Today's Science
Tomorrow's Technology

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A course of lectures contributed
in the 25th International Science School
for High School Students,
sponsored by the Science Foundation for Physics
within The University of Sydney,
at The University of Sydney
26 June — 7 July, 1989

Pergamon
Sydney • Oxford • New York
Toronto • Frankfurt • Beijing • São Paulo • Tokyo

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Preface

The Science Foundation for Physics within the University of Sydney is now in its thirty-fifth year. Throughout its existence one of its principal aims has been to encourage the brightest and best of our youth to follow careers in science. To further this aim it has organised and underwritten a series of International Science Schools for High School Students, now held every two years in the University of Sydney. Scholarships to attend these Schools are now awarded on each occasion to some 130 Year 11 (fifth form) high school pupils--105 from Australia, 25 from overseas. These scholars have been selected on the basis of their academic performance. In awarding the scholarships the Foundation's intention is to honour academic excellence and to encourage and stimulate the scholars by bringing them together to hear lectures on some of the most exciting contemporary developments in science given by lecturers whose work forms part of that development.

The lectures are aimed at year eleven students but they should also be appreciated by a wider audience—by the educated non-scientists in the community and even by scientists who wish to be aware of developments in fields other than their own. The lectures for the 1989 School cover a wide range of topics in science and explore the important relationship between science and technology.

On behalf of the Foundation I wish to thank the lecturers for having given their time in preparing these lectures for publication and in presenting them to the International Science School.

The students chosen to attend, from Australia and from overseas, deserve the approbation of the community. The Science Foundation for Physics is pleased to honour and reward their ability and hard work.

M.H. BRENNAN
Sydney, June 1989

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CHAPTER 1

High Temperature Physics and Fusion

Robert A. Gross

Introduction

We live in a world that exposes us to a very small range in temperature, typically from about 0 to 100 degrees Centigrade. As curiosity developed to learn more about the universe, scientists realised that the condition of nearly all matter in space is very different from that of matter on Earth. Some of the cosmos is very cold, close to absolute zero temperature. Most of the matter in space (stars) is rather hot, at temperatures of some tens of millions of degrees. From time to time, when stars collapse and then explode in supernovas, even more extreme states of temperature occur.

Cosmologists, who study the formation of the universe, conjecture that at the very earliest time everything was extremely hot and consisted of a strange soup of matter and radiation. Near the beginning of time temperatures were greater than a million-million degrees Kelvin and the universe was composed mostly of pi mesons. Somewhat later, as the universe expanded and things cooled down, the universe was filled by electrons, positrons, photons, neutrinos and anti-neutrinos. The evolution of the universe during these early times is a fascinating field of study. A very fine description of these early times in the universe has been written by Steven Weinberg in his beautiful little book entitled *The First Three Minutes*.[1] I recommend that you read it.

There is an absolute zero in the scale of temperature and this corresponds to the state when there is no molecular motion. On the Centigrade scale, absolute zero is -273.15°C. There is, however, no known maximum value for temperature. Temperature is a way to characterise the energy of a statistically large number of particles. The particles may be atoms, molecules, electrons, ions, photons, or any of the other fundamental forms of matter that physicists have discovered. These particles can have relativistic speeds and arbitrarily high values of kinetic energy. Very high temperature gases can react (burn) due to nuclear transformations that result from very high energy particle collisions. This is the way we believe that the periodic elements, as we know them, were constructed. The molecules from which each of us is made, as well as those that constitute the world around us, were first forged in some earlier very very high temperature gas.

In these lectures about high temperature physics we will limit our attention to the energy range of a few thousand electron-volts, i.e., a few tens of millions of degrees Kelvin. In this temperature regime of a few kilovolts most of the state of the universe as we know it is found today. This is the energy regime in which some of the most interesting and important nuclear chemistry takes place. The science of the behaviour of matter in this temperature regime is called plasma physics. We will first examine and study some of the principal concepts in kinetic theory and plasma physics that are helpful in understanding the interesting properties and behaviour of very high temperature gases. Then we will explore what many believe is the most important technical application of plasma physics, i.e., the quest to develop a major new energy resource for mankind, controlled fusion energy. This is in keeping with the theme of the 1989 Sydney University's Science School, 'Today's Science, Tomorrow's Technology'.

