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ATOMIC PHYSICS IN THE CONTROLLED THERMONUCLEAR RESEARCH PROGRAM

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A. INTRODUCTION

Since the beginning of thermonuclear research in the USA in the early 1950s, high temperature plasma parameters have been dominated by atomic processes. For the first twenty years the plasma physicists were preoccupied with plasma instabilities and diverted little of their attention to atomic processes occurring in the plasma. Only in the past few years with the success of toroidal plasmas of the tokamak type has it become evident that atomic physics is of vital importance to the understanding of plasma heating, cooling, and diagnostic. More recently, as plasma engineers have started conceptual designs of proto-type fusion reactors, the need for the solution of atomic physics problems occurring in high temperature plasmas has become urgent.

The importance of atomic physic problems becomes very real if we compare the atomic and nuclear cross sections for particles in a thermonuclear reactor. For a 10 keV ion temperature D-T plasma the nuclear cross section to produce a neutron with 14 MeV energy is 10^{-29} cm^2. The charge exchange cross section for a resonance collision is approximately 10^{-15} cm^2. Thus, if we equate the reaction rate for production of neutrons to the loss of a deuteron we have

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$$n_D n_T \sigma_N v_D = n_O n_D \sigma_A v_D$$

where n_T and n_D are total tritium and deuteron densities and n_O is the density of neutral particles. The velocities are the same so that $n_T \sigma_N = n_O \sigma_A$. For a plasma with a deuteron density of 10^{14} cm^{-3} we are left with the requirement that $n_O = 1$ cm^{-3}. If we only require an energy breakeven, we can relax the neutral density requirement by the ratio of energy gained to energy lost, which is 10^3. Thus, the neutral density for energy breakeven is 10^3 cm^{-3}. These conditions are extremely difficult to achieve in present-day plasmas.

In this report the atomic processes involving plasma heating, cooling and diagnostics will be discussed. Also, of interest are those atomic processes involved in the interaction of a high temperature plasma with the vacuum wall. Due to time and space limitations these processes will not be discussed. In the interest of brevity remarks will be confined to tokamak type plasmas, whose present parameters are

T_e (electron temperature)	- 1 - 2 keV
T_i (ion temperature)	- 0.5 - 1.0 keV
n_e (electron density)	- 2.5 x 10^{13} electrons/cc
τ_E (energy containment time)	- 5 - 10 x 10^{-3} sec
T (pulse time)	- 50 - 300 x 10^{-3} sec
r (minor torus radius)	- 10 - 30 cm
R (major torus radius)	- 0.5 - 1.0 m
I_p (ohmic heating current)	- 100 - 300 kA

The corresponding parameters of planned proto-type reactors are

T_e - 5 - 10 keV
T_i - 10 keV
n_e - 5 x 10^{13} - 5 x 10^{14}cm^{-3}
τ_E - 1-4 sec
r - 1 m
R - 4 m
I_p - 2 - 3 MA

B. PLASMA HEATING

In the past, heating of toroidal plasmas has been accomplished by applying a current pulse to a set of toroidally-wound coils. The plasma acts as the secondary winding of this set of coils and a voltage of 2 - 5 volts is induced around the torus. This induced voltage supplies the driving force to heat the electrons which in turn transfers energy to the plasma ions. As the electrons approach energies of 1-2 keV the effective energy transfer through coulomb collisions from electrons to ions approaches zero such that the ions are no longer heated. Thus, supplementary ways must be found to heat the ions.

One approach to supplementary heating is to inject into the plasma large currents of neutral atoms and through resonant charge exchange collisions with plasma ions, the resulting energetic protons are captured by the confining magnetic field. These protons thermalize by energy transfer to both ions and electrons. In injection heating, it is necessary to have knowledge of the collisional processes in the ion source and the conversion cell where neutrals are formed.

For present day injection heating experiments pulsed ions sources have been developed for ion currents up to 50 amps and energies of 10-25 keV with a pulse length of 20 millisec. In this energy range the atomic and molecular ions are converted in gas conversion cells through charge exchange and dissociative collisions. Of importance to the injection process is the rate at which impurity atoms from the ion source enter the plasma confinement region. Due to space charge blowup it is not practical to use magnetic analysis to preselect the beam current before neutralization. It is imperative that we know the electron capture cross sections of C^+, O^+, N^+, Pt^+, Fe^+ and Ta^+ in gases of H_2, He and N_2. Also, needed in order to assess the rate at which these impurity atoms enter the plasma are the electron stripping cross sections for atomic species of these ions in the energy range 10-150 keV.

