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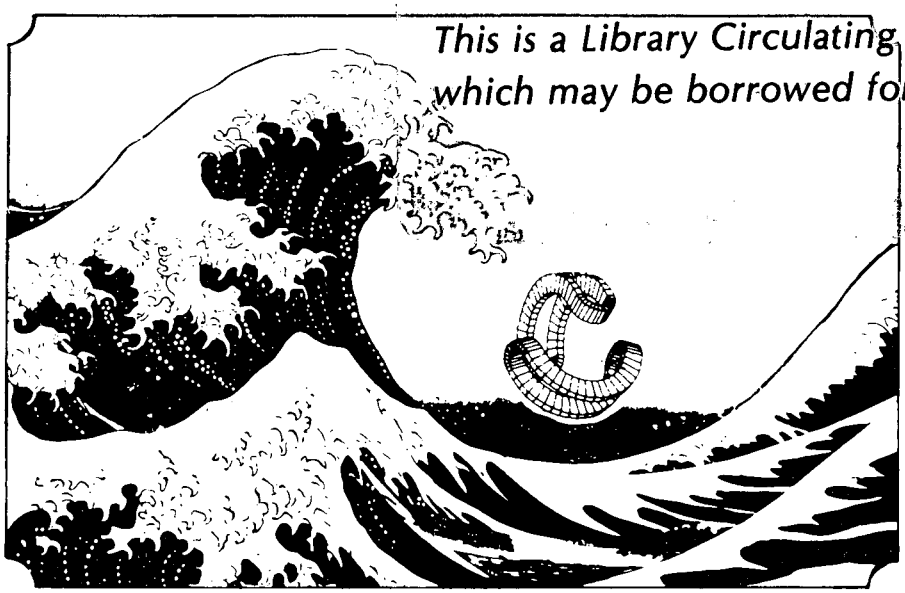
July 1985

ATOMIC PROCESSES IN FUSION PLASMAS

SANTA CRUZ SEMINAR



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JULY 31 - AUGUST 2, 1985

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ATOMIC PROCESSES IN FUSION PLASMAS

Santa Cruz Seminar

July 31 - August 2, 1985

Organized by:

R.E. Olson, University of Missouri/Rolla

A.S. Schlachter, Lawrence Berkeley Laboratory

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ATOMIC PROCESSES IN FUSION PLASMAS

SANTA CRUZ SEMINAR

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Session (Electron-ion Collisions) Kresge College, Town Hall		2:00 pm - 5:15 pm
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SANTA CRUZ SEMINAR

PROGRAM

THURSDAY, AUGUST 1

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R.J. Fonck:	Applications of Charge-Exchange Recombination Spectroscopy for High Temperature Plasma Diagnostics
J.C. Weisheit:	Atomic Collision Processes in Dense Plasmas

POSTERS 11:30 am- 12:15 pm

ELECTRON-ION COLLISIONS (G.H. Dunn) 2 - 5:15 pm

R.A. Phaneuf:	Single Ionization of Multiply Charged Ions by Electron Impact
A. Müller:	Multiple Ionization of Ions by Electron Impact
Y. Itikawa:	Distorted-Wave-Method Calculation of Electron-Impact Excitation of Ions
M.S. Pindzola:	Theoretical Studies of Electric Field Effects on Dielectronic Recombination

FRIDAY, AUGUST 2

ION-ATOM COLLISIONS (E. Salzborn) 9 am - 12:15 pm

H.B. Gilbody:	State-Selective Electron Capture by Multiply Charged Ions in Atomic Hydrogen
P. Hvelplund:	State Selective Electron Capture for Multiply Charged Ion-Atom Collisions
J.F. Reading:	Multi-Electron Effects in Ion-Atom Collisions
M.R.C. McDowell:	Applications of the Classical Trajectory Monte Carlo (CTMC) Method to Charge Exchange

ION AND ATOM SOURCES AND BEAMS (K.H. Berkner) 2 - 5:15 pm

T.J. Morgan:	Fast Light Atom Beams: Collisional Production and Loss of Excited States
L.W. Anderson:	Production of Polarized Beams
A.W. Kleyn:	Resonant Charge Transfer in Atom-Metal Collisions
J.R. Hiskes:	Atomic and Molecular Processes in Negative Ion Plasmas

CONTRIBUTED PAPERS

Electron Impact Ionization of Helium and Lithium-Like Ions
R. I. Campeanu and L. Nagy

Charge Exchange Spectroscopy on DITE and ASDEX
B. Duval, P.G. Carolan, A.R. Fields, N.C. Hawkes, N.J. Peacock, J. Spence and H.P. Summers

Electronic Properties of Hot Dense Plasma
K. Fujima and T. Watanabe

Polar Dissociation of H_3^+
W.G. Graham, M.B. Hopkins and A.C.H. Smith

Charge Equilibrium of Fast Heavy Ions Traversing Through Hydrogen Gas Target
S. Karashima and T. Watanabe

Observations of Charge-Transfer Recombination in Alcator C
E.S. Marmar, J.E. Rice and J.L. Terry

Compilation and Evaluation of Atomic Data for Fusion in Japan Atomic Energy Research Institute
Y. Nakai, T. Shirai and K. Ozawa

Progress in Developing a Negative Ion Based Neutral Beam Injection System
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Giant Impurity Sawtooth Following Pellet Injection in Alcator
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Influence of Dynamic Screening Effects on the Rates of Inelastic Collisions in the Dense Plasmas
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Attenuation of a 100 KeV Lithium Beam in a Plasma
E.J. Synakowski, S.B. Zheng, R.D. Bengtson, W.P. West and D.M. Thomas

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Differential Electron Scattering Cross Sections for the First Optically Forbidden and Resonance Transitions in MgII, ZnII and CdII
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Impurity Species Evolution and Neutralisation Relevant to Neutral Beam Injectors
F.B. Yousif, J. Geddes and H.B. Gilbody

Impact Excitation of Fine-Structure Levels in Hydrogen-Like Ions
B. Zygelman and A. Dalgarno

INVITED TALKS

THE NEXT DECADE OF ATOMIC PHYSICS IN FUSION RESEARCH*

C. F. Barnett

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Since the beginning of an active effort in magnetically confined fusion research in 1951-52, atomic physics has played a significant role in the heating, cooling, modeling, and diagnostics of high temperature plasmas. In the late 1950's there was overwhelming optimism in controlled fusion research that high temperature plasmas could be achieved and fusion energy would be a reality. This optimism gave way to a period of pessimism in the 1960's when all plasmas were beset by instabilities, including the universal instability. With the achievement of a modest high temperature plasma in the tokamak configuration, optimism was at an all-time high and reactor design studies were initiated. In the early 1970's measurements at Princeton and Oak Ridge confirmed that electron and ion temperatures in the center of tokamak plasmas were being limited by optical radiation from partially ionized W, Mo, or Au impurities originating at the limiter or walls. It was at this time that plasma physicists recognized the important role of atomic physics in the heating, cooling, and diagnostics of a high temperature plasma. For the past decade the support and funding of atomic physics relevant to fusion has grown enormously. In the mid-1980's we are seeing again the optimism being replaced by pessimism with decreasing funding in the national fusion program.

To be a prophet and predict the role that atomic physics will play during the years 1985-95 is difficult. During the past ten years tremendous progress has been made in understanding and accumulating data for atomic and molecular physics in fusion research. Nevertheless, we still do not have a clear understanding of the atomic processes occurring in plasma. The many charge states and excited quantum states for impurity particles make it impossible to obtain the required data experimentally. The philosophy must be adopted to perform several benchmark experiments in order to confirm theory and develop scaling laws or rules. From our present understanding of the role of atomic physics in high temperature plasmas, we

can predict some of the most obvious future needs: (1) extension of experimental cross sections or reaction rate coefficients to high charge states, i.e., $Fe^{(21-26)+}$; (2) role of inelastic collisions in particle transport; (3) excitation of multicharged positive ions; (4) extension of cross sections and rate coefficients to regions of interest in plasma edge and divertor regions ($E < 200$ eV); (5) do reaction rate coefficients as measured in plasmas compare favorably with those calculated from beam cross section measurements? (6) increased understanding of electron impact ionization of impurity ions including multiple ionization; (7) what effect does dielectronic recombination have on decreasing the charge state in a high temperature plasma?