Kinetic theory

The scientific study of the property and behaviour of gases blossomed in the late nineteenth century and the product of those early physics studies was an outstanding intellectual achievement. That body of knowledge is found today under the title of kinetic theory of gases. We need some of the basic concepts from the kinetic theory of gases in order to discuss high temperature physics and fusion. I hope that some of you will study this subject in detail so that you can see the beauty and intellectual achievement that it encompasses. Let's examine some of these ideas and learn the language that is used to describe them.

We speak generically of all the independent constituents of a gas, i.e., molecules, atoms, electrons, ions, neutrons etc., as 'particles'. These particles are in constant motion. When the number of particles is statistically very large and enough collisions have taken place between particles that equilibrium exists (i.e., no more macroscopic changes take place as time goes on), then it is found that the particles have a velocity distribution that is related to their mass and to the temperature of the gas. This velocity distribution is called the Maxwell-Boltzmann distribution, named after two famous scientists who first calculated it. The mean speed v of all the particles that make up such a gas was found to be

$$v = (8kT/\pi m)^{1/2} \tag{1}$$

where k is the Boltzmann constant ($k = 1.380 \times 10^{-19}$ J/K), T is the gas temperature in degrees Kelvin, and m is the gas particle mass. The particles have kinetic energy due to their motion and the mean energy E, for all these particles of gas in equilibrium with a temperature T, is

$$E = 3/2\,(kT) \tag{2}$$

At very high temperatures the velocity distribution of the speeds of the particles may not have had sufficient time to achieve equilibrium (i.e. a Maxwell-Boltzmann distribution). It is however still convenient to speak of the temperature of the gas, even though its constituent particles are not in thermal equilibrium. The temperature is then defined from the following simple relation:

$$1/2\,(m<v>^2) = 3/2\,(kT) \tag{3}$$

where $<v>$ is the mean particle speed appropriately averaged over all the particles. Thus, the temperature of a gas, T, is a measure of the mean kinetic energy of the particles of the gas. If the particles have an energy that is equivalent to that which results from an electron being accelerated through one volt of potential, then we speak of the gas as having a temperature of one eV, that is equal to e/k where e is the charge on the electron or e/k = 11,600° K. Thus, one electron volt is a temperature equivalent of 11,600 degrees Kelvin.

Another convenient measure is the distance a typical particle travels before it collides with another particle. This distance is called the particle mean free path and is designated by the Greek letter λ. The mean free path is related to the nature of the force field (for example the electric field) that surrounds the particle. By studying how particles interact, a cross section σ (sigma), is defined that is a measure of the 'size' of the particle. The cross section, σ, has dimensions of area. The relationship between the particle mean free path, its cross section for collision, and the density of particles, n (i.e., the number of particles per unit volume) is

$$\lambda = 1/n\sigma \tag{4}$$

The collision cross section often depends upon the energy of the colliding particles and upon the nature of the force field between particles. Neutral atoms or molecules at room temperature are found to have collision cross sections of about 10^{-20} m^2. Particles in a high temperature gas consisting of say, electron and hydrogen ions at a temperature of 10 keV, will have cross sections for collision of about 10^{-24} m^2, i.e., they appear to be much smaller than particles at room temperature. There are cross sections defined for other types of physical events. For example, there are cross sections for collisions that result in atomic excitation, for nuclear reactions, for atom-photon absorption, for photon scattering etc. The cross section concept is very useful in physics.

Energetic collisions between particles may be violent enough to dislodge one or more bound electrons from a neutral atom. The atom then has a positive electric charge and is called an ion. The fraction of the atoms in a gas that are ionised is a problem that was first analysed by the Indian physicist Saha in 1920. He found that the ion number density n_i (ions per cubic metre) is related to the gas temperature as shown below:

$$n_i p_e / n_a = C_1 u(T) T^{5/2} e^{-E_i/kT} \tag{5}$$

where n_i is the density of ions, p_e is the electron gas pressure, n_a is the neutral particle density, C_1 is a constant ($C_1 = 6.67 \times 10^{-2}$ in SI units), $u(T)$ is a slowly varying function of temperature, and E_i is the ionisation energy for the atom (i.e., the energy required to remove the bound electron from the atom). The energy required to remove the most outer-bound electron from atoms varies from a few eV to several tens of eV. The Saha equation is dominated by the exponential term and therefore when $KT >> E_i$, n_i/n_a gets very large. That is, the gas is highly ionised.

