characterized by the degradation spectrum or the track-length distribution. From its knowledge one can calculate the yields of ions, excited states, and other initial species as well as the statistical fluctuations of those yields.

The new generalization of the Spencer-Fano theory shows how to treat the time-dependent aspects of the degradation spectrum and the yields of ions and other species in a material subjected to a time-dependent radiation source such as a short pulse of energetic particles used in pulse-radiolysis experiments. Indeed, the work was prompted by such recent experiments [Cooper et al. (1982)] that reported the temporal behavior of fluorescence from well-identified excited states in gases after a short-pulse irradiation. These experiments unequivocally showed the role of subexcitation electrons in exciting solute or impurity molecules. Calculations [Dillon et al. (1988)] by use of the generalized Spencer-Fano theory gave results in excellent agreement with experiments.

Sanche's lecture summarizes a series of numerous experiments by his group on the behavior of electrons in solid films. These experiments represent a feat in current experimental physics. Until a decade or so ago, quantitative measurements on the behavior of slow electrons (i.e., electrons at kinetic energies below a few tens of eV) had been virtually non-existent. Fully using recent advances in electron optics, vacuum techniques and surface science, Sanche and co-workers conduct measurements, and their results are now filling gaps of our knowledge. Their experiments use a beam of electrons having a selected range of energies within 5-40 meV. Targets are thin films (1-20 nm in thickness) of materials condensed from the gas phase on a metal surface at cryogenic temperature in an ultra-high vacuum chamber. Materials studied include water, organic hydrocarbons, and other molecular substances. Transmitted or reflected electrons are analyzed in angle and energy at high resolution, at varying energies of the incident electron beam.

Results are rich in implications to both basic physics and applications. In particular, they show similarities of energy-losses in condensed matter to those in the gas phase in certain respects, and at the same time point to notable differences between condensed matter and the gas phase in other respects. Recognition of these similarities and differences is essential in the realistic modeling of track structures and other studies.

Tougaard's lecture treats another avenue of attack to the elucidation of the electron behavior in solids, i.e., analysis of the energy spectra of electrons ejected from solid surfaces, resulting from the photoelectric effect, charged-particle impact, or ensuing Auger effects. In general, those ejected electrons originate from a thin layer of atoms near the material surface, but experience various interactions before emerging from the surface and being analyzed eventually. Therefore, the energy and angular distribution of those ejected electrons carries information about those interactions, e.g., cross sections for elastic and inelastic scattering. In collaboration with P. Sigmund and others, Tougaard carries out ingeneous analyses of the electron transport and thereby extracts a great deal of cross-section data.

Results are in part compared with theoretical evaluations based on dielectric-response functions, and are in part applied to calculations of the electron degradation spectra. The work by Tougaard and others complements the work by Sanche and others in two respects. First, Tougaard and others primarily concern electrons of higher energies, i.e., 100-2000 eV. Second, materials studied are metals and inorganic solids. Knowledge of electron interactions in these materials are crucial to radiation dosimetry and instrumentation and are also essential to the basic understanding of physics as well as to applications such as electronic devices and surface technology.

CONCLUDING REMARKS

The foregoing topics represent only a few examples in the rich physics related to electron slowing-down processes; certainly, there are many other important areas that we could have reviewed. In conclusion, it is worthwhile to recall two general issues involved in the subject: the cross-section determination for individual collisions, and the transport analysis of the consequences of many collisions to the electron behavior and to the state of the material. The cross-section determination is intrinsically related to the electronic structure of atoms, molecules, and solids. The transport analysis is a branch of statistical physics and chemical kinetics. The distinction between the two general issues is sometimes clear-cut, but is sometimes intricate, e.g., in the consideration of slow electrons in condensed matter as discussed by Sanche. Consequently, full elucidation of electron slowing-down processes requires a wide perspective over many branches of physics, both experimental and theoretical.

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INDEXING TERMS

physics
electron slowing-down
electron degradation
cross section
transport theory