Tandem Mirror Approach to Magnetic Fusion

David E. Baldwin, Livermore

(Lawrence Livermore National Laboratory)

The concept of containing a plasma long enough for thermonuclear fusion to take place, by means of a straight magnetic field in which the reacting particles describe substantially circular paths, was amongst the first to be explored. In its simplest form, the reacting volume consists of a cylindrical tube inside a solenoid, into which ions are injected tangentially, there to become trapped. Some longitudinal motion is however inevitable as a result of scattering and it was quickly perceived that a simple solenoid would need to be kilometres in length for ions to be trapped for a useful length of time.

It was logical then to try to close the ends magnetically by a high field mirror that would reflect the majority of the ions back into the reacting volume. However the more one tried to "cork the bottle" by increasing the reflectivity, the more unstable the plasma became. Interest in the technique waned, and research concentrated on the various forms of toroidal configuration.

While it is still probable that the first demonstration of thermonuclear fusion with magnetic confinement will be achieved in a tokamac device, it has become recognized over the past five years that magnetic mirror confinement offers the best long term alternative. Active research aimed at optimising such a system is being carried out in Japan, the USA and the USSR although does not seem to have attracted a great deal of attention yet in western Europe.

This resurgence of interest in the mirror approach arises from a combination of experimental and theoretical results. Until 1975, efforts to contain a plasma for appreciable periods had been frustated by RF noise in the plasma which increased the loss from the bottle to unacceptable levels. In 1975, however, in the 2XIIB experiment at the Lawrence Livermore National Laboratory (LLNL), USA, it was demonstrated that this phenomenon could be controlled. Shortly afterwards, at Novosibirsk, USSR, and at LLNL, the development of the ambipolar trap, or tandem mirror configuration (TM), opened the way towards a much improved mode for plasma confinement based on the mirror principle. Initial tests of this concept at LLNL and elsewhere have confirmed the promise of the original expectations.

The following summarizes the physics properties of three generations of mirror devices: the single-cell mirror machine, the original TM concept, and the TM modified by thermal barriers. With this final feature, which is soon to be tested experimentally, the TM becomes a viable candidate for a fusion power plant.

SINGLE-CELL MIRRORS

TM confinement based on the single-cell mirror machine is shown in Fig. 1. It will be evident immediately that the magnetic geometry is "open" in the sense that magnetic lines leave the confinement volume, which can be contrasted with the "closed" geometries of tokamaks and stellerators, in which the magnetic lines lie on closed surfaces within the plasma volume.

In simple mirror machines, Fig. 1(a), the strength of a solenoidal magnetic field $B = |\vec{\mathbf{B}}|$ is increased at the ends, forming the mirrors that reflect ions having a sufficient pitch angle, $\cos^{-1}$ ($\mathbf{v} \cdot \mathbf{B}/vB$), or magnetic moment to energy ratio, back towards the middle. Ions with a pitch angle less then a certain minimum are lost along the axis.

For ions to be confined over a useful period they must be reflected backwards and forwards for up to 10^6 times. This is only possible if the magnetic moment $\mu = V_{\perp}^2 / 2B$ is approximately constant (adiabatically invariant), otherwise there will be axial losses due to pitch angle scattering.

Under most conditions, the electrons in the plasma are scattered more rapidly than the ions and so are lost at a higher rate. This results in the plasma becoming positively charged until the potential becomes typically four to five times the electron temperature T_e. (In plasma physics it is normal to speak of the electrostatic potential of the plasma in terms of the potential energy of the particles expressed in eV. Similarly, temperature is used as an expression of energy from the relation $E = k_B T$.) At this point, the electrons become electrostatically held by the ions which are themselves confined adiabatically by the magnetic field. This binding of the electrons to the ions greatly reduces the electron heat loss that would otherwise occur along the open field lines. It should be noted nevertheless, that those electrons that are lost as the ions are lost, have energies five to six times T_e.