Some history

In 1932, Professor H.C. Urey at Columbia University discovered that there is another form of hydrogen, twice as heavy as the more common form. This hydrogen isotope has a neutron in its nucleus. He called this isotope deuterium. When combined with oxygen, it is called heavy water. Urey sent some samples to Professor E. Rutherford at Cambridge University where he was studying the structure of the nucleus by bombarding targets and observing the trajectories of the scattered particles. In 1934 Rutherford, together with Oliphant and Harteck, bombarded deuterium laden targets with an energetic deuterium beam and observed truly extraordinary phenomena. The deuterium nuclei reacted energetically and one of the products of this nuclear reaction was a particle, never seen previously. Rutherford conjectured correctly that it was an even heavier form of hydrogen (two neutrons in the nucleus). This discovery of heavy-heavy hydrogen is the isotope called tritium. It is radioactive and has a half-life of about twelve years. It was observed that when deuterium collided with tritium they reacted exothermally to form helium and a neutron. These were nuclear reactions!

These historic experiments were the earliest thermonuclear reactions observed in the laboratory; perhaps an even greater reason for their historic significance is the fact that today these isotopes of hydrogen are considered as the primary fuels for fusion energy. Since these historic nuclear fusion experiments by Rutherford and colleagues, many other fusion nuclear reactions have been observed, all of them occurring at energy above a keV. In contrast to chemical reactions that involve energy transformation of a fraction of an eV, nuclear reactions involve energy transformations of many keV. There are more than fifty fusion reactions (see *Fusion Energy*[2]) where light elements fuse exothermally into heavier elements, representing the potential for a very large energy resource. To have a nuclear fusion 'burn' we can note from equation (5) that such high temperature gases (at many keV) will surely be fully ionised. The study of fully ionised gases, called plasmas, has been a major topic of research for physicists during the past forty years. To understand the scientific challenge of achieving a controlled thermonuclear burn, we need to learn some of the basic ideas and language of plasma physics.

Plasma physics

The study of plasma physics is a large undertaking usually, requiring several years of graduate study. That is obviously beyond what we can hope to achieve in this short set of lectures; nonetheless, it is possible to set forth some of the most important concepts to help with the understanding of fusion energy. These physics concepts are summarised below. More details can be found in the book *Fusion Energy*[2] or in the text by F.F. Chen entitled *Introduction to Plasma Physics*[3].

Debye Length

One of the most important and fundamental length scales in plasma physics is the Debye length λ_D, given by the following formula:

$$\lambda_D = 6.90\times 10^1 (T_e/n_e)^{1/2} \qquad (6)$$

where T_e is the electron gas temperature and n_e is the electron number density. All quantities are in international or SI units. The Debye length is a measure of the distance that the electric field of a charged particle can penetrate into the surrounding sea of charged particles. If the number of particles within a Debye sphere is much greater than one, then many particles are simultaneously interacting with each other, and these charged particles will exhibit collective or many-body effects. Such a gas is called a plasma. The many-body interactions result in very interesting plasma properties.

Mean Free Path

The mean free path of a particle in a plasma is defined by the distance required to deflect the particle's momentum 90° from its original trajectory. In a plasma this deflection is the sum of numerous small angle deflections caused by many particles interacting simultaneously with the test particle. The formula for mean free path of a hydrogen particle in a plasma is rather difficult to derive, but it can be approximated rather well by the following formula:

$$\lambda = 1.78 \times 10^{9} T^{2} / n \ln \Lambda \tag{7}$$

where $\ln \Lambda$ is a slowly varying function whose value is of the order of ten to twenty. The important thing to note from equation (7) is that at extremely high temperatures the mean free path gets very large. For example, for a fusion plasma at 10 keV and number density of 10^{20} particles per cubic metre, the mean free path is fifteen or more kilometres! Thus, a hot fusion plasma in a chamber in the laboratory will be essentially collisionless. To prevent the hot particles from immediately streaming directly to the cold walls of the container, something ingenious must be done.

