Atomic physics in fusion development

The next step in fusion development imposes new requirements on atomic physics research

by R.K. Janev

In establishing the scientific and technological base of fusion reactors, several broad scientific disciplines are involved.

Plasma physics and the associated plasma technologies (including large superconducting magnets) deal with the problems of creation and confinement of a high-temperature plasma, its stability, heating to required thermonuclear temperatures, and long duration. Some outstanding problems of fusion plasma physics and technology today are the achievement of quasi-continuous operation of tokamak devices by non-inductive current drive, high levels of thermal insulation under conditions of powerful external plasma heating, and high values of the kinetic-to-magnetic pressure ratio in the plasma (so-called plasma beta).

Nuclear physics is involved in fusion not only through basic energy production reactions, but also through aspects of thermonuclear fuel cycle (nuclear chemistry) and fusion reactor safety.

Material sciences and technology are critical to fusion since the first wall of the reactor chamber must sustain very high power loads (several MW/m^2), high heat flux thermal stresses, and should not heavily contaminate the plasma with high-Z impurities resulting from the plasma-wall interactions. Severe constraints are imposed not only on the materials for the first wall, but also on all other plasma-facing components, such as limiters, target plates in magnetic divertors, and antennas for radio-frequency plasma heating.

Atomic physics is also an essential constituent of fusion research. It is involved in many important areas such as the plasma-energy balance, plasma heating, ignition and burn control, and plasma diagnostics.

The above four scientific and technological areas do not exhaust the scope and complexity of ongoing fusion research, but are at present its most essential components. A wide engineering base also is required in the design and operational stages of large fusion devices, and the experiments on these devices cannot be run in a controlled manner without the help of supercomputers.

The real figure of merit for a fusion reactor is the fusion reactivity ($n\tau_E T$). The present fusion experiments can achieve only about one-tenth of the value 3×10^{21} m^{-3} s keV required for a reactor. The largest tokamaks (JET, TFTR, JT-60, DIII-D), presently operating only with hydrogen or deuterium, have already achieved reactor level temperatures ($T \sim$ 20–30 keV), thermal insulations ($n\tau_E \sim 4 \times 10^{20}$ m^{-3} s) and plasma betas ($\beta \simeq 6\%$), albeit in different experiments.

The ongoing conceptual design activities on the International Thermonuclear Experimental Fusion Reactor (ITER), carried out under the auspices of the IAEA, are led by the philosophy to bridge this gap and demonstrate plasma ignition and long-duration thermonuclear burn.*

Atomic physics in fusion research and technology

To appreciate the level of importance of atomic physics in fusion, it can be noted that at temperatures relevant to thermonuclear burn (15–20 keV), atomic processes proceed with rates that are eight to ten orders of magnitude faster than the rate of thermonuclear deuterium-tritium (D-T) reactions. Since most of the atomic processes are endothermic, they would consume the plasma energy long before the fusion reaction could start. Even in a pure D-T plasma, the bremsstrahlung emitted in electron–plasma ion collisions emits larger amounts of energy than can be produced by the D-T reactions if the temperatures are below ~4 keV. This plasma radiation cooling mechanism alone prevents plasma ignition for temperatures below 5 keV. The heavier atomic species, even if only present in trace quantities in the fusion plasma may radiate enormous amounts of energy (mainly through bremsstrahlung and line radiation). Thus, concentrations of iron ions above 1% of the plasma density prevent ignition of a D-T plasma at any temperature. This critical concentration value for tungsten amounts to only 0.1%. The detrimental effects of heavier atomic species, appearing in a