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*Research supported by the Office of Fusion Energy, U.S. Department of Energy under contract No. DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

Applications of Charge-Exchange Recombination Spectroscopy for High Temperature Plasma Diagnostics

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In the last few years, Charge-Exchange Recombination Spectroscopy (CXRS) has rapidly matured as a versatile diagnostic tool for fusion-grade plasmas. The basic technique consists of measuring the intensities and profiles of emission lines excited in charge-exchange reactions between fast neutrals, usually from hydrogen or deuterium neutral beams, and low-Z ions, usually fully stripped H, He, C, or O. The measurements of plasma ion temperature and bulk motion via CXRS has become the technique of choice for spectroscopic measurements of these quantities in most of the major tokamak fusion experiments. With a spatial resolution of a few cm and a temporal resolution of at least 2 msec, this technique has allowed observations of rapid ion temperature fluctuations due to sawtooth oscillations in tokamak discharges. CXRS has also provided significant advances in our ability to measure low-Z ion transport without significant complications due to atomic physics uncertainties. Finally, it holds promise for a feasible means of measuring the fast-alpha particle distribution in an ignited fusion plasma. Activity in further development of CXRS for plasma diagnostics is concentrated on two fronts. First, the increasing complexity, expense, and inaccessibility of large-scale experiments necessitates the development of complex instrumentation with multi-spatial, -spectral, and -temporal capabilities which can perform detailed measurements in a single plasma discharge. This is feasible due to the availibility of long-wavelength transitions between moderately high Rydberg levels (n = 4 to 10) of the emitting ion which are excited via charge exchange. These transitions allow the use of fiber-optically coupled optical systems in hostile enviroments. Second, in spite of the acceptance of CXRS as a plasma diagnostic tool, significant atomic physics issues remain unresolved, and these issues can have substantial influence on future developments of CXRS. At present, there is a high premium on the determination of accurate rate coefficients for the excitation of high-n transitions in elements such as He^{+}, C^{5+}, and O^{7+}. Also, line profile measurements are becoming sufficiently precise that the detailed energy dependence of these rates must be considered. Even if the fundamental excited state population due to charge exchange is known, our understanding of atomic and plasma processes such as ion-ion collisions, Stark mixing, and/or Zeeman mixing must be further developed to allow an accurate estimation of the cascade processes giving rise to observed line emissions. Measurements of line intensity ratios for emissions excited by charge exchange have been performed on the ISX-B and PDX/PBX tokamak experiments as preliminary steps in evaluating such complications.

ATOMIC COLLISION PROCESSES IN DENSE PLASMAS*

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High temperature, high density plasmas have long been studied in connection with stellar interiors. Much recent interest in the properties of such plasmas has been fostered by efforts to achieve controlled thermonuclear fusion by means of inertial confinement; and, now, short-wavelength (XUV) laser design also required an understanding of atomic phenomena in hot and dense plasmas. Atomic physicists mostly have paid attention to the adjective "hot," and have continued to develop experimental and theoretical techniques for determining energy levels, oscillator strengths, electron impact cross sections, etc., of highly stripped ions in vacuo. Progress in these areas has been notable.

In contrast, implications of the adjective "dense" have largely been ignored. Some progress has been made in understanding plasma pertubations of atomic structure and radiative processes, but our knowledge of plasma effects on atomic collisions is very limited (cf. Weisheit, 1984). A rigorous treatment of scattering in a dense plasma leads to an intractable many-body problem, so the main purpose of this lecture is to identify much simpler - yet still realistic - approximations for the environmental impact of dense plasma. As an introduction, we first consider elastic collisions, and review and extend Spitzer's (1962) analysis of Rutherford scattering in a plasma. We then consider inelastic collisions, and outline two very different physical models. In the first, one avoids reference to individual scattering events and treats transitions as being due to the action of the stochastic electric microfield produced by all plasma electrons and ions. In the second, one uses the ordering of various timescales (e.g., collision duration, mean time between collisions) to obtain model potentials that mimic the plasma's influence in various regimes.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

After summarizing the few investigations that have been published, we suggest several topics for future research in this challenging subject.

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SINGLE IONIZATION OF MULTIPLY CHARGED IONS BY ELECTRON IMPACT*

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The stimulus of the fusion program and the availability of improved ion sources continue to produce a significant expansion of the base of accurate experimental data for electron-impact ionization of multiply charged ions. Systematization of experimental and theoretical studies along isoelectronic (same electronic structure), isonuclear (same species) or isoionic (same charge) sequences has helped to identify new ionization mechanisms and to produce an enhanced level of understanding of the ionization process. In many cases, the cross section for these so-called indirect ionization channels dominate by more than an order of magnitude that for direct ejection of an outer-shell electron.

Direct ionization cross sections may be estimated quite reliably by first-order quantum-mechanical perturbation treatments such as the distorted-wave Born approximation.[1,2] The Lotz semiempirical formula[3] is also widely used, and has been shown to predict direct ionization cross sections to much better than a factor of two in most cases. Direct ejection of inner-shell electrons may also lead to net multiple ionization, depending on the binding energy of the ejected electron, and the relative probabilities or branching ratio for autoionization versus radiative stabilization of the "hole" state.

Contributions to the ionization of a multiply charged ion produced by the excitation of an ionic inner-shell electron to an autoionizing state were first identified for Li-like ions by Crandall et al.[4] Reasonable agreement has been obtained with experiment in many cases by simply adding theoretical cross sections for the appropriate excitation process to the direct ionization cross section, ignoring possible interference effects between these channels. Because the cross section for excitation of an ion by electron impact is finite and most often largest at its threshold energy, the excitation-autoionization process for a strong, well-isolated transition produces a distinctive and readily identifiable signature in the ionization cross section. The cross sections for such transitions are

expected to fall off asymptotically as 1/E for dipole-forbidden excitations, and as $1/E^3$ for spin-forbidden excitations, whereas cross sections for both dipole-allowed excitations and for direct ionization fall off much more slowly, as $\ell n\ E/E$. Thus the signature of an excitation feature in the ionization cross section gives useful information about both the threshold energy and the nature of the excitation process which leads to autoionization. Coupled with a branching ratio for autoionization versus radiative decay, this signature can provide a quantitative basis for evaluating theoretical methods for electron-impact excitation cross section calculations. More exotic ionization mechanisms, such as resonant-recombination double-autoionization are also predicted to play a role in some cases.[5]

As illustrative examples of the role of indirect ionization mechanisms in single ionization, recent experimental results will be presented for electron-impact ionization of multiply charged ions in the Xe-isonuclear[6] and Mg-isoelectronic[7] sequences.

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*Research supported by the Office of Fusion Energy, U.S. Department of Energy under contract No. DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

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MULTIPLE IONIZATION OF IONS BY ELECTRON IMPACT

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Electron impact ionization of atoms and ions is a fundamental collision process which occurs in many different kinds of environments. It governs the production of highly stripped atoms in any hot plasma in the laboratory as well as in stars and the prediction of charge state abundances of ions in solar flares, ion sources, or in fusion plasmas requires the knowledge of cross sections for electron impact ionization.

The production of a highly charged ion A^{Z+} in a plasma can proceed step by step in successive single ionization processes

$$e + A^{q+} \rightarrow A^{(q+1)+} + 2e \quad q = 0,1,2,... \qquad (1)$$

where only one electron is removed in each step. Ions A^{Z+} can also be produced in a sequence of multiple ionization processes in which one projectile electron removes several electrons from the target atom in one collision

$$e + A^{q+} \rightarrow A^{(q+k)+} + (k+1)e \quad q = 0,1,2,... \ , \ k = 2,3,4,... \qquad (2)$$

It was generally assumed that the probability of such a process would be small. Recent experiments on electron impact multiple ionization of multiply charged ions demonstrate, however, that these collisions may have large cross sections.[1,2] Thus the time development of charge state abundances of atoms exposed to electron impact may be seriously influenced by multiple ionization processes.

Removal of several bound electrons from an atom or ion by one incident projectile electron may proceed by the following mechanisms:

1. The incident electron may eject k electrons from the target atom in k successive electron-electron collisions inside the atom or by transferring enough energy to a target electron which then can ionize other electrons within the same atom (direct multiple ionization).

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2. The incident electron may remove a target electron so suddenly that the remaining ion shakes off additional electrons when the orbitals relax after the sudden change in the effective potential.
3. The incident electron may produce an inner-shell vacancy and the subsequent autoionization results in a net multiple ionization.

Direct multiple ionization as defined above does not necessarily exclude processes (2). Both include final state interactions. The classical picture of process (1) involves multiple interactions of the projectile electron with the target electrons. Hence the total probability of direct multiple ionization depends on a product of single-interaction probabilities. As the charge state of an ion increases, the number of target electrons goes down and the electron binding energies go up. The cross sections for direct single ionization decrease therefore, and as a consequence the probability for direct multiple ionization rapidly goes down along an isonuclear sequence of ions. Nevertheless, there may be considerable contributions to multiple ionization from process (1). To give an example: the cross section $\sigma^d_{1,3}$ for direct double ionization of Ar^{1+} ions reaches a value of nearly 5×10^{-18} cm^2 at an electron energy of 150 eV.[3]

The shake off mechanism (2) has been used to explain double ionization of He and Li^{1+} ions. The calculations reproduce the order of magnitude of measured ratios $R = \sigma_{q,q+2}/\sigma_{q,q+1}$ of cross sections for double and single ionization. R is about 1/250 for He and 1/350 for Li^{1+} which apparently indicates low probabilities for multiple ionization in few-electron systems. More complex atoms, however, may have large cross sections for multiple ionization by electron impact: $\sigma_{1,3}$ for Bi^{1+} ions is not less than 7×10^{-17} cm^2 at 120 eV[4] and the ratio R reaches 0.8 for Ba atoms indicating comparable probabilities for multiple and single ionization. A reason for this is the possibility of multiple ionization in the two-step process (3) which is based on a single interaction of the projectile with an inner shell electron. The net multiple ionization follows "automatically." It requires no second interaction of the projectile electron with the target ion and it is only determined by the branching ratios of relaxation processes following the production of the inner shell vacancy.

