MEETING REPORTS

NATO ADVANCED STUDY INSTITUTE ON ATOMIC AND MOLECULAR PROCESSES IN CONTROLLED FUSION, PALERMO, ITALY, JULY 19-30, 1982

The purpose of the North Atlantic Treaty Organization (NATO) Advanced Study Institute on Atomic and Molecular Processes in Controlled Fusion was to bring together students and research workers in both atomic physics and fusion research (for both inertially and magnetically confined plasmas) and to provide them with a set of survey lectures on the role of atomic physics in fusion. The program consisted of lectures by senior fusion research workers on the general nature of fusion research (elementary plasma physics and fusion physics, status of experiments, etc.) and on how atomic processes affect fusion experiments, survey lectures by senior research workers in atomic physics discussing theoretical and experimental methods for providing the atomic data of use to the fusion community, and seminars by the conference participants on research topics of current interest. There were 88 participants from 12 countries at the conference. The survey lectures will appear in a book entitled *Atomic and Molecular Physics of Controlled Thermonuclear Fusion*, edited by C. Joachain and D. Post, and published by Plenum Publishing Company as part of the NATO Advanced Study Institute Series B: Physics.

Atomic processes impact fusion research in basically four areas: the central plasma in which the fusion reactions are to occur, the boundary region where the plasma comes into contact with a wall or other solid material, plasma heating, and plasma diagnostics. In magnetically confined plasmas, the major influence that atomic processes have on the central plasma is fueling through charge-exchange of protons and hydrogen atoms and energy losses due to line radiation from impurity ions. Understanding the basic atomic physics of multiply charged ions is, therefore, important. The greatest hope for reducing or eliminating the impurity radiation is through control of the plasma/wall interface that is the source of the impurities. Atomic and molecular processes play an important role in determining the edge plasma parameters.

To a very large extent, tokamaks and mirrors owe their successes in the 1970s to neutral beam heating, and atomic processes play a large role in the production and stopping of neutral beams. About one-half of all plasma diagnostics relies on atomic processes.

In research on inertially confined plasmas, atomic processes play a key role in the central plasma since the pellets to be imploded contain materials with $Z > 1$. Equation-of-state data and opacities are crucial to understanding the pellet implosion hydrodynamics. The atomic physics of dense matter ($n_e \gtrsim 10^{25}$ cm^{-3}) is an exciting new area. The interaction of the pellet debris is a second crucial area involving atomic physics. Both the construction of drivers (lasers, light ion, and heavy ion) and the interaction of the driver with the pellet ablation layer involve atomic physics, and, as in magnetically confined plasmas, many diagnostic measurement techniques rely on atomic physics. Thus atomic processes play an important role in fusion research.

The conference began with an overview of fusion research presented by G. Grieger (Garching). Then the general principles of magnetic fusion and inertial fusion were discussed respectively by J. Hogan [Oak Ridge National Laboratory (ORNL)] and R. Haas [Lawrence Livermore National Laboratory (LLNL)]. Then 12 topics in atomic physics and the applications of atomic physics to fusion were covered in some detail. There were four lectures on theoretical methods in atomic physics. C. Joachain (Brussels) discussed recent developments in theoretical methods, M. R. C. McDowell [University College (UC) London] surveyed electron impact collisions, B. Bransden (Durham) lectured on charge-exchange and ionization by heavy particles, and G. Ferrante (Palermo) covered collisions in intense electromagnetic fields. On the experimental side of atomic physics, K. Dolder (Newcastle) discussed electron collisions (excitation and ionization), F. DeHeer [Institute for Atomic and Molecular Physics (FOM), Amsterdam] covered charge-exchange and ionization by heavy particles, and F. Brouillard (Louvain-la-Neuve) surveyed Rydberg states and dissociation.

Six lectures were given on the role of atomic processes in fusion research. H. Drawin (Fontenay-aux-Roses) covered both spectroscopic diagnostics and the general role of atomic processes in high-temperature, low-density plasmas. Atomic processes in the dense plasmas of interest to inertial confinement were surveyed by R. More (LLNL). M. Harrison (Culham) gave an overview of the atomic and molecular physics involved in plasma/wall interactions, D. Post [Princeton Plasma Physics Laboratory (PPPL)] discussed plasma diagnostic techniques based on particles, and neutral beam heating was covered by R. Pyle (Berkeley) and D. Post (PPPL).