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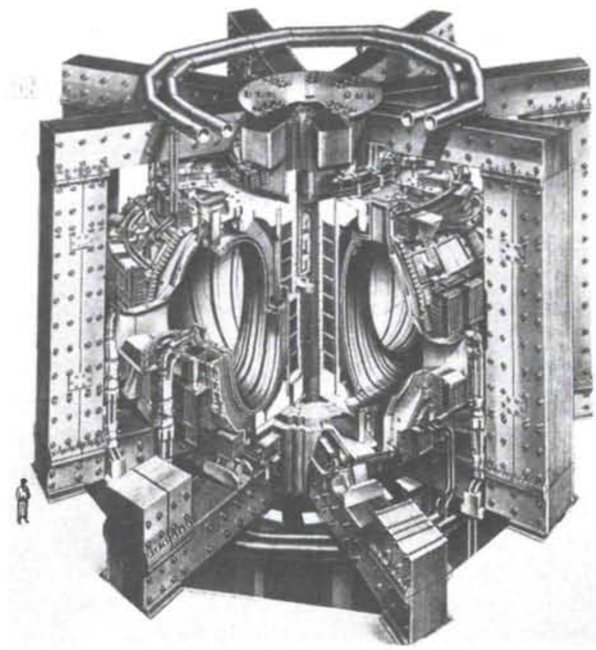
* ITER is a co-operative project involving the European Community, Japan, United States, and USSR.

hydrogenic plasma as impurities, already have been recognized in the earlier stages of fusion research. The presence of impurities in a confined plasma, however, is unavoidable due to its interaction with the walls of the containment vessel. Keeping the level of plasma impurities within tolerable limits is a prerequisite for attaining high plasma temperatures and ignition.

To minimize the plasma–wall contact and prevent high-wall impurity influxes from entering the plasma, a material or magnetic limiter must be introduced at the plasma edge. The boundary plasma flow is then directed into localized regions, which in the case of magnetic limiters (divertors) can be located even outside the main plasma chamber. This directed boundary plasma flow carries along the impurities released on the walls (as well as the plasma particles diffusing towards the walls) into special regions, from where they can be pumped out from the system. Apart from this double-shielding function, the divertors and limiters have several other beneficial effects on the confining system: significant reduction of first-wall thermal loads, recycling of hydrogen isotopes within the system, and build up of a radiation cooling layer at the plasma edge which keeps the near-wall plasma cold and, therefore, incapable of inducing significant material release from the walls.

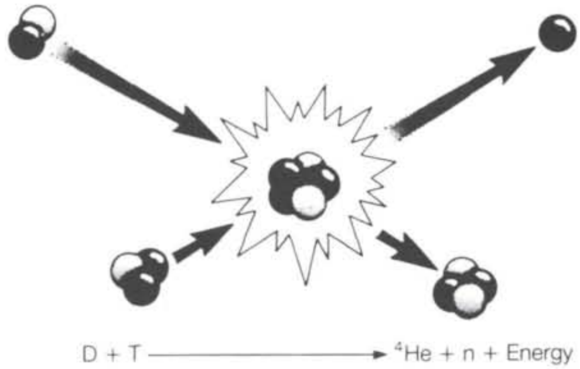
Optimization of the positive functions of limiters and divertors to a great extent depends upon tailoring the atomic particle content of the boundary plasma, including the composition of the first wall, limiter, and divertor plate materials. The atomic physics involved in this optimization includes a large variety of gas-phase atomic collision processes, as well as a similarly large variety of particle–surface interaction processes. The particles involved in the boundary plasma gas-phase processes are the basic plasma constituents (electrons and nuclei of hydrogen isotopes), wall impurity atoms and ions (in a wide range of charge states), and molecular species such as hydrogen, metallic oxides, and hydrocarbons, present in this region due to the low near-wall temperatures (5–50 eV). Inelastic collision processes between these plasma constituents are so numerous and complex that prediction of their combined effects on the plasma energy transformation and plasma particle transport requires an enormous amount of information regarding their collisional characteristics. The global effect of these processes is, however, experimentally known: they transform the plasma energy into radiation, thus



Artist's drawing of the Joint European Torus (JET), under the auspices of the European Community.