In complex ions the inner shells such as the 5d shell in Bi may have binding energies close to those of the outer shell ($\approx$45 eV for the 5d

subshell of Bi^{1+} compared to ≈15 eV for the 6p subshell), and the number of equivalent electrons in the inner shell can be high compared to that in the outer shell (10 electrons in the 5d subshell of Bi^{1+}, 1 electron in the 6p subshell). Hence the probabilities to remove one electron from an inner or an outer shell may be close to each other. Since the inner-shell vacancy can still provide enough energy for the ejection of a second electron the ratio R defined above may be close to 1 in complex atoms.

For lighter ions such as Ar^{q+} we found important contributions to multiple ionization arising from L-shell ionization with subsequent Auger processes.[5] As q increases the probability for direct multiple ionization decreases rapidly while the inner-shell contribution remains nearly constant and therefore can by far dominate the cross section for multiple ionization of a multiply charged ion. The reason for this behavior is the slow change of binding energy of the L-shell along a sequence $1s^2 2s^2 2p^6 3s^2 3p^{6-q}$ with q = 0,1,2,3,4 and the resulting slow decrease of the probability of a single ionization in the L-shell. The subsequent autoionization occurs with probabilities above 0.99 for $q \leq 6$ and thus leads to the increasing relative importance of L-shell contributions to multiple ionization of Ar^{q+} ions.

The high cross sections found for electron impact multiple ionization of ions indicate that modeling of ion charge states in plasmas should be carefully revised. A simple calculation of charge state abundances of Xe atoms exposed to an electron flux at 700 eV shows that the inclusion of multiple ionization reduces the electron density required to produce Xe^{6+} ions in a given time by not less than a factor of 2.

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Distorted-Wave-Method Calculation of Electron-Impact Excitation of Ions

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Electron-impact excitations of atomic ions are fundamental processes in fusion plasmas. The photon emission caused by the excitation, for instance, determines the power balance of the plasma and provides a useful plasma diagnostics. A measurement of the excitation cross section, however, is very difficult. No new data have been reported since the last (XIII) ICPEAC on the cross section measured by beam method.[1] Only a few papers have been published reporting the plasma-type measurement of rate coefficients. We are obliged, therefore, to rely almost exclusively on theoretical methods to obtain the cross section.

There are three types of theoretical methods. The most sophisticated one is to solve coupled equations among various channels (the close-coupling or R-matrix method). This is believed to give very accurate results. It is laborious, however, to apply this to a wide variety of collision processes. The other extreme is the Born or the Coulomb-Born approximation. This is the simplest method and reasonably reliable in the calculation of dipole-allowed transitions at higher energies. A simple but more widely-applicable method is a distorted-wave (DW) approach. This is based also on the first-order perturbation theory, but takes into account the wave distortion and electron exchange. A proper combination of these three theoretical methods should be used to provide necessary data on the excitation process relevant in fusion plasmas.

The DW method has widely different approaches. The present author has recently proposed a simple version of the DW method.[2] The method has been applied to the excitation of He-, Be- and C-like ions. The result is quite satisfactory when compared with the more elaborate calculations of the close-coupling or R-matrix type. Some details of our method with a brief review of other recent calculations will be presented at the Seminar.

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THEORETICAL STUDIES OF ELECTRIC FIELD EFFECTS ON DIELECTRONIC RECOMBINATION*

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Dielectronic recombination is the process by which a free electron collisionally excites a bound electron of an atomic ion and forms a doubly excited resonance state which then stabilizes through the emission of a photon. External electric fields can have a pronounced effect on dielectronic recombination cross sections. They not only can field ionize high Rydberg states, but they can also cause a redistribution of the angular momentum among the doubly-excited states which may significantly enhance the total dielectronic recombination cross section. This field mixing enhancement has been demonstrated by a number of approximate theoretical calculations.[1,2,3]

We present the results of field-dependent intermediate-coupled calculations of dielectronic recombination cross sections associated with the $2s \rightarrow 2p$ excitation in C^{3+} and O^{5+} and the $3s \rightarrow 3p$ excitation in Mg^{+}, P^{4+}, and S^{5+}. The eigenvectors for the doubly-excited resonance states were determined in these calculations by diagonalizing a Hamiltonian which includes the internal electrostatic and spin-orbit terms as well as the Stark matrix elements. The variation of the cross sections with the external electric field will be presented as a function of principal quantum number and electron energy. The theoretical results are compared with recent crossed electron-ion beams measurements of the dielectronic recombination cross sections.

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*Research supported by the Office of Fusion Energy, U.S. Department of Energy under contract No. DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

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STATE-SELECTIVE ELECTRON CAPTURE BY MULTIPLY CHARGED IONS IN ATOMIC HYDROGEN

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In Belfast we have used[1,2,3,4] the technique of translational energy spectroscopy (TES) with highly dissociated hydrogen in a tungsten tube furnace to study processes of the type

$$X^{q+} + H(1s) \rightarrow X^{(q-1)+}(n,\ell) + H^{+} \pm \Delta E$$

leading to electron capture into specified states of the product ion. For exothermic processes at velocities $v < 1$ a.u., where a quasi-molecular description of the collision is appropriate, selective capture into a limited number of product ion states may occur very effectively through pseudo-crossings of the adiabatic potential energy curves at internuclear separations $R_c \simeq (q-1)/\Delta E$ a.u.

In our technique the primary ion beam X^{q+} of well defined energy T_1 is passed through the furnace target and the kinetic energy T_2 of $X^{(q-1)+}$ ions formed in single collisions is determined. The energy defect ΔE corresponding to each excited state channel is then given by $\Delta E \simeq \Delta T = T_2 - T_1$ provided $\Delta E/T_1 \ll 1$ and the scattering is confined to small angles. Studies of the relative product ion yields for each channel, with a knowledge of the total cross section for electron capture into all final states, allows determination of cross sections for capture into specified states n,ℓ within the limitations of the available energy resolution. The latest improvements in our measuring procedure, which involve the use of a position sensitive detector[4], provide an energy resolution of up to 1.5 eV.

Measurements have so far been limited to ions with $q = 2$ and 3 and we have data for C^{2+}, C^{3+}, N^{2+} and N^{3+} ions in H within the energy range 0.6 - 18.0 keV.

For C^{3+} in H our latest measurements[4] compare quite favourably with theoretical predictions[5] but reveal, in addition to the predicted four main product channels $C^{2+}(^3P^o, ^3S, ^1S$ and $^1D)$, an important contribution from the $C^{2+}(^3D)$ product channel for which $\Delta E = 0.78$ eV. An interesting comparison can also be made with recent measurements[6] based on the complementary technique of photon emission spectroscopy (PES).

For N^{2+} in H, cross sections for capture into the $^3D^o$, $^3P^o$, $^1D^o$ and ^3P states of N^+ have been determined[3]. Cross sections for the dominant $^3D^o$ low energy channel are in reasonable accord with theoretical predictions[7].

For C^{2+} in H collision channels involving both ground state and metastable primary ions can be unambiguously identified[2]. The main ground state channel leading to $C^+(^2D)$ ions corresponds to that predicted by theory[8].

A detailed analysis of our data[4] for N^{3+} in H is precluded by the possibility of many ground state and metastable primary ion channels which cannot be resolved. Nevertheless, our observations are at variance with recent theoretical predictions[9] for the ground state channel.

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State selective electron capture for multiply charged ion-atom collisions

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Ions or atoms can be brought into an excited state in collisions with energetic particles such as protons and electrons or via interaction with electromagnetic radiation. If we restrict ourselves to multiply charged ions of moderate energy, electron capture in collisions with atoms is an important mechanism for production of excited states in the product ions. The large potential energy which a multiply charged ion brings into such a collision can be distributed in various ways. It can be transferred to kinetic energy of the collision partners, to energetic free electrons, or to photons. In most cases the energy is distributed to at least two of the three possible channels.