Gyro Radii

Charged particles spiral about magnetic lines of induction. A balance between the Lorentz and centrifugal forces results in a gyro radius formula for electrons (r_{ge}) and for hydrogen ions (r_{gi}) as follows:

$$r_{ge} = 3.13 \times 10^{-8} T_e^{1/2} / B \tag{8}$$

$$r_{gi} = 1.34 \times 10^{-6} T_i^{1/2} / B \tag{9}$$

Charged particles are 'bound' to straight magnetic lines of induction, somewhat like beads on a string. The electrons are more closely bound to the magnetic field than the ions. Other effects such as curvature of the lines of induction or magnetic field gradients, or electric fields, cause the particles to drift away from the magnetic lines of induction. Magnetic fields can be used to prevent rapid streaming of hot particles to the walls of a confinement chamber. But the design of a confining magnetic 'bottle' must be very clever in order to achieve effective confinement.

Alfven Speed

When a plasma contains a magnetic field the ionised gas can transmit a low frequency wave that does not occur in ordinary gases. It is as though the lines of magnetic induction behave as rubber bands and the ions, spiralling along the magnetic line, provide the magnetic lines with a mass density per unit length. When the magnetic line is disturbed, a small amplitude disturbance propagates along this line. It is called an Alfven wave and is named after its discoverer, H. Alfven, who was awarded the Nobel prize for his pioneering research in plasma phenomena. An Alfven wave propagates in a hydrogen plasma at a speed b given by the following expression:

$$b = 2.19 \times 10^{16} B/n_i^{1/2} \tag{10}$$

Alfven wave speed increases with the strength of the magnetic field B, and decreases with the square root of the ion number density n_i. In fusion plasmas the Alfven speed is often higher than the acoustic or sound speed. It is the fundamental way in which disturbances propagate in a plasma.

Bremsstrahlung Radiation

Plasma electrons are accelerated when they collide with ions and this results in their emitting radiation called bremsstrahlung, a German word meaning 'braking radiation.' Since the electron is free or unbound, both before and after interacting with an ion, this radiation is sometime referred to as free-free radiation. For a hydrogen plasma the power of free-free radiation P_{ff} is found to be

$$P_{ff} = 1.59 \times 10^{40} n_e n_i T_e^{1/2} \tag{11}$$

The important and interesting thing to note is that bremsstrahlung radiation power increases as the square root of the electron temperature, whereas a black body radiates in proportion to the fourth power of the temperature. As we will see, this has important consequences and helps make fusion a possible energy source.

Nuclear fusion reactions

When it is possible to produce more stable nuclear configurations by combining two less stable nuclei, energy is released in the process. Such reactions are possible for a great many (about 80) pairs of nuclides. This is illustrated in Figure 1.1. The binding energy per nucleon has a maximum around iron (atomic mass number $A = 56$). The light elements can therefore be fused to produce heavier and more stable elements, releasing in the process fusion energy. The heaviest elements can be broken apart (fission) resulting in more stable nuclei. The masses of the products of these reactions are slightly less than the masses of the reactants, and the products have higher kinetic energy as the mass loss is converted into energy according to $E = mc^2$. The most important fusion reactions for commercial applications are listed below.

Deuterium-Tritium (the D–T reaction):

$$^2D + {}^3T \rightarrow {}^4He\,(3.5\text{MeV}) + {}^1n\,(14.1\text{MeV}) \tag{12}$$

This reaction is significant because, as we will learn, it has the lowest ignition temperature and has the potential to develop the highest fusion power density. Because of this it is the reaction chosen for first generation fusion power plants. Deuterium is plentiful and inexpensive, but tritium is very rare and radioactive (beta decay). Tritium can be manufactured by bombarding lithium with neutrons. The end products or ashes of the D–T reaction are alpha particles (helium 4) and energetic neutrons. The neutrons from