Fusion research

The promise of fusion is based on the 17.6 mega-electron volts (MeV) energy released in a D (T, ^{4}He)n fusion reaction, and on the availability of deuterium (D) in nature. A fusion reactor must breed by itself the required tritium (T) in the blanket surrounding the reaction chamber through the n(^{6}Li, ^{4}He)T and n(^{7}Li, n'^{4}He)T nuclear reactions. Lithium is also sufficiently abundant in nature. The technical feasibility of fusion relies on confining a high-temperature ($\geq 10^8$ K = 10 keV) D-T plasma long enough isolated from the walls of the containment vessel, so that fusion reactions can occur on a scale such that ignition of the thermonuclear fuel becomes possible. Establishment of the scientific and technological base for fusion plasma ignition and controlled burn has been the principal objective of fusion research over the past 40 years. Magnetic confinement of low-density ($\sim 10^{20}$ m^{-3}), high-temperature (10–20 keV) plasmas is at present the leading concept in this research, and requires thermal plasma insulation times of about one second, or longer. Within this concept, the toroidal magnetic configuration known as tokamak has already demonstrated achievement of plasma parameters relevant to reactor conditions.



providing a cooling mechanism which protects the walls from the high-thermal fluxes coming from the hot plasma core. Optimization of the edge plasma radiation cooling requires a large database on atomic and molecular collisional and radiative processes.

The collision processes of plasma constituents with the surfaces of plasma-facing material components (the first reactor wall, limiters, divertor plates, etc.) have even more critical influences on the properties of the edge plasma and, through it, on the overall plasma parameters. These processes may lead to copious production of plasma impurities, and directly, or indirectly, are responsible for the erosion of the first wall and other material boundaries exposed to the plasma. These processes have a complex nature and the information about them is rather limited (particularly for materials of fusion interest).

The multitude of gas-phase and surface atomic processes occurring in the plasma edge region, not only has a direct impact on the energy balance in the plasma and its confinement, but also on reactor technology. These processes (as well as nuclear interactions with boundary materials) are responsible for the erosion of the reactor first wall and, therefore, have a critical importance in determining the options for candidate reactor materials.

Another area in which atomic physics is providing an important contribution to fusion development is the heating of fusion plasmas. Magnetically-confined plasmas require external energy for their heating to fusion temperatures. The Ohmic heating in tokamaks can raise the plasma temperature to only a few keV, far below the required level. The most efficient method to date for coupling energy to the plasma from external sources is the injection of energetic neutral hydrogen atoms into the plasma interior. In the course of their penetration into the plasma, the neutrals are ionized (in collisions with the plasma particles), confined by the magnetic field, and they distribute their energy to plasma electrons and ions through collisions.

All existing large tokamaks today are heated by energetic neutral beams (supplemented by radio-frequency wave heating), and powers up to 20 MW have been coupled to the plasma. The neutral beam injection method also has the potential of transferring a large amount of momentum to the plasma, thus inducing a non-inductive current drive in it. This current drive is required for the continuous operation of a tokamak fusion device.

The neutral beam plasma heating method is almost entirely based on the results of atomic physics research. The efficiency of the method depends on the intensity of ions extracted from an ion source, their neutralization in a gaseous cell (after being accelerated to required energies), and on their penetration into and stopping in the plasma. In all these three stages of the beam production and application, the role of atomic physics is essential: optimization of the ion source and neutralization cell are technological problems which can be solved only by an adequate knowledge of atomic collision processes. The beam energy deposition into the plasma also requires very detailed information on the ionization and other processes of beam atoms with plasma particles and plasma impurities. Incompleteness of the atomic database required for calculating the beam energy deposition can lead to drastically inadequate estimates of the required beam parameters and, thereby, of the required beam production technology.

Finally, a third area in which atomic physics is deeply incorporated in fusion research is plasma diagnostics. Many parameters of the fusion plasma (temperature, density, energy and momentum content, etc.), including their spatial and time variations, have to be measured in order to obtain a clear physical picture about its state, and on that basis, to be able to control its behaviour. Most of the plasma diagnostic methods are based on effects inherent to atomic (ionic) particles, or arising due to their interactions. Spectroscopic methods, based on the bremsstrahlung and impurity line radiation of plasma constituents, provide a large body of information about the basic plasma parameters (electron and ion temperatures and densities, their spatial distributions and time variations) and about the composition and distribution of plasma impurities. Active and passive atomic beam diagnostic methods provide additional, or independent, information about the plasma composition and parameters. The plasma diagnostic methods also require a very accurate knowledge of the collision and radiative characteristics of plasma constituents.