Since the excited states of the product ions form a discrete spectrum, information about state selective electron capture can be obtained through measurements of either kinetic-energy change or through electron or photon spectroscopy. Obviously the three different ways of gaining information about excited state populations have their advances and disadvantages which will be discussed and illustrated in my talk.

A characteristic feature associated with electron capture by multiply charged ions is that only a narrow band of excited states is populated. I will discuss simple models which

explain this behaviour such as the classical over-barrier transition model and the Landau-Zener model. Measured state selective electron capture cross sections for ions with charge states 4+, 8+, and 18+ will be used as examples in order to illustrate general dependencies and collision energy, projectile charge state, and target ionization potential.

Our recent work on state selective electron capture studies by means of energy gain-, photon-, and electron spectroscopy is described in the following three articles:

Energy-gain spectroscopy of state-selective electron capture for multiply charged Ar recoil ions, by E.H.Nielsen, L.H.Andersen, A.Bárány, H.Cederquist, J.Heinemeier, P.Hvelplund, H.Knudsen, K.B.MacAdam, and J.Sørensen. J.Phys.B 18 (1985) 1789-

Cross sections $\sigma_{n\ell}$ for electron capture collisions between medium velocity, highly charged ions, and molecular hydrogen, by J.Sørensen, L.H.Andersen, P.Hvelplund, H.Knudsen, L.Liljeby, and E.H.Nielsen. J.Phys.B 17 (1984) 4743-

Experimental investigation of the mechanisms creating projectile continuum electrons in highly charged ion-atom collisions, by L.H.Andersen, M.Frost, P.Hvelplund, and H.Knudsen. J.Phys.B 17 (1984) 4701-

Multi-Electron Effects in Ion-Atom Collisions. J. F. READING and A. L. FORD, Texas A&M U. Atoms have more than one electron. This forbids many transitions because electrons are fermions. Nevertheless because of the inclusive nature of many types of experiment such as characteristic Auger or x-ray emission measurements the role of these Pauli correlations is often surprisingly suppressed. This is called the single electron theorem. If more than one state is measured, e.g. charge transfer accompanied by an x-ray these Pauli correlations often small because of incoherence can become large. This occurs when coherence is present and is called a CESIME process. Calculations will be presented which illustrate these effects.

Another important correlation is the electron-electron force. This is more apparent in two electron transitions such as double ionization. A new theoretical method of accurately computing such cross sections, the Forced Impulse Approximation will be described, and compared to recent experiments.

Applications of the Classical Trajectory Monte Carlo (CTMC) Method to Charge Exchange

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The history of the CTMC method (Abrines and Percival[1], Olson and Salop[2], Olson [3], Hardie and Olson [4] is summarised, and the extensions to general central potentials by Peach et al [5], with applications by Willis et al [6] discussed at more length, illustrated by the TFD potential for N^{q+} (q = 1,5) and the distribution of momentium in the ground state of He. A comparison is made for

$$He^+ + H \rightarrow \sum_{n,\ell} He(n,\ell) + H^+$$

of the use of bare Coulomb potentials, and of separate model potentials for the singlet and triplet states of He. Switching potentials are introduced and shown to be unsatisfactory for this case. A similar analysis is carried out for the symmetric case

$$He^+ + He^+ \rightarrow \sum_{n,\ell} He(n\ell) + He^{++}$$

In both cases the spin averaged results are in close agreement with experiment.

All stages of ionization of C,N and O in collision with H and He were examined[9] using a simple TFD model potential for each case

$$V(r) = -P(r)/r \qquad r \geq r_0$$
$$= -Z_{eff}(q-1)/r, \quad r < r_0$$

with

$$P(r) = q_v\left[1 - e^{-\gamma r}\right]$$
$$\gamma = r_0^{-1} \ln\left[q_v/(q_v - Z_{eff}(q-1))\right]$$
$$r_0 = (3\sqrt{2}N)^{2/3} Z_n$$

and a simple scaling law obtained for all cases: namely the modified total loss cross section

$$\tilde{\sigma}_L = Z_{eff}(T)\sigma_{cab} + \sigma_{ion}$$

is a universal function such that

$$\left(\frac{I_o}{I_H}\right)^2 \tilde{\sigma}_L / (Nq) = A\left\{\left(\frac{q}{\tilde{E}}\right)\left[1 - \exp(-\tilde{E}/a)\right]\right\}$$

with

$$A = 4.69\ 10^{-16}\ cm^2\ ,\quad a = 31.25$$

and

$$\tilde{E} = \left(\frac{I_H}{I_o}\right) E\,(keV\,amu^{-1}) / q.$$

Further applications[7] are made to

$$Au^{q+} + He \rightarrow Au^{(q-1)+} + He^+,\quad 7 \le q \le 25$$

showing good agreement with experiment at 100 keV amu^{-1} except for $10 \le q \le 15$. The effects of the pseudo-potential[18] are examined in detail for $Fe^{13+} + e^-$ and shown to be unimportant for q large for total cross sections, but to significantly alter the (n, ℓ) distribution of final states.

The distribution of captures among final (n, ℓ) states for bare ions on hydrogen is compared with the quantal results of Bransden and his collaborators[10, 11, 12] for He^{++} and Li^{3+} and satisfactory agreement found except (in some cases for final s- states) in the energy range

$25 \le E\,(keV\text{-}amu^{-1}) \le 75.$

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Fast Light Atom Beams: Collisional Production and Loss of Excited States

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Fast ion and atom beams are used for many different applications in Controlled Fusion Research. They serve to heat and fuel plasma as well as drive currents in tokamaks and reduce end losses in tandem mirror machines. Diagnostic applications are numerous and diverse with new techniques emerging constantly.

The atomic physics of fast light ion and atom beams has been studied for many years starting with electron transfer cross section measurements in gases in the late 1950's. Almost thirty years of investigation has resulted in a large body of information on atomic collisional properties of fast light ions and atoms, with the data readily accessible through the Controlled Fusion Atomic Data Center at Oak Ridge National Laboratory. These data have greatly aided our understanding and use of fast beams. Still, a complete picture of the fundamental collisional processes associated with the interaction of fast simple systems such as hydrogen, helium, and lithium is not available, and many interesting atomic physics questions remain unanswered. One area of interest is the collisional properties of excited states. Excited states in neutral beams enhance the stopping characteristics as well as introduce reionization losses. Fusion diagnostic schemes employing excited states are under active investigation, and the production of intense beams containing excited state distributions taylored to a particular application may prove useful.

The present talk will concentrate on some recent results concerning the collisional production and loss of excited states of fast simple atoms. In particular, two properties of neutral atom excited states will be discussed. Their formation via negative ion electron detachment collisions and their destruction via collisions with neutral perturbers. Recent excited state

formation cross sections measurements for H^- + H, H_2, and Ar collisions will be presented as well as results by other investigators for He^- and Li^-. Comparisons with excited state formation via electron capture will be made. Cross sections for excited state destruction via collisions with neutral atoms and molecules (Ar, N_2, CO_2, and SF_6) will be presented. Recent results show unambiguously that in the limit of high excitation a fast hydrogen atom behaves as two independent particles (e^-, p) in collisions with neutral perturbers.

Production of Polarized Beams

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Nuclear polarized beams of fast hydrogen ions for use in nuclear accelerators are produced using the following different polarized ion sources; (i) the atomic beam polarized ion source, (ii) the Lamb shift ion source, (iii) the colliding beam ion source, and (iv) the optically pumped ion source. Currently these polarized ion sources can produce polarized H^+ ion beams greater than 100 μA and polarized H^- ion beams of 1-35 μA. These beam currents are far below those that might be desired for use in fusion reactors. This talk will focus on operation of the optically pumped polarized H^- ion source and the prospects for increasing the current from polarized ion sources by collisional pumping.

Haeberli suggested the production of polarized ions using the capture of a polarized electron by an H^+ ion passing through an optically pumped alkali vapor.[1] Anderson[2,3] has analyzed the optically pumped ion source in detail. Mori et al.[4] have recently constructed and tested an optically pumped polarized H^- ion source. This ion source has produced an H^- ion current of 15-35 μA with a nuclear polarization of 0.6-0.4. Because of the large H^- ion currents and high nuclear polarization obtained, the optically pumped polarized H^- ion source is promising for future use with nuclear accelerators.