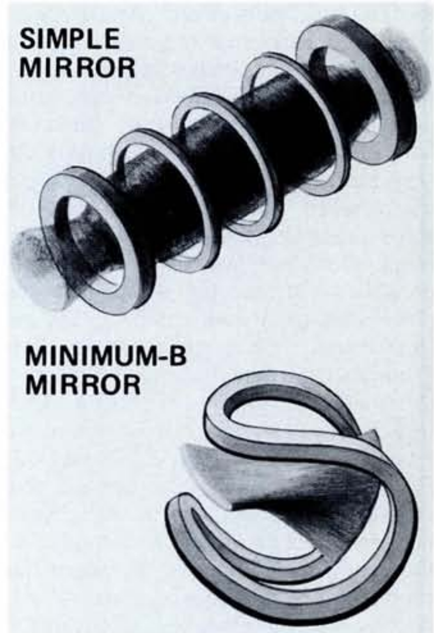

Fig. 1 — Two types of single-cell mirror machine with (shaded) their confined plasmas. In both, $|B|$ is maximum at the ends; in the simple mirror, $|B|$ decreases radially, whereas in the minimum B, it increases.

A measure of the rate of ion loss through scattering, and so the rate at which ions need to be replaced to maintain the plasma density, is given by the average time taken for particles to be scattered after multiple collisions through 90°, i.e. from an ideally confined trajectory to a total loss situation. This time τ_{ii} is given by:

$$\tau_{ii} \propto E_i^{3/2} n_i^{-1}$$

where the mean energy is E_i and the particle density n_i.

Ions of energy below a certain minimum, despite the confining field, are expelled by the positive potential, which means that mirrors cannot be fuelled by the ionization and subsequent heating of cold gas within the mirror volume. They must be fuelled by energetic atoms, whereas other types of fusion device might be ignited (i.e. fuelled by cold gas and heated by charged reaction products).

In experiments, the injection of beams of energetic neutral atoms normal to $\vec{\mathbf{B}}$, which then become ionized, has proved a successful means of filling with ions having confined pitch angles. Such a process however requires a substantial injection of power. Calculations indicate that, as a result, the power amplification factor Q, that could be obtained in a single mirror reactor, would barely exceed unity, and would be too low to be of economic interest.

Instabilities

This picture of classical confinement in mirrors, by no means reveals the whole story. Problems of stability of the configuration to both low-frequency, long-wavelength modes and to high-frequency, short-wavelength micro-instabilities have dominated research in almost all mirror experiments to date. Indeed, the experimental milestones of the programme can be measured in terms of the success achieved in controlling instabilities.

In simple mirrors, because the magnetic field decreases from the centre line out, in other words, the volume of tubes of equal magnetic flux increases with radius, there is a continuous tendency for the inner high pressure tubes to exchange with outer tubes of lower pressure. It is this exchange process that occurs in the low-frequency interchange mode, and plasma loss by the resulting sideways motion is a common effect in configurations like Fig. 1(a). However, by creating a minimum-B well with conductors of the sort of shape shown in Fig. 1(b), the mode can be stabilized. In such field configurations, the modulus B transverse to, as well as along, $\vec{B}$, increases. Energy is then required to move a magnetic moment radially as well as axially, and the configuration is stable to all perturbations that conserve μ. Experimentally, this simple picture has been borne out completely.

Micro-instabilities arise from the absence of ions with small energy or pitch angle, their distribution being inverted in $v_{\perp} = |\vec{B} \times \vec{v}| / B$. Such a distribution is not inherently stable and there is an associated free energy. Provided proper collective modes of oscillation exist, the inversion can relax by feeding energy into oscillations — the same process that is found in a laser. At the same time, because the mode frequencies are of the order of the ion gyrofrequency, and their wavelength normal to $\vec{B}$ is on the scale of the gyroradius, μ is not conserved.

Experimentally, questions relating to micro-instabilities and the associated velocity-space scattering have dominated all interchange-stable, minimum-B mirrors. The striking success of 2XIIB came from the simultaneous injection of high- and low-energy ions, the first, as neutral-atom beams in the transverse direction and the second as warm plasma streaming along $\vec{B}$. In effect, this stream supplied the usually absent low-energy ions, and the energy inversion was removed. Although this caused reduction in T_e through heat conduction along the flowing plasma, it increased the ion lifetime 10-fold and permitted build-up of hot ions to the point that the plasma pressure equalled, and even exceeded, the central magnetic pressure.

Theoretical modelling of the process proved very successful, bolstering confidence in the ability to describe these modes in other operating regimes. The understanding acquired, then played an important part in the design of the Tandem Mirror Experiment (TMX) that initially tested the TM concept, and extrapolations of the methods are used in the conceptual designs for TM reactors.

Although it is now recognized that the mirror configurations described so far cannot achieve sufficient confinement to act as reactors in themselves, the characteristic positive potentials of the plasma and the ability to hold high plasma pressure are profitably employed in the tandem configuration.