The overview of fusion research by G. Grieger (Garching) began with the elementary ideas involved in fusion such as the basic nuclear physics of fusion reactions, the basic idea of confinement and ignition, and the general physics constraints of fusion. He then introduced the general idea of inertial and magnetic confinement, outlining the promise and the difficulties of each technique. The general concepts of toroidal and linear magnetic confinement systems were outlined, and tokamaks, stellarators, reversed field pinches, bumpy tori, and mirror devices were discussed. The importance of heating, diagnostics, and impurity control were elaborated for each concept.

The second half of Grieger's lecture described the International Tokamak Reactor effort, for which he is the European coordinator. His talk outlined the plasma physics constraints and the engineering considerations necessary for designing a tokamak reactor scale experiment. The most relevant point of his lecture for the conference was the importance of impurity control, particularly using divertors.

J. Hogan (ORNL) then described, in more detail, the general features of each approach to magnetic confinement fusion. He first covered the plasma physics issues concerned with successful experiments: orbits, transport, equilibrium and stability for tokamaks, tandem mirrors, stellarators, and bumpy tori. He discussed the role of atomic physics in each scheme and the current status of the experiments in each area. He concluded by citing charge transfer of hydrogen and multiply charged ions as an example where the atomic physics community has made a real contribution to plasma physics experiments.

R. Haas (LLNL) gave a general introduction to inertially confined plasma research. He covered the general principles of driver technology, pellet design and physics, and reactor concepts. He then concentrated on how the physics of pellet implosion experiments has directed the research in driver technology toward ion beams and short wavelength lasers. Lasers with wavelengths of 1 to 10 μm are found to generate a large population of high-energy ($\gtrsim$100-keV) electrons, which heat the center of the pellet increasing the difficulty of compressing it. The requirements for a driver are given in Table I. The constraints on new lasers are that they have wavelengths of 5000 Å or less, be efficiently excited, and be storage lasers with relatively low photoabsorption rates.

TABLE I

Performance Requirements for Inertial Confinement Fusion Drivers

Parameter	Conservative	Optimistic
Driver efficiency (%)	$\gtrsim$6	$\gtrsim$1
Wavelength or ion voltage	$\lesssim$0.3 μm 10 GeV uranium 5 MeV proton	$\lesssim$2 μm 20 GeV uranium 20 MeV proton
Energy (MJ)	3 to 5	>1
Peak power (Terawatt)	200	>100
Pulse rate (Hz)	>4	>1

R. More (LLNL) then discussed the atomic physics of the plasma pellet, both the "corona" surrounding the pellet where the energy of the driver is absorbed and the ablation takes place, and the center of the pellet, which is expected to be sufficiently dense ($n_e \sim 10^{25}$ cm^{-3}) so that the distance between ions is comparable to the size of the orbits of the bound electrons. Understanding the atomic physics of high-density plasmas (composed of deuterium, tritium, and heavier elements), and thus the equation of state and opacity, is crucial to predicting the performance of the pellet with hydrodynamic calculations such as LASNEX. One important feature of the practical models now in use is that they must reduce to local thermodynamic equilibrium (LTE) in the appropriate conditions. This requirement leads to the use of an average ion approach and Thomas-Fermi models, which provide relatively simple and general treatments that can be incorporated in large hydrodynamic codes. Improvements to current models that are needed include the addition of dielectronic recombination in complex configurations at high densities, and better excitation and ionization rates at high density. The theoretical and experimental study of high-density plasmas will undoubtedly be one of the new expanding areas of atomic physics research.

H. Drawin (Fontenay-aux-Roses) surveyed the role of atomic processes in the central plasma of magnetic fusion devices. The main effect that these processes play is to cool the plasma via line radiation caused by electron excitation of partially ionized impurity atoms. A detailed knowledge of the electron impact ionization, excitation, and recombination cross sections and rates for the common impurities such as carbon, oxygen, titanium, iron, and molybdenum is essential in understanding the energy loss processes. The atomic structure of highly ionized atoms is an essential ingredient in the rates.