The optically pumped ion source work as follows. A beam of H^+ ions is extracted from an ECR ion source, which is in a large magnetic field. The H^+ ion beam is incident on a Na vapor target with an energy of 5 keV. This target, which is in the same large magnetic field as the ECR ion source and is colinear with the ion beam axis, is electron spin polarized by optical pumping with a dye laser beam. In this target some of the H^+ ions are neutralized by the reaction $H^+ + \vec{N}a^0 \rightarrow \vec{H}^0 + Na^+$ where the arrow indicates that the electron spin polarization of the Na target is transferred to the H^0 atoms that are produced in the reaction. The H^0 atoms are primarily formed in the n=2 level. The magnetic field at the target must be large enough that the orbital and spin angular momenta are decoupled in the n=2 level of hydrogen so that the electron spin polarization is not lost during the radiative decay to the n=1 level. The fast electron spin polarized n=1 level H^0 atoms emerge from the first target

and enter a second Na vapor target. The magnetic field at the second target is directed oppositely from the field in the first target. The fast electron spin polarized H^0 atoms pass suddenly through a region of near zero field between the two targets. This sudden passage through zero field transfers the electron spin polarization to the nuclear spin.[5] Some of the fast nuclear spin polarized H^0 atoms are converted to polarized H^- ions in the second target.

The following crude estimate of the potential H^- ion current shows why an optically pumped H^- ion source produces large polarized ion currents.[2,3] A 1W dye laser operating at a wavelength of 589.6 nm produces 3×10^{18} photons/sec. In a high magnetic field (I decoupled from S in the 3s level) 1.5 photons are required on the average to polarize a Na atom. Thus 2×10^{18} Na atoms can be polarized per sec. At a target temperature of 600°K, the average time between wall collisions is about 10^{-5} sec assuming the target is a long tube about 1 cm in diameter. Thus, even if the Na atoms are completely depolarized at each wall collision, a target with $\pi = 2 \times 10^{13}$ atoms/cm^2 is possible. The long target assures that little polarization is lost by effusion out the ends of the tube. The charge transfer cross section for the reaction $H^+ + Na^0 \rightarrow H^0 + Na^+$ is 6×10^{-15} cm^2 at 5 keV[6-8], so that about 12% of the incident H^+ ion beam picks up a polarized electron. Since the equilibrium fraction of H^- ions emerging from the second Na target is 7.3% at 5 keV[6-9], about 8×10^{-3} of the incident H^+ beam emerges from the second target as polarized H^- ions. Thus a current of about 8 μA of polarized H^- ions per mA of incident H^+ ions is expected. Both the technical problems involved in producing polarized H^- ions by charge transfer in an optically pumped target and possible improvements in the optically pumped polarized H^- ion source will be discussed in this talk.

The most important possible improvement in the optically pumped polarized H^- ion source is an increase in the Na target thickness. This is possible because of the discovery of wall coatings that permit a polarized Na atom to make a number of wall collisions before relaxation destroys the polarization. The most promising wall surfaces found so far are fluorocarbon rubber (such as viton or Fluor-L) with a relaxation time responding to about 15 wall collisions and dimethyl dichloro silane (dry film), with a relaxation time corresponding to about 50-150 wall collisions.[10]

If the polarized target can be substantially increased in thickness while maintaining a high polarization then repeated charge changing collisions will occur in the target resulting in a polarized beam produced by a process called

collisional pumping.[11,12] In order to understand collisional pumping, let us consider a H^+ ion beam incident on an alkali vapor with an energy of a few $keVu^{-1}$ or less. Unlike the situation for the optically pumped ion source, collisional pumping can occur in a low magnetic field so that in the ground level of the hydrogen atom the electron spin $\vec{J}$ and the nuclear spin $\vec{I}$ are coupled together to form total angular momentum $\vec{F} = \vec{J}+\vec{I}$. Therefore F and m_F (the eigenvalue of the projection of $\vec{F}$ along the magnetic field direction) are good quantum numbers. This requires a field B much less than the critical field B_c (hyperfine energy splitting divided by the Bohr magneton), which is 507 G for hydrogen. Following capture of a polarized electron by a fast ion, the hyperfine interaction transfers some of the electron-spin polarization into nuclear spin polarization. This occurs as follows. When the proton spin is parallel to the spin of the captured electron, the nuclear spin is unaffected; but when the proton spin is antiparallel to the spin of the captured electron, the hyperfine interaction causes both the electron and nuclear spins to oscillate while maintaining an m_F of zero. The combination of these effects leads to a net nuclear-spin polarization of 0.5, provided that the collision frequency is less than the hyperfine frequency. A subsequent electron-capture collision forming a H^- ion does not affect the nuclear spin. The cross section to strip an electron off a H^0 atom is negligibly small in alkali vapors at energies of a few $keVu^{-1}$. Subsequent electron stripping followed by capture of another polarized electron in the target further increases the nuclear polarization of the beam. Thus a succession of electron-capture and -loss collisions "pumps" up both the electron-spin and the nuclear-spin polarization of the fast beam. In the limit of very thick alkali target with an electron spin polarization of one, the fast hydrogen beam will be almost entirely in the F=1, m=1 state because this state can not capture a polarized electron.

Collisional pumping effects are also important for higher energy hydrogen beams passing through thick polarized hydrogen or alkali targets.

Problems such as radiation trapping, associated with producing thick electron spin polarized alkali or hydrogen targets will be discussed.

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RESONANT CHARGE TRANSFER IN ATOM-METAL COLLISIONS

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During the past few years we have investigated the resonant charge transfer mechanism in scattering a particle beam from a cesiated W(110) surface. Both positive ionization of alkali atoms and negative ionization of hydrogen atoms has been studied. We report measurements of the so-called ion formation probability, which is defined as the probability that a scattered particle is (positively of negatively) ionized after scattering from the surface, in dependence of the surface work function, particle velocity, etc. Especially grazing angles of incidence and of detection are investigated.

The underlying physics of surface ionization is shortly recalled. Close to the surface an ion induces an image charge in the metal, which induces a shift of the atomic affinity level. Electrons tunnel between the atom and the metal conduction band, thus giving rise to a finite level width. The probability that a static atom at a distance z from the surface is ionized is then determined by the overlap between the shifted and broadened affinity level and the conduction band. The ionization probability for a moving particle can be calculated from this quantity with a semi-classical theory.

It is found experimentally that the negative ion formation probability for scattered hydrogen atoms has a sharp maximum as a function of the cesium coverage at approximately 0.6 monolayers, where the surface work function has its minimum value of 1.45 eV. This maximum is observed for all primary energies in the investigated range (50-2000 eV). Its value depends strongly on the particle velocity after scattering, both normal and parallel to the surface. It is independent of the angle of incidence. The absolute maximum of this probability (0.67) is observed at a primary energy of 100 eV and a reflection angle of 70^{o}. The energy after scattering is roughly 85 eV. Our measurements are reasonably consistent with the results of a model, which is based on the theory outlined above.

We have found that the negative ion formation process is extremely sensitive to the presence of hydrogen on the W(110) surface. An experiment has been done in which hydrogen is either implanted by the primary beam, or adsorbed from the gas phase. In both cases a hydrogen coverage of the order of 0.5-1 monolayer leads to a reduction of the negative ion formation probability of roughly a factor of 5, whereas the work function of the surface is not affected. Furthermore, the reduction of the negative ion formation probability is found to be proportional to the number of adsorbed hydrogen atoms. This implies, that each individual hydrogen atom acts as a local "sink" for negative ion formation. A possible explanation for these phenomena is charge exchange between adsorbed atoms and negative ion projectiles.

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To investigate the interaction of projectiles with individual adsorbate atoms in more detail we have scattered Li^+, K^+ and Cs^+ ions from a cesiated W(110) surface to study the positive ion formation probability. For lithium and potassium it is found that the surface cannot be characterized by a single work function. The formation probability decreases linearly with increasing cesium coverage, which implies that the ionization process is governed by the local electrostatic potential of the individual cesium atoms rather than by the work function of the entire surface. In contrast to this, in the case of cesium the measurements show a direct dependence on the work function. These phenomena can be understood qualitatively by comparing the depth of the electrostatic potential well of an adsorbed cesium particle with the position of the ionization level of the projectile at the so-called freezing distance.

Finally, our measurements attribute to a better understanding of the physical processes in a surface conversion negative-ion source. Two basic effects are now recognized. First, the negative ion formation probability is strongly reduced by implantation of hydrogen into the convertor surface. Secondly, the equilibrium cesium coverage on the "converter" in a high density source, which can be calculated by balancing the fluxes deposited on and sputtered from its surface, is of the order of 0.25 monolayers only. This leads to a further reduction of the formation probability.

ATOMIC AND MOLECULAR PROCESSES IN NEGATIVE ION PLASMAS*

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Abstract

Negative ions are generated in hydrogen discharges via several processes including polar dissociation, dissociative recombination of molecular ions, dissociative attachment through excited electronic states, and dissociative attachment to vibrationally excited molecules. Upon examining the relative magnitudes for each of these processes the latter is found to be dominant in low temperature plasmas and for discharges optimized for maximum H^- production. The dissociative attachment process has been modelled in two approximations: [1-3] via an intermediate H_2^- resonance state or a direct electron capture induced by non-adiabatic coupling. These two approximations yield cross-sectional dependences in agreement with experimental values[4] for the lower portion of the vibrational spectrum but exhibit some differences in the upper portion of the spectrum. For maximum negative ion concentration or extraction, the dissociative attachment process maximizes for an electron temperature near one electron-volt.