TANDEM MIRRORS

In the TM configuration, high-density, mirror-confined plasmas in minimum-B end cells, electrostatically plug the end loss from a low field, solenoidal central cell. Moreover, by the external control of particle distribution functions in the end cells, confinement of the central cell ions in the self-consistent fields can be significantly improved.

Fig. 2 shows typical magnetic and electron density profiles. Although the overall potential is positive due to the electron loss through the open lines, the higher electron density in the plug n_p compared to the central cell, n_c, creates an electrostatic potential difference between the plugs and central cell given by Boltzmann's relation:

$$\phi_i = T_e \ln (n_p / n_c) \qquad (1)$$

(assuming $\vec{B} \cdot \nabla T_e = 0$, which is a reasonable approximation in view of the relatively free movement of the electrons along the lines). This potential confines, in the central cell, those ions having energies $\leq \phi_i$. The desired ratio n_p / n_c, is maintained by properly choosing plug and central cell particle sources.

The essential aim is to produce a high value of the product $n\tau$ (density x confinement time) which for hydrogenic ions, in systems combining magnetic (adiabatic) and electrostatic confinement is given by:

$$n\tau = n\tau_{ii}\, g(R) [1 + \phi_i / T_i] \exp (\phi_i / T_i)$$
$$\propto T_i^{3/2} [1 + (T_e / T_i) \ln (n_p / n_c)] (n_p / n_c)^{T_e/T_i} \qquad (2)$$

where $n\tau_{ii} = 5.6 \times 10^{10}\ T_i^{3/2}\ \mathrm{cm^{-3}.\ s}$,
T_i is the ion temperature in keV,
and $g(R) \cong 3$ is a slow function of $R = B_p / B_c$, the ratio of plug to central-cell magnetic fields. In the second form, Eq. (2) can be used to emphasize that an improvement in $n\tau$ over the mirror scaling values requires that $n_p / n_c > 1$ and that it is desirable for $T_e / T_i > 1$. When $\phi_i \cong 2.5 T_i$, confinement is enhanced 100-fold over that of an equal temperature, single-cell mirror.

This enhancement is the promise of the TM configuration: that relatively lossy mirror configurations can be used effectively to plug a large volume of reacting plasma with an overall improvement in energetics. The system is attractive from the engineering point of view, because the central cell is the simplest of magnetic configurations requiring only a straight and low field. The more complicated, high magnetic fields are restricted to the plugs and the plug-solenoid transitions. The device is intrinsically steady state in character, so that DC operation depends only on the successful removal of alpha particle reaction products.

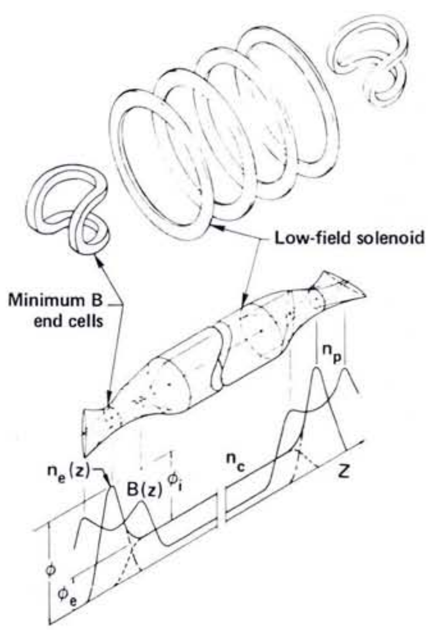

Fig. 2 — Magnetic coil configuration, plasma shape, and representative axial magnetic and density/potential profiles in a tandem mirror. Density and potential are shown together although strictly $\phi \propto \ln n$.

Several qualitative features of a TM reactor can be readily identified leading to the calculated reactor parameters given below. Since the plug ions are only mirror confined, power balance is favoured by their having a high energy in order to reduce the scattering cross section. This, combined with the requirement $n_p > n_c$, causes the plasma pressure in the plugs to be many times that in the solenoid. Creating the fields to maintain this pressure is a critical feature of the technology. Conceptual designs assume Nb_3Sn superconducting magnets operating in the range of 12 - 15 T.

Roughly one-half the injected plug power is transferred to electrons and is quickly distributed along the central cell; the electrons then heat the central cell ions by classical transfer. However, maintaining $T_e > T_i$ improves ion confinement as noted from Eq. (2). Electron heating via fusion-produced alpha-particles can lead to ignition in the central cell, provided energy transfer matches the energy lost per electron-ion pair, roughly $\phi_i + T_i + \phi_e + T_e$. Short of ignition, the confinement and power balance are improved by auxiliary electron heating, e.g., by electron cyclotron resonance heating.