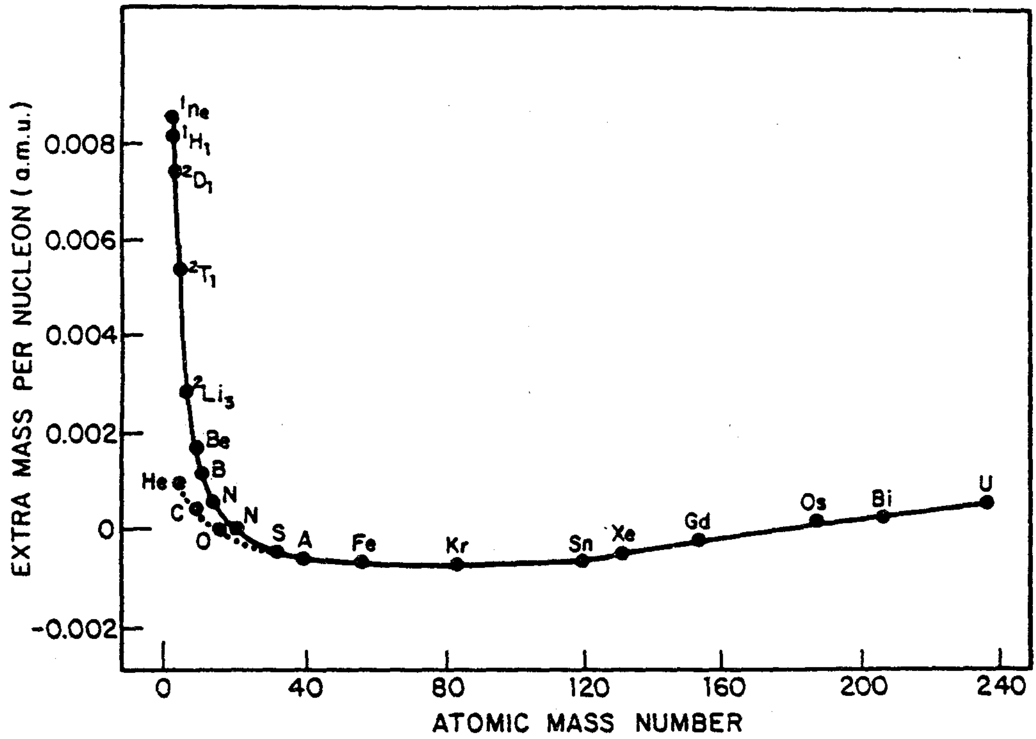

*Fig. 1.1 The extra mass per nucleon as a function of atomic mass number A. The most stable atoms occur in the range 50<A<90 (*Fusion Energy, *P3).*

this reaction will promptly leave the burning plasma. The 3.5 MeV alpha particles, because they are charged particles (ions) can, however, be confined by magnetic fields and therefore they may remain in the plasma where they can transfer their excess energy to the background plasma. Twenty percent (3.5/17.6) of the D–T reaction energy is in the ions. In this fusion reaction there are absolutely no radioactive ashes, but the energetic neutrons do present serious technical problems, particularly for the first wall of the plasma confinement chamber. The first wall becomes radioactive and may swell because of helium, created by neutron induced nuclear fission events, released inside the metal. The neutron flux leaving the burning plasma can be used to breed tritium, and also to help produce even more thermal energy via other nuclear fission events.

Deuterium-Deuterium

$$^2D + {}^2D \rightarrow {}^3He(0.82\text{MeV}) + {}^1\text{n}(2.45\text{MeV}) \qquad (13)$$

$$^2D + {}^2D \rightarrow {}^3T(1.01\text{MeV}) + {}^1H(3.02\text{ MeV}) \qquad (14)$$

Each of these deuterium reactions takes place with nearly equal probability, and therefore the products of each reaction form at about the same rate. The tritium and the helium 3, thus formed, can react in further fusion events. Thus,

$$
\begin{array}{lllr}
 & {}^2D + {}^2D \rightarrow {}^3He + {}^1n & 3.27 \text{ MeV} & \\
 & {}^2D + {}^2D \rightarrow {}^3T + {}^1H & 4.03 \text{ MeV} & \\
 & {}^2D + {}^3T \rightarrow {}^4He + {}^1n & 17.6 \text{ MeV} & \\
 & {}^2D + {}^3He \rightarrow {}^4He + {}^1H & 18.3 \text{ MeV} & \\
\hline
 & 6\,{}^2D \rightarrow 2\,{}^1n + 2\,{}^1H + 2\,{}^4He & 43.2 \text{ MeV} & \\
\text{or} & 3\,{}^2D \rightarrow {}^4He + {}^1H + {}^1n & +21.6 \text{ MeV} & (15)
\end{array}
$$

Neutron-free Fusion Reactions

There are other interesting fusion reactions that are more difficult to achieve because they have smaller reaction cross sections; therefore, higher temperatures are needed to ignite and burn them. They are important because they do not produce any neutrons. Some of the more interesting ones are listed below. More neutron-free reactions can be found in *Fusion Energy*[2].