M. Harrison (Culham) discussed the role of atomic physics in the plasma boundary of magnetic fusion devices. This topic is of crucial importance since the best hope for controlling impurities in the plasma is by controlling their source at the plasma edge. The plasma at the edge is typically cool (~5 to 20 eV) and of moderate density (10^{12} to 10^{14} cm^{-3}). Atomic and molecular hydrogen physics is important because the plasma recombines when it hits the walls and forms neutral atoms and molecules that reenter the plasma and are excited and ionized by electron impact. Multistep hydrogen excitations and ionization are important, as well as molecular dissociation, ionization, and recombination. The reflection properties of low-energy ions and neutrals striking surfaces are also important and poorly known. Other important issues involve differential cross sections for elastic scattering and charge-exchange at low energies (5 to 10 eV), which again are poorly known.

Very little is known about ionization and excitation rates at low temperatures for nearly neutral ions (W^{+3}, for example). Another process of interest is the low-energy charge-exchange of atomic hydrogen and partially ionized impurities.

R. Pyle (Berkeley) and D. Post (PPPL) discussed neutral injection. They pointed out that neutral beam injection has played a major role in the success of recent tokamak and mirror experiments and will be the major heating method on the large experiments in the 1980s (Japanese Torus-60, Tokamak Fusion Test Reactor, Joint European Torus, and the Magnetic Fusion Test Facility-B). However, the technological complexity of neutral beam systems makes them less attractive than radio-frequency (rf) heating methods, such as ion cyclotron rf heating, provided rf can be used successfully to heat plasmas. The present neutral injection systems use positive ion sources and neutralize the beam ions by charge-exchange. This limits the beam energy to ~80 to 90 keV/amu. Recent applications of atomic physics have included the development of a new ion source that has a reduced content of H_2^+ and H_3^+ compared to H^+.

If future (1990) neutral beam systems are to be competitive with rf, they will probably have to be based on negative ions. Atomic physics is important in the production of high currents of H^-, either in volume sources through the dissociation of vibrationally excited H_2 into H^- and H, in surface sources, and in double charge-exchange sources. Successful negative ion systems require neutralizers, based on either stripping collisions with a gas or plasma, or by photodetachment. Particularly promising for photodetachment is the use of a high-power oxygen iodine laser. There is also some interest in negative ion systems based on negative ions of elements like lithium, carbon, oxygen, sodium, or silicon. The potential advantages of such beams would be the high-injection energy possible with these beams, and therefore the small current required. The main issues again are production of high currents of negative ions and the efficient neutralization of the ions.

H. Drawin (Fontenay-aux-Roses) outlined the use of spectroscopic diagnostic techniques in magnetic fusion plasmas. The new developments in spectrometers include vacuum ultraviolet survey spectrometers with up to 1000 channels that can measure an entire spectrum with up to ~1-ms resolution, and curved crystal spectrometers that can measure spectra down to 1 Å with high resolution. New directions in the use of spectoscopic techniques include the use of Doppler broadening of forbidden lines of highly ionized ions (e.g., Fe^{+20}) to measure the central ion temperature and the use of ratios of line strengths of dielectronic satellite lines and resonance lines to measure the electron density and temperature. The comparison of the spectroscopically measured impurity charge state distributions and various calculated distributions assuming different levels of transport provides a measure of the impurity transport. This analysis requires a detailed knowledge of the line excitation rates, the ionization rates, and the recombination rates for all the stages of ionization of the impurity in question.

Diagnostics using particles for magnetically confined plasmas were surveyed by D. Post (PPPL). The main use of particle diagnostics is to measure the energy spectrum of the escaping neutral atoms to determine the central ion temperature. Heavy ion (thalium, rubidium, etc.) beams have also been used to measure the electrostatic potential of the plasma, a particularly important quantity for mirrors and bumpy tori. One of the most promising new techniques for measuring impurity densities is the measurement of charge-exchange recombination radiation using a modulated doping neutral hydrogen beam: $H^0 + A^{+Z} \rightarrow H^+ + (A^{+Z-1})^*(n,l) \rightarrow A^{+Z-1} + h\nu$. This method has several advantages over conventional spectroscopy in that it is a local measurement that does not have to be Abel inverted, it can measure the density of fully stripped impurities, and it is insensitive to the electron temperature. The method, however, requires a knowledge of the cross sections for populating the various (n,l) levels of the impurity. Other new directions will involve the use of lithium doping beams, the use of laser excitation and laser fluorescence of probing beams, and high-energy probing beams based on negative ions.