Given the powers per unit volume required to drive the plugs and central cell, p_p and p_c, their respective volumes, V_p and V_c, and the nuclear power density generated in the central cell, p_n, the overall power amplification factor is:

$$Q = p_n V_c / (p_c V_c + 2 p_p V_p)$$

If the central cell is ignited, $p_c = 0$, and an arbitrarily high Q is achievable with a sufficiently large volume ratio, albeit with a large total power $p_n V_c$. However, obtaining ignition by decreasing n_c to improve confinement, see Eq. (2), while increasing the length of the central cell to maintain $p_n V_c$, would reduce the nuclear power per unit length and the neutron flux density at the wall, i.e., the power output flux density. In order to get an economic value for this, while maintaing a high Q, it would be necessary to operate in a sub-ignition mode in TM's were it not for the introduction of thermal barriers.

Because the cross-sectional areas of the plugs and central cell are linked by magnetic flux conservation, the attainable Q also depends on the attainable β_c (= central cell plasma pressure/magnetic energy density). Higher β_c permits a lower central vacuum field as well as an increased positive field gradient away from the axis. It follows that for the same plug radius, the central cell radius can be larger, with both higher Q and power output flux density.

β_c is limited by the pressure that the magnetic field can hold stably without an anomalous loss of plasma. At low β_c, low frequency stability is ensured by the high-β end cells. In a line-averaged sense, the minimum-B plugs anchor the whole configuration. However, as β_c increases, the plasma pressure can bend magnetic lines, and field perturbations can develop in regions remote from the plugs whose stabilizing influence is then lost. The limiting values of β_c are detailed functions of the field and their calculated values depend on the plasma model. The magnetohydrodynamic model gives a β_c limited to about 0.2 by short-wavelength perturbations, but finite ion gyroradius effects raise this value, to an extent that is not yet known. An ability to calculate accurately the limiting value of β_c is most important because of its impact on reactor assessment. Consequently a great deal of theoretical effort is expended in this direction and conclusions must be corroborated by experiments.

The significance of radial transport increases with increasing axial confinement. As a loss process, transport in a TM differs from that in a closed line system. Charged particles are not transported to the radial walls, but only to an outer flux surface where they are no longer plugged against axial loss. This lost power then is deposited on walls remote from the plasma.

A particular transport process in a TM central cell results from resonance between the frequency of axial bounce, ω_b, and that of azimuthal drift due to radial electric fields, ω_{dr}. If $\omega_b >> \omega_{dr}$, the action integral associated with the fast motion is an adiabatic invariant and transport is slow, even in the presence of collisions. Unfortunately, resonance $\omega_b \cong \omega_{dr}$ occurs in typical TM designs so that the radial steps created by the break in symmetry in the end regions, enhance the transport even without collisions. Particle lifetimes, including this transport, are calculated to be comparable to purely axial lifetimes, but the existence of this form of transport limits some features such as density gradients.

Due to the confining potential ϕ_i, ions in the central cell do not suffer from an energy inversion which drives micro-instabilities. However, ions in the plugs are mirror confined and will be subject to familiar mirror instabilities unless they are controlled. In the TMX experiment at LLNL, instability was controlled by adjusting the system parameters so that the ion loss flux from the solenoid out through the plugs equalled the cold plasma stream found necessary to stabilize the single mirror cell in 2XIIB. Although successful in TMX, this technique could not be employed in a reactor because it implies too large a loss from the solenoid. It is necessary to seek another solution and it has recently been calculated that a different class of ion distribution can be stable to these modes without the addition of streaming cold plasmas. Confirmation of this improved stability will be an important task of the upgraded TMX currently under construction.

The reactor picture that emerges for TMs without thermal barriers is a distinct improvement over a single mirror, but it still has severe technological requirements for the modest performance it promises. It has central cell density $\cong 10^{14}$ cm^{-3}, temperature $\cong$ 40 keV and magnetic field $\cong 2T$. It requires plugs with electron density $\cong 10^{15}$ cm^{-3}, peak fields $\cong$ 17 T, and neutral-beam injection energies $\cong$ 600 keV with, or 1.5 MeV without, auxiliary electron heating. For power production of 1000 MW (e), it has a calculated $Q \leq 5$ and neutron wall loading ≤ 2 MW/m^2, assuming that the implied β_c of 0.7 can be achieved.