The equilibrium concentration of ions is dependent upon the negative ion loss processes. These principal loss processes include electron collisional detachment,[5] associative detachment through collisions of free atoms and ions,[6] ion-ion neutralization,[7] and ion-molecule collisions.[8]

The principal sources of molecular vibrational excitation are low-energy electron excitation via the negative ion resonance,[1] high energy electron

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excitation via the excited electronic singlet states,[9,10] and molecular ion auger-neutralization in wall collisions.[11] The explication of negative ion generation places emphasis on the formation and loss processes determining the steady-state vibrational population distribution in the upper portion of the vibrational spectrum. Principal vibrational loss processes are due to wall relaxation,[12] molecular collisional relaxation or V-T processes,[13] atomic relaxation collisions,[14] and high-energy-electron excitation processes.[15] The vibrational population distributions scale in a simple way with plasma dimension and density. The two-step nature of the negative ion formation process implies a specific discharge geometric configuration for optimum negative ion generation.

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CONTRIBUTED PAPERS

ELECTRON IMPACT IONIZATION OF HELIUM AND LITHIUM-LIKE IONS

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In the past few years the electron impact ionization of atomic ions has received great attention, especially in connection with fusion plasma studies. Among various quantum approximations the DWE method of Younger [1] is particularly attractive as it produces reliable ionization cross sections for reasonable small computing cost. In our calculations we have employed Younger's approximation for the direct scattering amplitude, but we have calculated the exchange amplitude in the standard way, rather than in the "unphysical" model of Younger.

Table 1 presents our scaled DWE ionization cross sections (uI^2Q in units of $\pi a_o^2 Ry^2$) for the realtive impact energy $u=E_i/I$, I being the ionization potential of the target. At this energy the effect of the electron exchange is maximum.

Target	Li II	B IV	N VI	BIII	C IV	N V	O VI
uI^2Q	3.59	3.97	4.06	1.66	1.80	1.86	1.93

Table 1.

Our results are by 1.5 to 5% higher than the DWE results of Younger, being in better agreement with the crossed beams measurements of Crandall et al [2]. Only for Li^+ Younger's data agree better than ours with the measurements of Peart and Dolder [3].

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CHARGE EXCHANGE SPECTROSCOPY ON DITE AND ASDEX

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Measurements of the enhanced line emission from hydrogenic Oxygen and Carbon ions during beam injection of hydrogen atoms in a Tokamak plasma have been made using multichannel detector spectrometers. Observations of the spectrum on DITE (with a primary neutral energy of 25 keV) encompass the Lyman series in the XUV region (1s - np, $n < 9$), $\Delta n=1,2$ transitions in the VUV and visible transitions, and in ASDEX (with a primary neutral energy of 42 keV) the VUV ($n > 1$) and visible ($n < 12$) transitions have been studied. Analysis of the effective excitation process for each observed transition involves the cascade correction of theoretical charge exchange cross sections to bare ions and electron impact excitation of the hydrogenic ion state. The effective excitation cross sections thus derived automatically produce a sensitivity calibration for multichannel instruments for transitions dominated by C/X.

The plasma environment can modify the cascade correction and impact excitation processes by mixing of the atomic levels from ion collisions and atomic level perturbations caused by the ambient magnetic and electric fields. The rates for these processes are compared to the atomic decay rates as a function of plasma density and temperature and the consequent changes in the cascade correction is presented. The X-ray resonance transitions in the DITE experiments are thought to be dominated by electron impact excitation of the hydrogenic ground state, following changes in the ionisation balance caused by the neutral heating beams. In contrast the Y-rast lines in the VUV and visible in both experiments seem to be dominated by prompt C/X excitation.

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Electronic properties of hot dense plasma

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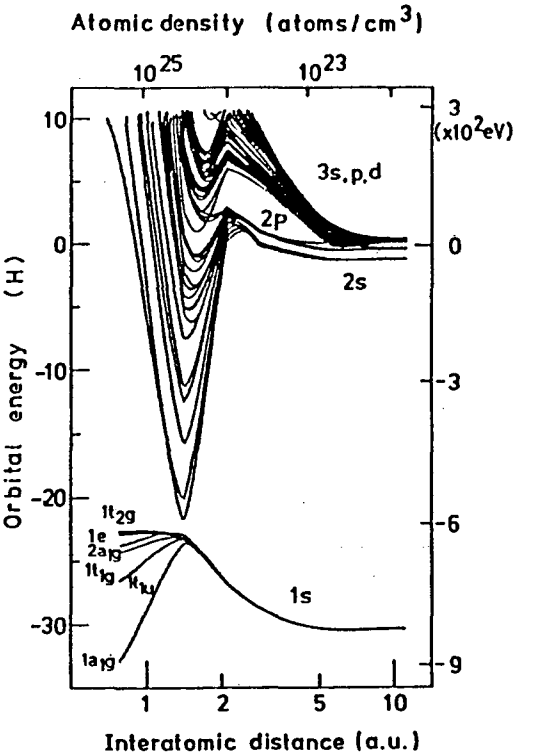
The knowledge on electronic properties of hot dense plasma, generated by ICF, is indispensable for the study of radiation heating and/or cooling and energy loss rate of charged particles etc. Most theoretical works to these ends are based on an atomic picture, in which effects of high temperature and density are taken into consideration by assuming an appropriate effective potential. Though the wave functions of a single atom in those works reflect the perturbations from surrounding ions in an indirect manner, the mixing of atomic wave functions with those of neighboring ions is thoroughly neglected.

In order to estimate this contribution to the electronic properties of plasma, we have tried a molecular calculation for neon clusters using the Discrete Variational X_α method. The density considered here is up to about one thousand times that of usual solid. The temperature is from 0 to 1 KeV.

The repulsive interaction between electrons and the kinetic energies of them increase as plasma density goes high. On the contrary, valence electrons lower their energies by making bonding orbitals. Because of these competitive effects energies of valence electrons do not change monotonically upon the density.

Since most electrons are thermaly ionized at high temperature, electron population in bonding orbitals becames small. This makes the results of cluster calculation close to those of atomic.



Orbital energies for a neon cluster at T = 0 eV.

POLAR DISSOCIATION OF H_3^+

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The need for intense negative hydrogen ion beams for neutral beam injection systems has led to interest in the processes giving rise to H^- production in low and medium density hydrogen discharges. In such discharges H_3^+ ions are present in a significant, if not dominant, concentrations. Therefore H^- production involving these ions needs to be considered. There are two processes of particular interest:

1) Dissociative attachment to H_3^+ by thermal electrons:

$$H_3^+ + e \rightarrow H_3^* \rightarrow H_2^+ + H^-$$

This can be neglected following experimental measurements[1] that indicate a peak value for this cross section of about $1.6 \times 10^{-18} cm^2$.

2) Polar dissociation of H_3^+ by fast electrons:

$$H_3^+ + e \rightarrow (H_3^+)^* + e \rightarrow H^+ + H^- + H^+ + e$$

In the absence of any experimental or theoretical estimates of the magnitude of the cross section, this process has in the past been ignored. However, recent gas phase collision measurements[2] have indicated the cross section might be quite large and there is now a new interest in the process.

We are using an electron-ion crossed beam apparatus[3] at the Culham Laboratory (UKAEA/Euratom Fusion Association) to measure the cross section for polar dissociation of H_3^+. The results to date are preliminary and only relative measurements for electron energies from 8 to 150eV are available.

The dependence of the H^- production cross section on electron energy exhibits two maxima. The lower energy maximum is due to dissociative attachment. The second broad maximum centred around an electron energy of about 80eV is evidence of polar dissociation. The maximum value of this structure is approximately equal to that for dissociative attachment. If the present low electron energy measurements are normalized to the dissociative attachment cross section of Peart et al[1], this yields a maximum value for the polar dissociation cross section of $7 \pm 4 \times 10^{-19} cm^2$. This is consistent with recent gas phase polar dissociation cross section measurements[4] and indicates that the polar dissociation of H_3^+ does not play a significant role in the production of H^- in hydrogen discharges.

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CHARGE EQUILIBRIUM OF FAST HEAVY IONS TRAVERSING THROUGH HYDROGEN GAS TARGET

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The charge distribution of an incident ion as a function of projectile velociy, its range and its average equilibrium charge are studied theoretically. The calculations are made for atomic hydrogen gas target. The charge of the ion is determined by the equilibrium between electron loss from the ion and electron capture from a hydrogen atom to the ion. The charge states of the ions are calculated in two cases; to assume a local balance condition for the electron loss and capture process and to solve a rate equation for the charge state fraction function under non-local balance condition, both only taking into account of single electron loss and capture processes. In the calculations we use empirical formulas for electron loss and capture cross section by making some simplification. Calculations for the charge state fraction as functions of ion ranges under non-equilibrium condition have been carried out in the cases of Ne, Ar, and Xe ions. Calculations for the charge state under local balance condition have been made in the cases of C, Ne, Ar, Kr, I, and U ions.