The above examples were drawn to illustrate the role which atomic physics research has played and continues to play in the development of fusion. Although on the level of present-day fusion devices, atomic physics provides fairly satisfactory solutions to those fusion research problems in which its role is essential (impurity control, neutral beam heating technology, diagnostics). The next step in fusion development (engineering test reactors) imposes new requirements on atomic physics research.

Atomic physics issues in fusion reactor development

Concurrent with the beginning of fusion reactor development, the involvement of atomic physics in fusion increasingly has entered the technological area. The specific forms and subjects of this involvement will certainly undergo changes and modifications as fusion technology evolves. It is, therefore, appropriate to analyse the role of atomic physics in fusion reactor development in the context of the design of next-generation fusion devices, such as ITER. The physics of thermonuclear burning plasma, the complete understanding of which is also included in the programme of next-generation fusion development, imposes also certain problems for atomic physics research. A similar situation exists in thermonuclear burn control.

One major issue in the design of next-generation fusion test reactors is the choice of adequate first wall materials. This problem has two aspects: one related to the thermo-physical properties of the first wall (metallurgical stability, heat transfer, radiation damage), and another related to the edge plasma conditions and impurity control. As mentioned earlier, the edge plasma conditions are determined by the gas phase and particle–surface atomic collisions and have a strong impact on the energy content of the plasma, its energy confinement time and stability, and on the operation of divertors. The control of edge plasma conditions is, therefore, essential for the successful operation of a thermonuclear fusion reactor. The plasma edge is the doorway to the main reacting plasma. Since there is a strong correlation between the central and boundary parts of the plasma, modifications in the latter are rapidly transmitted into the burning plasma core. Thus, control of the edge plasma conditions is a way to control the thermonuclear burn.

A very extensive database on the atomic gas phase and particle–surface processes is obviously required to successfully control the edge plasma conditions. This database is still rather scarce, and its completion requires substantial research efforts. Many atomic and surface physicists are currently involved in generating the required database.

The edge plasma processes do not only influence the plasma ignition and thermonuclear burn, they also determine the erosion rates of plasma-facing materials and, thereby, their lifetimes. The first-wall reactor technology also must provide a solution to the problem of fast erosion induced by the plasma–wall interaction processes.

Another specific aspect of the control of edge plasma conditions is the exhaust of the thermonuclear ash. The 3.5 MeV alpha particles, produced in D-T fusion reactions, have an important role to provide energy to the plasma after ignition, for maintaining the burning process. After thermalization, the presence of "cold" alpha particles in the plasma dilutes the thermonuclear fuel, and they have to be continuously removed from the reaction zone.

Fortunately, these alpha particles diffuse towards the plasma edge, from where they can be directed, together with the other wall impurities, into the separated divertor chamber and pumped out of the system. Atomic processes of fusion alphas with other plasma constituents (particularly with impurity ions) may strongly influence both their thermalization in the reaction zone and their removal from the main chamber. Again, a large atomic database is required to predict and control the helium ash exhaust.

The design and technology of magnetic divertors requires a particularly large amount of atomic and plasma–surface interaction data. Divertor plates should accept heat and plasma particle fluxes several times higher than those which flow to the first wall of the reactor chamber. Severe erosion of the material would occur if both the plates and the divertor chamber are not properly designed. Aside from the proper choice of plate materials, the divertor design must include the provision for an operation regime with intense hydrogen recycling between the plates and nearby plasma with the aim to produce a cold, high-density plasma near the plates. The heat and particle flux loads on the divertor plates are then drastically reduced, and so are the erosion rates. In order to sustain the high recycling regime around the plates, the rate with which the divertor chamber is pumped out should also be extremely high. The energy and momentum transport by the neutral gas (accumulated in the divertor chamber due to the recycling process, with densities larger than the plasma density) involves an extremely wide range of atomic and surface processes, the data for which are required to predict the effects of this transport.