As experiments proceed to the proto-type fusion reactor it is necessary to increase the injected particle energy to the region of 150-200 keV. Two methods have been proposed and are being developed to obtain neutral hydrogen beams at these high energies. (1) Negative D^- ions are obtained directly from an ion source, accelerated to the desired energy, and stripped in a suitable gas target. (2) Conventional positive ion sources are used, hydrogen beams are extracted at 1-2 keV, and passed through an alkaline vapor cell where 10-20% of the incident ions are converted to D^-. Our knowledge of the mechanisms producing D^- in the ion source is very limited. Collision cross sections involving electrons on D_2 or D_2^+ in various states of vibrational excitation need to be known over the energy range from threshold to 500 eV. Current experiments indicate that tremendous gains in negative ion source output can be obtained by contaminating the walls and cathode of the ion source with alkaline vapors. The reaction kinetics must be known for deuterium atomic and molecular neutrals and ions interacting with surfaces contaminated with Cs, Mg, Na and Li in the energy range 5-500 eV.

Conversion of atomic and molecular ions to D^- ions in a alkaline vapor cell demands a multiplicity of cross sections that are not presently available. Considerable work has been done for D^+ ions interacting with Cs, Na, and Li vapor. Of more interest than cross sections are the D^- equilibrium fractions formed in these vapor cells. Discrepancies of a factor of three exist in the D^- equilibrium fraction from Cs cells. Very little information is available for the formation of D^- from collisions of D_2^+ and D_3^+. Since the low energy D^- ions formed must be accelerated, it is imperative that we know the differential scattering cross sections for D^- production from both atomic and molecular species.

Cross sections are available for the stripping of D^- in many gases in the energy region 3-50 keV and above 300 keV. This intermediate region needs to be filled in. Of more importance the peak fraction of D^0 resulting from D^- stripping needs to be measured. As the stripping gas density is increased from 10^{13} cm^{-3} to 10^{16} cm^{-3} the D^0 fraction goes through a maximum and then decreases. These maxima need to be identified for gases such as H_2, He, N_2, O_2, Ne, Ar, and H_2O in the energy region 0.1-1 MeV.

In attempts to design and predict the behavior of the next generation plasma experiments, physicists must understand the trapping processes of the injected beam. If only hydrogen ions occur in the plasma, one can show that the injected neutrals will be trapped approximately uniformily across the magnetic field. However, with impurity ions present with moderate densities at the plasma boundary, the neutrals particles may be ionized locally, setting up an instability. This instability may occur in two ways: (1) large pressure and electric field gradients at the plasma boundary; (2) trapping at plasma boundary may lead to increased charge exchange loss. These particles will bombard the vacuum wall, giving more impurities, and resulting in a cascade process that will prevent any heating from the injected beam. We must know charge exchange cross sections for multiply-charged atoms of O, C, Fe, Au, and W with H and H_2 in the energy range 5-200 keV.

C. PLASMA COOLING

Atomic physic processes in a hot fully ionized plasma contribute an important cooling or loss mechanism which may limit the obtainable temperature in an operating thermonuclear plasma.

Ideally, a thermonuclear plasma would consist of deuterons and tritons. However, in existing plasmas, impurity ions and atoms are present in concentrations up to 5%. In some of the experiments it has been shown that up to 40% of the power loss of today's plasma was through line radiation from these impurities which have been estimated to be up to 40 times ionized. These impurities arise through particle and photon bombardment of the surrounding surfaces and from charged particle bombardment of the limiter. The limiter is an annular W or M_O ring placed at one point at the periphery of th. plasma to prevent circulating particles from burning a hole in the plasma vacuum wall. Under fusion conditions the temperature will be greater and these heavy impurities may be up to 70 times ionized. Thus, for heavy ions such as W the power loss may be so great that the temperature necessary for fusion may not be obtainable.

Transitions between atomic energy levels in fusion type plasmas involve excitation or ionization by electron collisions and subsequent de-excitation through radiative transitions. For energies several times greater than threshold the Born approximation may be used to compute the desired information. In the range of threshold the resonant transitions are the highest and are not amendable to Born calculations although some success has been achieved by using close coupling computations for predicting excitation cross sections. For contemporary plasmas a need exists for excitation and ionization cross sections for multiply-charged O and C particles plus the heavier impurity ions that may be present.

Two recombination processes are of critical importance in plasma cooling. These are (1) radiative recombination and (2) dielectronic recombination. The importance of radiative recombination lies in the Z^4 dependence of the recombination radiation. For impurity ions in the plasma the effective "Z" of partially stripped atoms will be the net charge of the ion before recombination. Some of the impurity ions (W, Nb, Mo, Au, Fe) will be only partially stripped for 10 keV plasmas. Thus, it is important to obtain recombination rates for these impurities in all states of ionization for plasma electron temperatures up to 20 keV.