$$ {}^2D + {}^3He \rightarrow {}^4He + {}^1H \tag{16} $$

$$ {}^1H + {}^6Li \rightarrow {}^4He + {}^3He \tag{17} $$

$$ {}^1H + {}^{11}B \rightarrow 3\,{}^4He \tag{18} $$

The basic fuels for fusion reactors can be deuterium, tritium, helium, lithium or boron. Deuterium is plentiful and easy to separate from other forms of hydrogen. Tritium is scarce because it has a twelve year half-life; it has to be manufactured but this is rather easy if there is a source of neutrons that can be employed to bombard lithium. Neutrons interacting with lithium form tritium as products. Lithium is a common chemical and there are large reserves. Helium-3 is very scarce, but it is known that there are significant amounts in the lunar crust! Some very forward-thinking persons have suggested that mining the moon's surface and returning the helium-3 to Earth for fusion power plant fuel will be an important activity sometime in the future.

Why fusion energy?

Modern civilisation has been made possible by the availability of large quantities of cheap energy; never the less, every commercial form of large scale energy that has been used has, at one time or another, developed significant problems. Acid rain, the greenhouse effect, labour strife, melt-down, weapons proliferation, and too expensive, are words that characterise some of these problems. The major fossil fuel resource is coal and the major fission source is the nuclear breeder. Fusion can supply a third major alternative. If civilisation is to be sustained, it must not be dependent on any single source of energy, for surely some trouble will arise. Modern society, if it is to be stable and peaceful, must provide people with choices. The successful attainment of fusion power will give mankind a major new energy resource. This goal is extremely meritorious.

Fusion is the energy source of the sun and the stars. As the earth's fossil-fuel resources dwindle and the environmental impacts of fossil-fuel burning become more severe, there remain three known options for meeting the energy needs of modern civilisation; fusion, fission (breeders) and solar energy. Some people are deeply concerned about the very long time needed for safe disposal of the radioactive ashes from fission. Some others are skeptical about the probability of achieving economic large scale solar energy. I believe that civilisation will need all three, fission, fusion and solar.

At present, fusion is the least explored of these three energy options, but for the long term it offers major environmental benefits. Fusion, like fission, is a concentrated energy source that will make minimum demands on the use of land and structural materials for power plants. Fusion fuel is inherently safe against an uncontrolled energy release, and does not produce a radioactive ash. The fusion reactor vessel is activated by neutrons emanating from the fusion reactions, but this secondary radioactive waste is well below the level of fission-reactor wastes, and is expected to be further minimised by improvements in materials technology and in the fusion process itself. The supply of cheap fusion fuels is essentially limitless.

It appears, after forty years of fusion energy research and development that we are close to scientific success and that a better grasp of some plasma science and some technology development are all that separates us from a working fusion power plant.

Fusion-power density, ignition and confinement

The rate R_{ij} at which a reaction proceeds in a uniform gas mixture of species i and j may be expressed in terms of the reaction cross section σ and the number densities of the reactants. If σv is understood to mean the product of reaction cross section multiplied by the particle velocity, then

$$R_{ij} = a_{ij} n_i n_j \sigma v \qquad (19)$$

where $a_{ij} = 1$ if $i = j$, and $a_{ij} = 1/2$ if i is different from j. When considering a gas consisting of particles moving at different speeds, an appropriate average is taken over all speeds and velocities. This average is designated as $< \sigma v >$ and is called the reactivity. For a Maxwell-Boltzmann velocity distribution the values of the reactivity for some of the more important fusion fuels are given in graphical form in Figure 1.2.

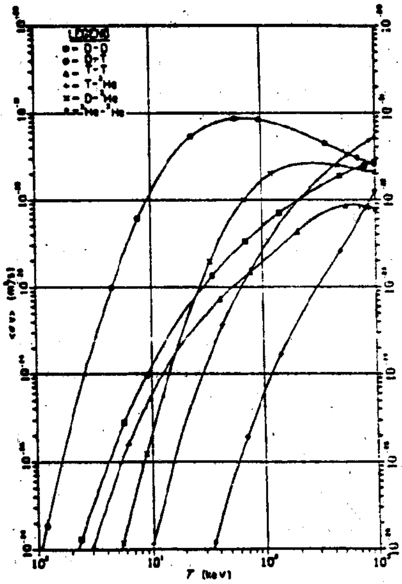

Fig. 1.2 Reactivities of some fusion fuels (Fusion Energy, *P 30).*

The rate at which fusion energy is produced per unit volume *P* is the product of the densities of the fuels, the reactivity, and the energy *Q* released per fusion event. Thus,

$$P_{ij} = a_{ij}\, n_i\, n_j < \sigma v > Q \qquad (20)$$

There is a relationship between the gas pressure *p*, the number density *n*, and the temperature *T*. This is called the ideal gas relationship and it is simply

$$p = nkT \qquad (21)$$

Another important dimensionless ratio is called β (beta). It is the ratio of gas pressure *p*, to magnetic field pressure $B^2/2\mu_o$. By substituting *p* and β in equation (20), we arrive at the following interesting form for the fusion power density.