The atomic physics lectures dealt with the experimental and theoretical data and the techniques used to obtain the results. The lectures on theoretical methods were begun by C. Joachain (Brussels) who reviewed recent progress in the field. He first discussed electron-atom and electron-ion collisions, starting with the low-energy region where all the open channels can be explicitly included in the total electron-atom (ion) scattering wave function. The close-coupling method and its modifications involving pseudostates and correlation functions were discussed, as well as variational techniques, L^2 methods, and the R-matrix approach. Theoretical methods appropriate for intermediate- and high-energy electron-atom (ion) collisions were then covered, beginning with recent extensions of the low-energy approach involving pseudostates, and then moving on to perturbation theory, the eikonal-Born series method, optical potentials, and distorted wave treatments. The difficulties arising at intermediate energies (pseudo-resonances, inclusion of exchange effects) were discussed, as well as those associated with electron impact ionization. Joachain then considered atom (ion)-atom collisions, beginning with fast collisions, where an "atomic picture" based on expansions of the scattering wave function in atomic eigenfunctions is physically reasonable. Expansions of this kind appropriate for excitation and charge exchange were discussed, including the use of electron translation factors. At low colliding velocities, "molecular pictures" are used to describe atom-atom collisions, and the lecture ended with a brief account of the perturbed stationary state method and its recent modifications involving traveling molecular orbitals and electron translation factors.

The theoretical methods appropriate for electron-atom and electron-ion collisions were then discussed in detail by M. R. C. McDowell (UC London). He first considered eigenfunction expansion methods, with particular emphasis on variational methods, and discussed recent results involving pseudostates and correlation functions, as well as distorted wave approximations. He then considered the excitation of positive ions near threshold, comparing the strengths and weaknesses of various distorted wave and close-coupling approaches. He next covered excitation by fast electrons, comparing Coulomb-Born, distorted wave, and close-coupling results. McDowell then turned to electron impact ionization of positive ions. The standard techniques (Coulomb-Born, Coulomb-Born with exchange, etc.) were derived, their difficulties discussed, and the results of each technique were compared with the measurements. Ways of including autoionization effects were also covered. The lecture concluded with a useful discussion of the various data compilation efforts.

B. Bransden (Durham) surveyed theoretical methods applied to charge-exchange and ionization by heavy particles, concentrating on the special methods that have been developed to describe charge-exchange and ionization in the collision of fully stripped ions with atomic hydrogen in the ground state. He first discussed charge-exchange beginning with coupled-channel calculations, including electron translation factors, and then considered various less accurate, but useful, approximations. At intermediate velocities, he discussed in particular the unitarized distorted wave approximation and the classical trajectory Monte Carlo method, and at higher velocities the eikonal methods. At lower velocities, the multi-crossing Landau-Zener model, the absorbing sphere, and the decay models were reviewed. Bransden concluded his lectures by considering theoretical models for the ionization of H(1 s) by fully stripped ions.

G. Ferrante (Palermo) discussed atomic collisions in intense electromagnetic fields. He began by considering the problem of the potential scattering of a charged particle in a laser field, and then went on to discuss electron-atom and atom-atom collisions in the presence of strong electromagnetic fields. The presence of intense fields (such as produced in high-power lasers and in some astrophysical phenomena) was found to reduce most collision cross sections, particularly charge-exchange. Ironically, the magnetic fields in magnetically confined plasma experiments were found to be too low to change any relevant collision rates. Only the intense fields of the order of those generated by high-power lasers or inhomogeneous currents in laser-imploded pellets produced noticeable rate changes.

K. Dolder (Newcastle) described the experimental study of electron impact collisions. There are three ways to measure electron impact ionization cross sections: crossed beams, plasma spectroscopy, and ion traps. Crossed beams of electrons and multiply charged ions yield the best data, but are limited by present ion sources, which cannot yet produce large currents of highly charged ions. New directions involve using large-scale ion sources, such as Fe^{+15}, from tandem accelerators, systematic studies of lower charge state ions, the study of correlation effects such as excitation-autoionization, autoionization, and multiple ionization, and measurement of cross sections for lowly charged ions of direct relevance to fusion research. The grand prize experiment is the measurement of dielectronic recombination.