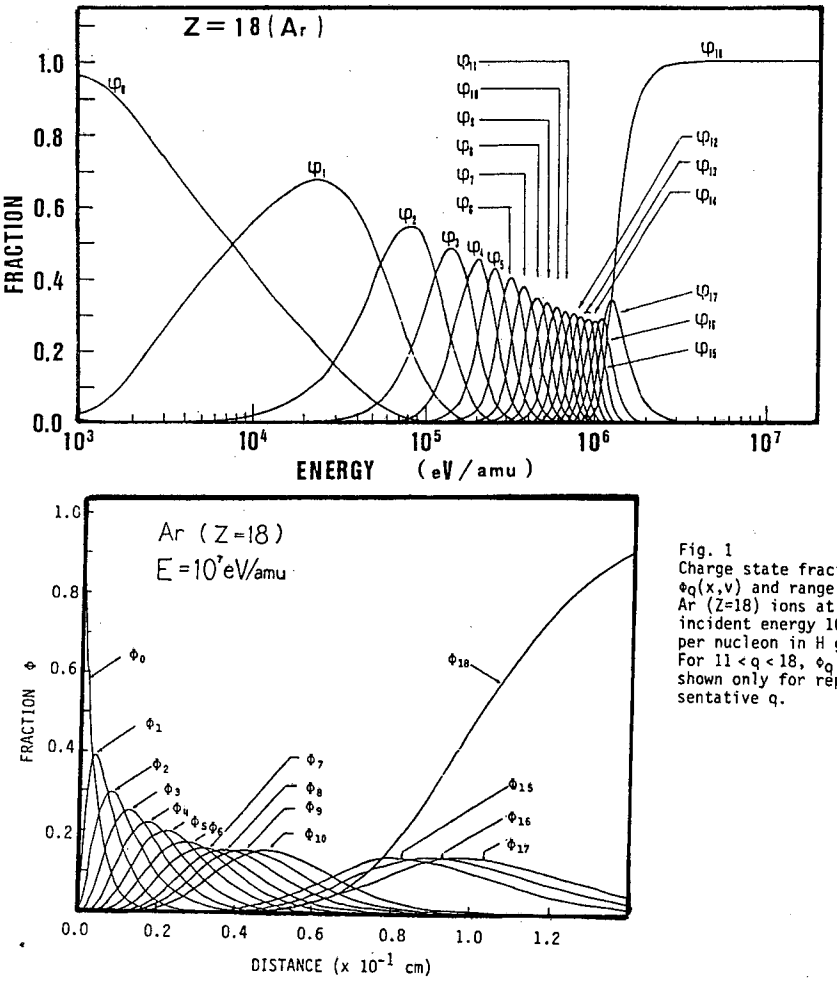

Fig. 1
Charge state fractions $\Phi_Q(x,v)$ and range x for Ar (Z=18) ions at incident energy 10 MeV per nucleon in H gas. For $11 < q < 18$, Φ_Q is shown only for representative q.

Observations of Charge-Transfer Recombination in Alcator C.

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X-ray spectra of He-like argon (Ar^{+16}) have been obtained for the transitions $1snp \rightarrow 1s^2$, with $3 \leq n < \infty$, from Alcator C tokamak plasmas. In the periphery of the plasma, the n = 9 and 10 and $15 < n \leq 40$ levels are predominantly populated by charge transfer to Ar^{+17} from intrinsic neutral hydrogen in the ground and first few excited states. Neutral hydrogen density profiles are deduced from these measurements. The first experimental observations of the reactions Ar^{+17} $(1s\,^1S) + H_o^*$ (n = 2,3) $\rightarrow Ar^{+16}$ $(1snp\,^1P) + H^+$ are presented and their cross sections are examined. In addition a simple energy conservation model is presented and used to predict the n levels which should be predominantly populated in the recombined ion.

This work has been supported by U.S. Department of Energy Contract No. DE-AC02-78ET51013.

Compilation and Evaluation of Atomic Data for Fusion in Japan Atomic Energy Research Institute

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Compilation and evaluation of atomic and molecular (A&M) data for fusion in JAERI have been carried out by A&M Section of Nuclear Data Center in cooperation with the Research Committee on A&M Data consisting of the members of in and outside of JAERI.

1. Atomic Collisions: Experimental data of atomic collision processes mainly on charge transfer and related processes relevant to fusion researches have been compiled and evaluated. For the particle probe diagnostics of JT-60, an injection system of He^{o} of 200 keV, 3.5 amp has been constructed in parallel with neutral beam heating system. In these systems, the processes

$$A^{q+} + B \rightarrow A^{(q-1)+} + B^{+} \qquad (1)$$

and

$$A^{q+} + B \rightarrow A^{(q-1)+*} + B^{+} \rightarrow A^{(q-1)+} + B^{+} + h\nu \qquad (2)$$

are important for measurements of impurity densities and ion temperature. A universal semiempirical formula of cross sections of process (1) is given for practical use of these data. Cross section data for the process (2) involving capture into specific excited states (nl) of the product ions in H, H_2 and He have been available from 1982, and we have started to compile this process from 1984.

2. Particle-Material Interaction: (1) Data on elemenary processes for hydrogen recycling in fusion materials, (2) surface effects on damaged profiling in materials by ion bombardment, and (3) electron-material data are now being compiled and evaluated.

3. Atomic structure: Atomic energy level, spectroscopic, and transition probability data of ionized atoms of wall materials such as Ti, Fe, Ni, Mo, Nb etc. are being compiled and evaluated in the forms of wavelength tables and Grotrian diagrams.

All the compiled data of above three items are now stored in our computer system by our own formats. Some of them are available to interested users on magnetic tapes on their requests as well as other informations related to these data compilations, which have been published as JAERI-M reports.

Progress in Developing a Negative Ion Based Neutral Beam Injection System

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Abstract

Future large tokamaks may require neutral beam injection at energies above 80 kV/nucleon. Given the poor neutralisation efficiency of positive ion beams at these energies, a neutral beam injection system based upon negative ions will be required.

Recent progress at Culham Laboratory in the development of such a system will be reported. This will include:

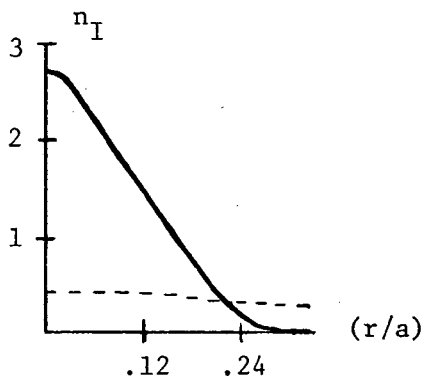
(a) The operation of a volume source to produce an H^- beam of 60 mA cm^{-2}.

(b) An investigation into the control of the electron beam also extracted.

(c) The performance of an optimised 30 kV negative ion accelerator.

GIANT IMPURITY SAWTOOTH FOLLOWING PELLET INJECTION IN ALCATOR.*

R. D. Petrasso, J. Parker, M. Greenwald, MIT -- By using x-ray arrays, an enormous impurity sawtooth has been observed to sometimes occur in the Alcator tokamak approximately 40 msec after the injection of frozen hydrogen pellets. Just before the internal disruption (i.e., sawtooth crash), a dramatically peaked impurity profile resides in the plasma center (plasma $Z_{eff} \sim 1.3$). The impurity profile is given approximately by a parabola to the 40th power, for $r/a \lesssim 0.3$ ($a = 16.5$ cm the limiter radius). In contrast, the electron density profile is given approximately by a parabola to the 2nd power. In this same region, the convection parameter, $aV_o/2D$, is approximately 40. (V_o, the convection velocity, and D, the particle diffusivity, appear in the impurity flux equation $\Gamma_I = - D\nabla n_I - n_I V_o\, r/a$.) This situation is also to be contrasted to typical (non-pellet) Alcator discharges where $aV_o/2D \sim 1$.[1,2] As shown below, just after the sawtooth crash the central impurity density is reduced by a factor of 10. Usually no dramatic repeaking of the impurities occurs after this sawtooth; this indicates that particle transport dramatically changes at this time.



The central impurity profile (in relative units), just before (solid line) and just after (dashed line) the sawtooth crash.

1 "Fully-Ionized and Total Silicon Abundances in the Alcator-C Tokamak," R. D. Petrasso, F. H. Seguin, N. G. Loter, E. Marmar, and J. Rice, Phys. Rev. Lett. 49 (25) 1826, 1982.