Such a performance might be quite attractive for a fusion-fission hybrid device, in which the 14 MeV neutrons would be used to produce fissile fuel for fission reactors and the Q requirements are less stringent. It is probably below that required for a pure fusion device. The picture improves considerably with the addition of thermal barriers.

THERMAL BARRIER TANDEM MIRRORS (TBTM)

Although the thermal barrier (TB) modification to the TM has yet to be tested experimentally, it promises to improve reactor performance while easing the technological requirements. The essential idea is to raise the plug-electron temperature T_{ep} above the central cell temperature T_{ec} by auxiliary heating in the plugs alone. In the weak collision regime, thermal contact between the plug and the central cell occurs by the trapping and detrapping of electrons in the ϕ_i well. To reduce this mixing, a negative dip $\phi_b > T_{ec}$, is introduced between the plug and central cell, see Fig. 3.

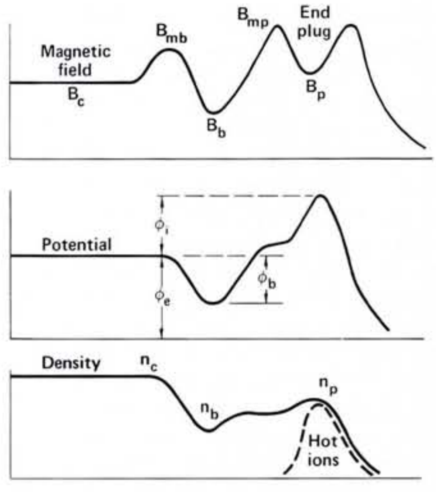

Fig. 3 — Typical magnetic, potential and density profiles for one end of a tandem mirror machine with a thermal barrier between the end cell and the central cell.

The value of ϕ_i required for a reactor is $\phi_i \cong$ 100 keV. The modest Q value given above resulted from ϕ_i varying as ln (n_p/n_c) while the ratio of plug injection power to fusion power varied as n_p^2/n_c^2, even with T_e optimized by auxiliary heating. A TBTM has the same ϕ_i, but with $n_p \leq n_c$. Consequently, more external power is saved by generating a TB than is needed to maintain it. With TBs, the Q values are higher, the neutral beam injection energies are lower, and the plug magnetic fields are reduced, due to the lower plug pressure.

Forming ϕ_b, requires a reduction in ion density in the barrier from n_c to n_b. This is done by throttling the ion flow into the region with a high magnetic field coil generating B_{mb} and then preventing the accumulation of thermal ions trapped in ϕ_b.

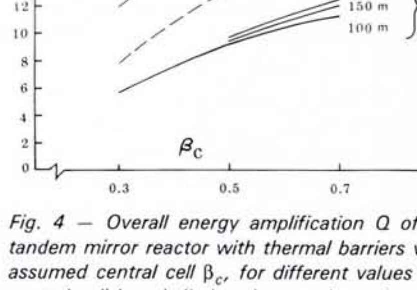

Fig. 4 — Overall energy amplification Q of a tandem mirror reactor with thermal barriers vs. assumed central cell β_c, for different values of central cell length (L_c) and two values of peak magnetic field (B_{mirror}): 12 T upper group, 9 T lower.

This step requires external power to pump out the ions as they scatter and become trapped in the barrier. As a pump, the first experiments will use charge exchange of trapped ions with a neutral-atom beam which is injected into the barrier region at a pitch angle corresponding to no trapping in the local mirror field.

With the barrier in place and local heating applied, T_{ep} can increase. As illustrated in Fig. 3, an increasing ion density $n_p > n_b$ will generate a local potential $\phi_b + \phi_i$ that scales with T_{ep}. In effect, the heating power applied to the plugs tends to push electrons out of that region, and the well depth $\phi_b + \phi_i$ increases accordingly to preserve charge neutrality.

The first real test of thermal barrier effectiveness will come in an upgrade of TMX in early 1982. Current theoretical studies include calculations of electron-power transfer rates, ion filling rates and charge exchange pumping effectiveness, electron cyclotron heating methods to raise T_{ep} and, of course, the stability properties of this new configuration.

In most other respects, the TBTM resembles the conventional TM and the considerations of the preceeding section hold. As an indication of TBTM reactor possibilities, Fig. 4 shows the calculated reactor Q versus the attainable β_c for the conditions listed. Based on these results, an economic $Q \cong 10$ would require either $\beta_i \cong 0.5$ at the lower magnetic field, or at lest $\beta_c \cong 0.3$ at the higher.