There are two ways to measure electron impact excitation: crossed beams and plasma spectroscopy. The first method produces high quality data but is extremely difficult, and the second method produces ambiguous data. The major priorities are to obtain data for isoelectronic series, and to extend crossed beams to highly charged ions. In the latter case, one would expect poor signal-to-background ratios in addition to problems with wavelength selection and absolute calibration in the vacuum ultraviolet and soft x-ray region. The lecture ended with a plea for the invention of a better method for measuring excitation cross sections.

F. De Heer (FOM, Amsterdam) discussed the measurement of charge-exchange and ionization by heavy particles. He first surveyed the existing multiply charged ion source techniques. These include drift tubes, laser-produced plasmas, low arc current plasmas, high arc current plasmas, beam foil stripping, recoil ions from a tandem, and plasma discharges. The cross sections were measured either by crossed beams, or passing the beam through a target gas and measuring the product charge states. New directions include using optical (visible, ultraviolet, and soft x-ray) spectroscopy to determine the excited states of the collision products, and the use of energy gain techniques, merged beam techniques, and coincidence techniques. Of particular interest will be the measurements of the excited state distributions resulting from charge-exchange, the differential cross sections for charge-exchange, and the measurement of charge-exchange at very low relative velocities.

F. Brouillard surveyed Rydberg atoms. Rydberg atoms are important since neutral hydrogen exists at the plasma boundary, and since dielectronic recombination and excitation-autoionization and other collective effects often involve intermediate steps that are Rydberg atoms. Rydberg atoms may also be important for pressure ionization in dense plasmas. The items of interest are the radiative lifetimes of Rydberg atoms and their behavior in electric fields and during collisions. The radiative lifetimes can be calculated with reasonable accuracy at medium n in the dipole approximation, but some discrepancies exist for high n, particularly for Rydberg atoms with multi-electron cores. Not much experimental data exist.

In static electric fields, field ionization offers a simple and useful identification technique. Oscillating fields can lead to transitions and field ionization. Again there is little experimental work available. The collision properties of Rydberg atoms with neutral atoms have been studied extensively at low energies. There a "free electron" model with corrections is reasonably consistent with the data. There is little or no data for $n \gtrsim 50$, and no data for fast collisions.

Many of the conference participants discussed current research problems in seminars. R. Geller (Grenoble) described the work he and his colleagues are doing on electron cyclotron resonance mirror ion sources. Other talks on experimental atomic physics included a discussion of the Harvard dielectronic recombination experiment by G. Lafyatis and a description by B. Johnson of the electron impact ionization measurements at Brookhaven, as well as the excitation and radiative capture experiments there, and a description by I. Williams (Belfast) of measurements of Balmer Alpha emission in collisions of H_n^{+m} with H_2, which may be useful in measuring the molecular hydrogen ion content of neutral beam ion sources. T. Morgan (Wesleyan) described his measurements of charge-exchange cross sections for hydrogen and helium beams in metal vapor targets, stressing the new understanding gained from the work of R. Olsen on the potential curves for such collisions. S. Bliman (Grenoble) discussed his group's measurements of the excited state distributions produced by charge-exchange of completely ionized ions and molecular hydrogen. P. Defrance (Louvain-la-Neuve) discussed his group's measurements of the electron impact ionization of atomic hydrogen (which was produced by photodetachment of H^-). C. Cisneros (Mexico) surveyed the work she and her collaborators did at ORNL on the collisional dissociation of HD_2^+ molecular ions in H_2. C. Conde (Portugal) discussed his measurements and calculations of electroluminescence in noble gases. M. Lennon (Belfast) discussed the work at Belfast on measuring the energy distribution of collision products in coincidence to determine the excited states produced in atomic collisions, a very promising technique.

A large number of papers were given on theoretical results for atomic collisions. There were two talks on the effects of magnetic fields on collisions: B. Spagnolo (Palermo) on charge-exchange collisions and S. Bivona (Palermo) on particle scattering in a laser-produced plasma. P. Greenland (Harwell) discussed his calculations of differential cross sections for high-energy electron capture collisions, and C. Whelan (Cambridge) described his calculations of cross sections for electron-hydrogen collisions. There were many more papers on charge transfer. S. Bienstock (Harvard) described his group's calculations of low-velocity charge transfer of C^{3+} ions in atomic hydrogen. M. Lieber (Arkansas) discussed his work on charge transfer calculations using eikonal methods. R. Allen (Newcastle) described his work on calculating charge transfer cross sections in proton alkali collisions using model potential methods. W. Fritsch (Berlin) discussed the use of a modified two-center orbital expansion in a close-coupling calculation of low-velocity ion atom collision.