2 "Studies of Fully-Stripped Silicon in the the Alcator-C Tokamak," R. D. Petrasso, N. Loter, F. H. Seguin, E. Marmar and J. Rice, Bull. Am. Phys. Soc. 27 (8) 1037, 1982.

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* Work supported in part by the Experimental Plasma Research Branch of the Office of Fusion Energy.

INFLUENCE OF DYNAMIC SCREENING EFFECTS ON THE RATES OF INELASTIC COLLISIONS IN THE DENSE PLASMAS

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In the serveral investigations (see e.g. [1,2,3]) devoted to the study of the dense, laser-produced plasmas an assumption is tacitly made, that the plasma does not influence the rates of different inelastic collisions, e.g. the rates of the electron induced atom excitation and ionisation. But, in fact, the dynamic screening effects pronounced at the high plasma densities can influence essentially the rates of these processes. It was found, for instance, in [4]) that the rates of an atom excitation from the ground state by the electrons calculated in the Born approximation are smaller than those calcualted neglecting of these effects by a factor $(\omega_o/\omega_p)^4$) if $\omega_p >> \omega_o = \Delta E/\hbar$. (Here ω_p is the plasma frequency and ΔE is the atom transition energy).

In this paper the calculations described in [4]) are extended in several respects:

1) The rates of the electron induced transitions between excited levels of hydrogenics are calculated with the dynamic screening effects taken into account under an assumption that the plasma is a classical one;
2) The rates of the electron induced ionisation of hydrogenics are calculated under the same assumptions;
3) The rate coefficients obtained in this way are applied for calculation of the effective recombination and ionisation coefficients for the plasmas of the type studied in [3]).

It was found that the three body recombination coefficients can be strongly reduced as a result of the dynamic screening effects.

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Attenuation of a 100 KeV Lithium Beam in a Plasma. E.J. SYNAKOWSKI, S.B. ZHENG, ROGER D. BENGTSON, W.P. WEST and DAN M. THOMAS, The University of Texas at Austin and GA Technologies, Inc. Attenuation and excitation of a 100 KeV lithium beam used for current profile measurements on the TEXT tokamak has been modeled via a collisional radiative model. The population of the 2p level has been calculated as a function of position both with and without a coaxial exciting laser turned to the 2p-2s resonance line. Charge exchange, ionization, and collisional excitation processes for electrons, protons, and heavy impurities were considered along with laser excitation. Reasonable agreement with experimental data is obtained. The effects of mixing between Zeeman levels due to collisions are examined.
*Work supported in part by the DoE Contract Nos. AT03-84ER53158 and AC05-78ET53043.

ELECTION IMPACT IONIZATION OF $A\ell^{+*}$

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We have calculated the cross sections for the electron impact inner-shell excitation of $A\ell^+$ using the R-matrix method.[1] The autoionizing states arising from the $2p^5 3s^2 3p$, $2p^5 3s^2 3d$ and $2p^5 3s^2 4s$ configurations are believed to give the most important contribution to the excitation-autoionization cross sections. These states together with the ground $3s^2\ {}^1S^e$ and $3s3p\ {}^{1,3}P^o$ states are included in the R-matrix expansion. In order to account for resonant-excitation-double-autoionization process which may give significant contribution to electron impact ionization, we included large number of bound terms of appropriate symmetry in the expansion.

The excitation energies and the oscillator strengths of the terms are calculated using the configuration-interaction program.[2] For the study of excitation-autoionization we are interested in the transitions of the type $3s^2\ {}^1S^e \rightarrow 2p^5\ 3s^2 3p\ {}^{1,3}S^e,\ {}^{1,3}P^e,\ {}^{1,3}D^e,\ 2p^5 3s^2 3d\ {}^{1,3}P^o,\ {}^{1,3}D^o,\ {}^{1,3}F^o$, and $2p^5 3s^2 4S\ {}^{1,3}P^o$ followed by decay by autoionization. The total cross section is the sum of the excitation cross sections for all these transitions. At each electron energy results are obtained for nine values of angular momenta L = 0 to 8. These partial waves gave converged cross sections for many transitions. However, for transitions where convergence could not be achieved with nine partial waves, the contribution from higher partial waves has been calculated using program NIEM.[3] The results will be presented at the meeting.

*Supported by DOE, Office of Basic Energy Sciences.

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DIFFERENTIAL ELECTRON SCATTERING CROSS SECTIONS FOR THE FIRST OPTICALLY FORBIDDEN AND RESONANCE TRANSITIONS IN MgII, ZnII and CdII

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The electron energy loss method is used in a crossed electron-ion beams apparatus[1] to measure differential electron scattering cross sections in MgII, ZnII and CdII at a center of mass (electron) energy of 50 eV. The electron beam, of energy resolution of 0.55 eV (FWHM), was made to intersect the ion beam at 90°, and inelastically scattered electrons were detected by a 180° hemispherical electrostatic analyzer in the angular range $4^\circ \leq \theta \leq 17^\circ$. Scattered electrons were detected at energy losses corresponding to the resonance and first optically forbidden transitions in the ions investigated.

Relative differential cross sections (DCS) were obtained for the $ns^2S \rightarrow np\ ^2P$ resonance transitions in these ions, where n = 3,4 and 5 correspond to transitions in MgII, ZnII and CdII respectively. The area under the energy loss peak was measured at each angle, and the relative data made absolute by normalizing the measured cross section in MgII to theory[2] at $\theta = 12^\circ$.

We report for the first time anywhere DCS for an optically forbidden transition in an ion. The ratio of the area under the energy loss peak for the first optically forbidden transition, to the area under the energy loss peak for the resonance transition was measured at each angle. Using the known DCS for the respective resonance transitions, cross sections were obtained for the unresolved $3s\ ^2S \rightarrow 3d\ ^2D$, $4s\ ^2S$ transitions in MgII and the $5s\ ^2S \rightarrow 5s^2\ ^2D$ transition in CdII. Due to the low signal in the $4s\ ^2S \rightarrow 4s^2\ ^2D$ transition in ZnII, only an upper limit estimate could be made for the DCS at $\theta = 12^\circ$.

The cross sections for the forbidden transitions in MgII and CdII are comparable to those of their respective resonance transition. In MgII the slope of the DCS for the optically forbidden transition is found to be shallower than the slope for the resonance transition, whereas for CdII the slopes of the $5^2S \rightarrow 5^2P$ and $5^2S \rightarrow 5s^2\ ^2D$ transitions are found to be similar. Moreover, results show that at 50 eV the cross section for the resonance transition is largest for CdII followed by MgII and ZnII. This is inconsistent with the measured oscillator strengths for these transitions, which show MgII as the largest, followed by ZnII and CdII.

This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

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IMPURITY SPECIES EVOLUTION AND NEUTRALISATION RELEVANT TO NEUTRAL BEAM INJECTORS

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The high energy hydrogen atom beams used for the supplementary heating of plasmas in Tokamak devices are formed by electron capture neutralisation of a hydrogen ion beam usually extracted from an electron bombardment ion source. The numerous impurity ions also formed in the source are neutralised and enter the plasma where they enhance the energy loss mechanism. Experimental data on the neutralisation of beam impurity ions as a function of neutraliser target thickness (usually H_2) enables the optimum target thickness conditons to be established and allows estimates of the impurity content to be made from impurity analysis carried out on the ionised fraction in a thick target using, for example, magnetic momentum analysis.

We have measured the fraction of an ion beam in varius charged states -1, 0, +1 and +2 ($F_{\bar{1}\infty}$, $F_{0\infty}$ etc) after equilibrium has been established. The ions C^+ N^+ O^+ Cu^+ and Mo^+ were studied in passage through hydrogen gas within the energy range 10-100 keV. At 30 and 80 keV the evolution of the neutral and charged components has been recorded as a function of H_2 target thickness. In addition molecular ions OH^+, H_2O^+ and CH_n^+ (n = 1 - 4) have been passed through the target and the evolution of ion fragments has been monitored as a funciton of target thickness at 30 and 80 keV energy. Information on the neutral beam component has been deduced.

This work was carried out with the support of the UKAEA Culham Laboratory.

Impact Excitation of Fine-Structure Levels in Hydrogen-Like Ions B. Zygelman and A. Dalgarno, Harvard-Smithsonian Center for Astrophysics.-- Close coupling calculations for proton and electron impact excitation of the fine structure levels in hydrogen-like ions are presented. These calculations are used to obtain line intensity ratios for the Lyman-alpha components in the ions Ar^{+17}, Mg^{+11}, and C^{+5}. The effect of relativity on proton impact excitation cross sections of Ar^{+17} is investigated. We also present close-coupling results when the long range Coulomb proton-ion interaction is replaced by a short range Debye-Huckel potential. Some preliminary results for the excitation of Helium-like ions by protons are presented. Work supported by the U.S Department of Energy.

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