Conclusions

The expected improvements from single-cell mirror to tandem mirrors to tandems with thermal barriers are large, and the source of renewed interest in this fusion development line is clear. Experimentally, the TM programe is in its relative infancy. However, the concept is rooted in extensive mirror experience, and the first generation of tandem devices demonstrated their superiority. New ideas are being analyzed, e.g., improved pumping techniques and alternative magnetic configurations that are directed toward increased axisymmetry. The next few years should bring very rapid progress.

FURTHER READING

For an excellent 20 year history of the mirror programme, see Ryutov D.D., *Nuclear Fusion* **20** (1980) 1068.

For reports on progress in the major experiments, see the proceedings of the Biennial IAEA Conferences on Plasma Physics and Controlled Nuclear Fusion Research.

For a description of thermal barriers, see Baldwin D.E. and Logan B.G., *Phys. Rev. Lett.* **43** (1979) 1318.

For details of conceptual reactor designs, see the LLNL Reports: "Tandem Mirror Reactor with Thermal Barriers", UCRL-84255 (1980) by Carlson G.A. et al., and "Status Report on the Fusion Breeder", UCRL-84436 (1980) by Moir R.W.

Primordial Helium

H. Andrillat, Montpellier

(Astronomy Laboratory, University of Languedoc)

One of the most dependable guides for interpreting cosmological data continues to be the general theory of relativity based upon a representation of the real by a four dimensional continuum, the space-time, with a curvature that is variable with time. These days, Friedmann's models are generally accepted, where the function $R(t)$ expressing the curvature is one of the three forms shown in Fig. 1.

Despite the uncertainties which still exist on the geometric nature of the Universe, through a lack of sufficiently precise or extensive measurements, there is a convergence of all these models on a singularity with $R = 0$ and a primordial explosion ($dR/dt = \infty$) — the big bang. This resulted in the Universe having an initial temperature of extreme magnitude, since the curvature is related to the radiation temperature $T(t)$ by the expression:

$RT = cte$; $T \to \infty$ when $R \to 0$.

Primordial Energy and Particles

All elementary particles and, in particular, the heavy particles, the hadrons — could be created out of the thermal energy of the primordial Universe. For a particle of mass m, the threshold for such creation is given by the equation: $mc^2 = kT$
where k is Boltzmann's constant
($= 1.38 \times 10^{-23}$ J/K)
and c the speed of light ($= 3 \times 10^8$ m/s). The threshold temperature for the creation of a proton ($m_p = 1.67 \times 10^{-27}$ kg) is thus 10^{13} K.

When the temperature of the Universe was very much greater than the threshold temperature for the production of a given particle P, particles of this type would be formed in very large numbers, with an equal number of antiparticles P'. Moreover, their mean free path would be very short as the density of matter, in this closely confined Universe so soon after its birth, would be huge. Consequently, particles and antiparticles annihilated each other as soon as they were formed, in equilibrium with the γ-radiation that created them and in a state of perfect exchange between matter and energy.

However, as the temperature of the Universe fell towards the threshold for the production of particles P and P', they were formed in ever decreasing numbers so that their annihilation by pairs became preponderant. At the threshold temperature, they disappeared from the scene, with the very important exception of protons and neutrons which remained to constitute the material component of the Universe. This was the first key moment when the temperature crossed the proton threshold of 10^{13} K.

Today the residual energy of the Universe, in the form of 3 K radiation, is unable to synthesize any massive particle, and matter, probably of one type only, can no longer be transformed into energy. Einstein's relation $E = mc^2$ is thus now of symbolic significance only, on the cosmic scale.

Condensation of Matter

It is now believed that while protons and antiprotons were initially formed in equal numbers, and were simultaneously annihilating each other, they could also decay in the physical conditions obtaining immediately after the big bang. Because of charge-parity violation, the rate of decay of the antiprotons was higher than that of the protons. Consequently, at the threshold temperature of 10^{13} K, there was an excess of protons of about 1 in 10^9, but this excess formed the essential matter of the Universe, once pair annihilation was completed.

The proton (or antiproton), it is postulated, is not completely stable but can

Fig. 1 — Friedmann models of the Universe
(A) hyperbolic (infinite Universe)
(B) parabolic (infinite Universe)
(C) elliptic (finite Universe)