The Connecticut group discussed their work on electron-ion collisions. Y. Hahn gave an excellent survey of how higher order effects influence ionization and recombination cross sections (e.g., excitation-autoionization and dielectronic recombination). K. Lagattuta discussed the effects of intermediate coupling and configuration interaction on dielectronic recombination rates, and D. McLaughlin described calculations of dielectronic recombination rates for the lithium isoelectronic sequence. G. Gillespie (La Jolla) covered his work on scaling of high-energy cross sections, and A. D. Stauffer (York University) discussed his work on the behavior of cross sections near the ionization threshold. B. Piraux (Louvain-la-Neuve) discussed second Born approximation calculations of the triple differential cross section for the ionization of atomic hydrogen and helium by fast electrons.

There were a number of talks by the fusion scientists and students. G. Zimmerman (LLNL) began the inertial confinement talks with a description of the use of an average atom non-LTE model to calculate the equations of state and opacities for a hydrodynamic description of the compression of a pellet of lasers. W. Morgan (LLNL) discussed his calculations of the production of non-Maxwellian electron distribution produced by inverse bremsstrahlung in laser-heated plasmas. G. Kerley [Los Alamos National Laboratory (LANL)] discussed equations of state and opacities calculated from ionization equilibria in dense plasmas using partition functions. F. Begay (LANL) discussed model calculations for the charge state distribution of low-Z atoms in a laser ablation experiment.

There were 11 seminars discussing work in magnetically confined plasmas. E. Mund (Brussels) gave an overview of the fission-fusion hybrid concept. M. Bacal (Ecole Polytechnique) discussed her experiments in the volume production of H^- and D^- in low temperature plasmas. J. Hiskes (LLNL) described calculations of the negative ion concentrations in hydrogen plasmas including molecular excitation by electron impact and deexcitation by impact with the wall. R. Hulse (PPPL) described models for the behavior of impurities in tokamaks, illustrating how impurity atomic physics is used by the fusion community. M. Bitter (PPPL) described his measurements of dielectronic recombination rates on the Princeton Large Torus tokamak and the use of dielectronic recombination satellites lines as a diagnostic tool for the electron temperature. K. Kadota (Nagoya) discussed the use of laser excitation of neutral lithium to measure the edge temperature and density in tokamaks. H. Winter (Vienna) discussed the use of a neutral lithium beam for charge-exchange recombination diagnostics in plasma experiments. T. Cook (ORNL) described the use of laser-induced fluorescence to study neutral and singly ionized impurities on the ELMO Bumpy Torus device at ORNL. F. Zadworny (Grenoble) discussed his modeling of a system for the production of negative ions of hydrogen by double charge-exchange of protons with a cesium jet. J. Bailey (Irvine) described the use of a gas puff Z-pinch to produce large amounts of soft x rays. H. Makowitz (Texas) reviewed some aspects of the plasma/wall problem, particularly the damage caused by disruptions. H. Kilic (Stevens) described some experiments on "plasmoids" at Stevens.

The conference was a useful mix of survey lectures and seminars on specific results. The general thrust of the field could be gauged from the meeting. In inertially confined plasmas, the two exciting areas involve development of new drivers (short wavelength lasers, light and heavy ion beams) and the behavior of matter at high densities and temperatures (10^{25} cm^{-3} and 10 to 10^4 eV) "solid-state plasma physics." In magnetically confined plasmas, the new areas of research involve impurity control by control of the plasma boundary, negative ion based neutral beams, and new diagnostic techniques such as charge-exchange recombination and forbidden line spectroscopy.

D. E. Post

Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, New Jersey 08540

C. J. Joachain

Universite Libre de Bruxelles
Campus Plaine C.P. 227
Bo. du Triomphe, B-1050
Brussels, Belgium

September 27, 1982

ACKNOWLEDGMENT

A portion of this work by D. E. Post was supported by the U.S. Department of Energy contract DE-AC-02-76-CHO-3073.