Another important technological area in fusion reactor development is plasma heating. The current concept of ITER envisages heating of the reactor core plasma by powerful deuterium beams, having an energy around 1 MeV. As discussed previously, the exact beam energy is determined by the required levels of energy deposition into the plasma and momentum transfer induced current drive. At such high energies, the beam attenuation depends upon a much wider spectrum of collision processes (involving excited beam atoms) than is the case with neutral beams of 100–200 keV energy, currently used in the large tokamaks. The effects of beam atom excitations may increase the beam stopping cross-section by a factor of two, and thus impose new requirements on the neutral beam technology. The production of intense neutral beams in the MeV energy range should be based on negative ion sources, whose efficiency is still inadequate. The physics of these ion sources is again determined by atomic, molecular, and surface collisions, and their technological advancement requires an extensive database for these processes.

The IAEA fusion-related atomic physics programme

Apart from its role in providing a framework for international collaboration in the field of fusion research (such as the INTOR Workshop and ITER conceptional design activities), and in organizing the biennial International Conference on Plasma Physics and Controlled Nuclear Fusion Research, the IAEA has its own fusion-related programmes in the fields of plasma physics, nuclear physics, atomic and molecular physics, and in the field of fusion technology and engineering. The Agency is also publisher of the international journal *Nuclear Fusion*, the *World survey of activities in controlled fusion research* (the first edition appeared in 1986, the second is now in preparation), and other publications resulting from scientific meetings and symposia organized by the Agency in the field of fusion research. The purpose of the Agency's specific programmes is to provide a forum for specialists for discussions of state-of-the-art and current problems on different areas of fusion research and technology. Through a number of research contracts and fellowships, the Agency also directly provides assistance to Member States in their national fusion research programmes. The advisory body for the Agency's programmes in the field of fusion is the International Fusion Research Council (IFRC).

The Agency's programme in the atomic physics aspects of fusion research started in 1976 by establishing a programme of atomic and molecular (A&M) data for fusion within the nuclear data section in the Division of Physical and Chemical Sciences, under the guidance of the IFRC subcommittee on A&M data for fusion. The Agency's programme in this field was given its initial direction by an advisory group meeting held in Culham, UK, in 1976, convened specifically to identify the short- and long-term needs for A&M data in fusion research. Today the principal objectives of the IAEA A&M data activities are to:

- establish and maintain an international database of evaluated and recommended A&M data for fusion;
- co-ordinate and support the development of an international A&M database for fusion (particularly through the co-ordination of the compilation and evaluation activities carried out in the national A&M data centers for fusion);
- establish, maintain, and publish an international bibliographic database for fusion;
- promote and support the production of A&M data for fusion through IAEA research contracts and co-ordinated research programmes, and other appropriate interactions with the atomic physics community; and
- disseminate evaluated A&M data to fusion laboratories and other users.

These objectives are being pursued by the IAEA in close collaboration with an international atomic data centre network and by extensive involvement of a large part of the atomic physics community and pertinent segments of the fusion community.

Significant progress has been made in establishing the evaluated A&M database for fusion which now contains recommended cross-section data for all collision processes of the basic hydrogen plasma constituents. Complete, or nearly complete, sets of collisional and radiative data also exist for the most important plasma impurities (carbon, oxygen, iron) and, in case of ionization processes, for all atoms and ions of fusion interest. The data are presented in a format which allows easy use in fusion application computer programs. The data compilation and evaluation is performed in a co-ordinated way through the A&M data centre network, while their validation and recommendation is done by internationally-selected groups of experts. The IAEA atomic physics database for fusion is now expanding in the field of plasma-wall interaction data. At the present stage, only the most fundamental particle–surface interaction processes are included in the programme. However, expansion of this work is expected to also cover data on more complex phenomena occurring in plasma–material interactions, including the properties of materials exposed to high heat and intense particle fluxes.

The current IAEA fusion-related atomic physics programme is concentrated on the completion of A&M databases required for modelling and diagnostics of large tokamak edge plasmas, transport and radiation of medium- and high-Z impurities, energetic (1–2 MeV) neutral deuterium beam penetration in reactor-grade plasmas, and on establishing a database for the fundamental particle–surface interaction processes. This programme integrates the efforts of the IAEA nuclear data section staff and the A&M data centre network, as well as many national atomic physics and surface physics research laboratories. This spirit of international co-operation continues to be instrumental in the creation of an international database of recommended atomic, molecular, and plasma–wall interaction data for fusion.