$$P = C\beta^2 B^4 < \sigma v > Q/T^2 \qquad (22)$$

where *C* is a physical constant. We can see from equation (22) that if we seek to maximise the fusion power density *P* in order to have an economic fusion power plant, then we want high beta, large magnetic fields, high reactivity, low ignition temperature and a large value of *Q*. The maximum of the reactivity times *Q* divided by the temperature depends only upon the fusion fuels chosen. The highest value for $< \sigma v > Q/T^2$ is found for deuterium-tritium fuel. It is nearly one hundred times larger than that for any other fusion fuel combination. Clearly, for large power density very large magnetic fields should be employed. This is a challenge to materials scientists because it is the stress in the magnet materials that limits the size of the magnetic field that can be used. The maximum value of beta is a question for plasma physics research. To find this beta limit for different magnetic confinement configurations is an active area of plasma research.

Consider a very large volume of hot plasma, so large that the boundaries are sufficiently far away that the plasma has uniform temperature and number density. How will such a large volume of idealised plasma lose energy? The photons from bremsstrahlung radiation have extremely large mean free paths in a fully ionised hydrogen plasma (about 10^{22}m) and all of them will leave the plasma. This ideal plasma radiation energy loss can be offset or balanced by the fusion energy that remains in a hot reacting plasma; this is accomplished by confining the hot ions that are released as the products of the fusion reaction. Figure 1.3 shows plots of the bremsstrahlung radiation loss and the fusion power that can remain in the plasma for both D-T and D-D fuels. Where the two curves cross (i.e., where the fusion power equals the bremsstrahlung) is called the ideal ignition point. For D-T fuels, ideal ignition is about 4.4 keV and for D-D it is 48 keV. If impurities (higher atomic weight ions) are present in the plasma, the radiation losses are larger and the ignition temperature is consequently higher. To ignite a fusion plasma it is absolutely necessary to keep the plasma fuel extremely clean and pure.

How long must a burning plasma be confined away from cool walls so that enough fusion energy is released to provide sufficient energy for a new batch of plasma fuel to be heated to high temperature and the process repeated? This confinement time question was first analysed by J. D. Lawson in 1957. He found that the product of the number density *n*, multiplied by the confinement time τ (tau) must exceed a certain numerical value that depends only upon the fusion fuels being burned and the overall power plant efficiency. For D-T fuel this Lawson value is