Dielectronic recombination has been known to the astrophysicists for several years. In this process an electron colliding with an ion with bound electrons may be captured into a doubly excited state, which may decay into a bound state by emission of two or more photons and can be represented as follows

$$e + X^{n+} \longrightarrow [X^{(n-1)^+}]^{**} \longrightarrow X^{n+} + e$$

$$\longrightarrow X^{(n-1)^+} + h\nu + h\nu'.$$

The upper reaction is an excitation collision while the lower branch is a dielectronic recombination process and can be much faster in high temperature plasmas than radiative recombination collisions. In solar corona it is well known that dielectronic recombination is 10^2 times faster than radiative recombination. The damaging aspect of dielectronic recombination is the reduction of the equilibrium charge state and increased power losses from the impurities. Thus, this process may demand that impurities be reduced to an impracticable level.

When a free electron is accelerated and deflected as it passes a positively charge particle a photon is emitted. This process is referred to as free-free Bremsstrahlung and is an important process in plasma cooling. Bremsstrahlung losses due to heavy charged impurities will be very harmful or if a plasma is heated by wave interactions such that the applied power is to the electrons the Bremsstrahlung loss will be damaging. Computations are needed to predict Bremsstrahlung losses from partially stripped impurities found in 10 keV plasmas.

D. DIAGNOSTICS

The two previous sections were directed toward understanding the heating and cooling of a plasma. Plasma diagnostics attempt to quantitatively determine plasma parameters (i.e. temperature, density, fields, etc.) as well as the properties of impurities present. A high degree of sophistication has been achieved in the measurement of spatial electron temperatures and densities through Thomson scattering of laser beams. However, many plasma parameters remain to be measured with this degree of precision.

For measurements of concentrations of heavy elements in CTR plasmas, it is essential to know the energy levels and wavelengths of the strong resonant lines, especially those with $\Delta n=0$. Two problem areas need to be investigated: (1) resonance lines of the copper and zinc isoelectronic sequence with particular attention to tungsten and gold need to be investigated to the upper end of the periodic table; (2) atomic structure of the first 40 states of ionization of W and Au for simple electronic configurations that lead to resonance lines need to be investigated. These tasks are both theoretical and experimental.

For quantitative measurements of impurity concentrations to predict power loss, it is necessary to know the transition probabilities of light elements (C^{n+}, O^{n+}) and the heavier impurities. Not only are transitions with zero change in principle quantum numbers important, but also the strong transitions with $\Delta n \neq 0$.

Heavy ion beam probes have been developed in the past few years to measure spatial plasma potential and densities. In this method a heavy ion beam with sufficient momentum is projected across the plasma. At some point in the plasma a fraction of the ions are converted to doubly charged ions by electron or other type ionization collisions. If the ion beam is deflected across the plasma, a detector line can be found such that doubly charged ions formed on this line will cross over at some point exterior to the plasma. Placing an electrostatic analyzer at this cross-over measures the change in particle energy which is directly proportional to the space potential at the point of ionization. The analyzer detector currents are proportional to the plasma density. This determination can be made quantitative if the electron and deuteron ionization cross sections are known for ions of Tl, Rb, K, and Ba. This information is needed in the energy range 0.05 to 1 MeV.

One technique useful for ion temperature measurements by Doppler broadening is to inject an impurity atom such as He, Ne or Ar. The excitation of triplet states in He-like configurations and subsequent radiative decay is being used for high temperature plasmas.

Two additional techniques being developed using atomic physics to determine plasma parameters deserve to be mentioned. In one a lithium beam is projected across a toroidal plasma. An electron collision excites the atom which radiates. By measuring the direction of polarization of this radiation the magnetic field direction at the point of ionization can be determined. By unfolding the magnetic field distribution the plasma heating current distribution can be determined. Theoretically, current distributions are important in tokamak stability and studies indicate that with fusion type reactors the large heating currents will flow along the plasma skin leading to an unstable configuration.

Present laser scattering involves short-wave length (8,000 Å) lasers in which the scattered spectrum provides information about the electron temperature and density. For long-wave (300-500 μm) lengths the scattered spectrum arises principally from ions and ion temperatures can be determined in this manner. Several laboratories are pumping CH_3F gas with CO_2 lasers to obtain coherent radiation at 496 μm. Radiation at this wave length is also useful as a μ-wave interferometer and has possible use through photon echo techniques to study trapped electron lifetimes.

In summary, one can conclude that indeed atomic physics plays a dominant role in plasma physicist's and engineer's quest for thermonuclear power. Only through solution and understanding of some of the problems listed in the preceeding pages will the scientific community meet the temperature and confinement criteria demanded of fusion plasmas.