$$n\tau > 10^{20}\ \mathrm{m^{-3}s} \qquad (23)$$

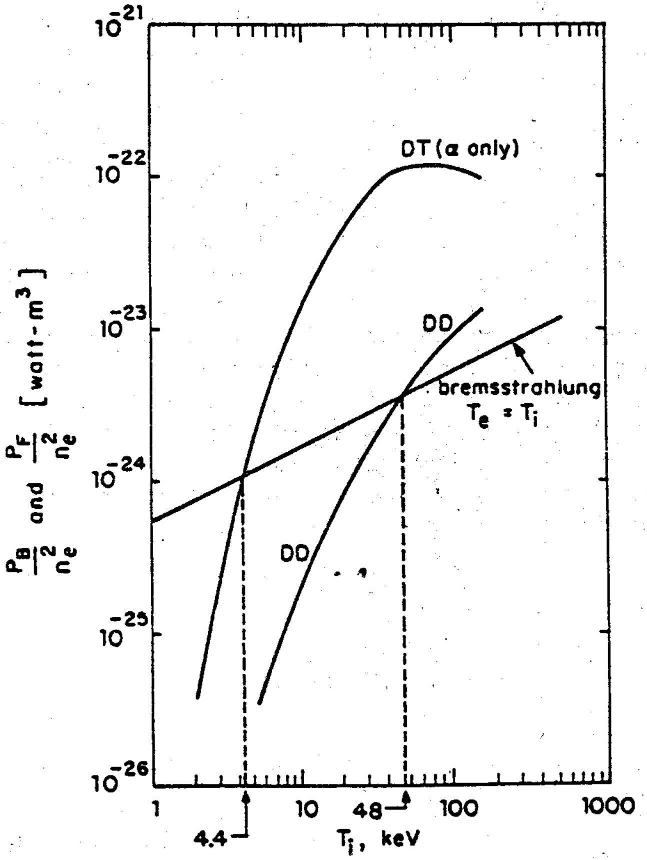

*Fig. 1.3 Ideal D-T and D-D ignition. The power generated by D-T and D-D fusion reactions and by bremsstrahlung radiation are shown as a function of temperature. The intercepts indicate the ideal ignition temperature (*Fusion Energy*, P37).*

For D-D, the $n\tau$ value must exceed about 10^{22} m^{-3}s; that is about two orders of magnitude higher than D-T. To achieve the Lawson criterion in plasma at fusion temperatures has been a scientific experimental goal for the past several decades. We are now near success and once accomplished this will represent a great scientific achievement. We will have more to say about this later in these lectures.

In summary, to release fusion energy in a controlled manner, light elements such as deuterium and tritium must be heated to above their ignition temperature and confined (or insulated) from walls for a sufficient time to exceed the Lawson $n\tau$ criterion.

Magnetic fusion

To achieve success in the development of fusion as a major energy resource, we have seen that light isotopes must be heated to their ignition temperature and confined from the walls of the confinement chamber for a sufficiently long time to permit the fusion energy that is released to greatly exceed that energy required to heat the gas and to overcome other energy losses. The technology employed to do this must also be such that the cost of fusion energy is competitive with other large scale (coal and fission) power sources. Environmental and societal aspects must also be acceptable.

Because deuterium-tritium fusion fuel has the lowest ignition temperature (about 5 million degrees Kelvin) and offers the highest fusion power density, a mixture of equal amounts of D-T is the fusion fuel that is considered by most fusion reactor designers today. However, aneutronic (no neutrons) fuels continue to attract research interest.

Most of the world's fusion research program has focused on magnetic confinement concepts. In all these concepts, some clever form of magnetic field or combination of fields is used to confine the plasma. Magnetic confinement concepts differ primarily in the geometry of the magnetic bottle and the time that it takes to create the magnetic fields. These differences in magnetic geometry have implications for the success of insulating the plasma from the wall, and the cost and complexity of the technology of the surrounding systems. Of course the design of any magnetic field confinement system must satisfy the basic physics laws of electromagnetic theory (Maxwell's equations) and this both constrains and challenges the designer's ingenuity.

The names of some of the fusion magnetic confinement concepts that have received the most study are listed below:

tokamak
tandem mirror
stellarator
reversed field pinch
spheromak
field-reversed configuration
dense Z-pinch

To date the tokamak has been the most successful and the most studied of all the magnetic field confinement systems. The tokamak concept was first proposed by Sakharov and Tamm in the USSR and independently by the New Zealander Liley. The word 'tokamak' is a Russian acronym that very roughly means toroidal (doughnut shape) chamber. To avoid plasma leaking out of the ends of a straight magnetic solenoidal cylinder (a very simple and attractive magnetic geometry, except for its open ends) the cylinder is bent into a torus or doughnut shape. A large toroidal electrical current is induced in the plasma to heat it to high temperature. Early in the history of fusion research it was found that when plasma was confined, it very often became unstable and rapidly wiggled violently, thereby quickly hitting the cold confinement walls. To avoid major macroscopic plasma instabilities, the toroidal field (toroidal is the direction the long way around the doughnut) had to be made very strong to stiffen the plasma column. The poloidal (short way around) magnetic field, that is caused by the toroidal electric current in the plasma, must be much weaker than the toroidal field. Figure 1.4 illustrates how this is achieved. The toroidal field is made by electric current flowing in the toroidal field coils. The poloidal field results from an electric current that flows in the plasma in the toroidal direction. This toroidal current both heats the plasma and helps confine it. The result of both the toroidal and poloidal magnetic field components is a spiralling magnetic field that has no ends and is everywhere within the closed toroidal chamber. These magnetic field lines make closed nested surfaces that provide confinement for the plasma.