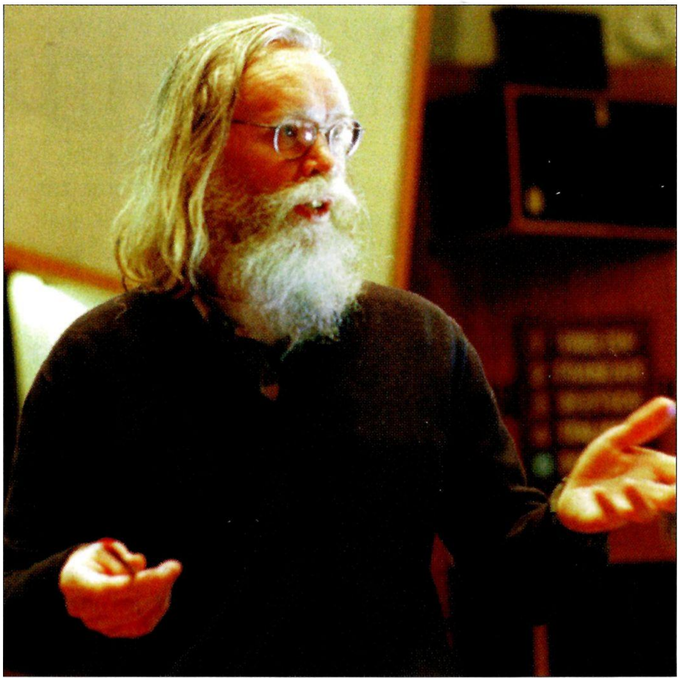
Why does CP violation

The seemingly obscure phenomenon of CP violation is increasingly being viewed as the key to a deeper understanding of both the behaviour of elementary particles and the Big Bang origin of the universe. Here, *John Ellis* of CERN explains how far and how deep the implications of CP violation extend.



Exploring the untracked expanses of the cosmos and the microworld – eminent CERN theorist John Ellis.

The visible universe is composed of matter particles – protons, neutrons and electrons – rather than their antimatter partners – antiprotons, antineutrons and positrons. If the Moon were composed of antimatter, then lunar probes and astronauts would have vanished in a fireball of energy as soon as they touched the lunar surface. The solar wind and cosmic rays do not destroy us, implying that the Sun and the Milky Way are also made of matter.

If there were any region of antimatter within our local cluster of galaxies, we would be able to see radiation from matter–antimatter annihilations at the boundaries. Moreover, the cosmic microwave background radiation shows no signs of disturbance by subsequent annihilation radiation, suggesting that there are no large regions of antimatter within at least 10 billion light years – and perhaps the whole visible universe.

The Big Bang should have created equal amounts of matter and antimatter. Why is there now so much of one and so little of the other? CP violation – an obscure effect seen only with certain kinds of elementary particles – could provide the answer.

Enter CP violation

A recent article by Gerry Bauer ("In hot pursuit of CP violation" *CERN Courier* June p22) set the CP violation scene. In 1964, James Cronin, Val Fitch and collaborators discovered that the decays of neutral kaons did not respect the symmetry known as CP – the combination of particle–antiparticle (charge conjugation – C) and mirror (parity – P) symmetry.

It had been known since 1957 that weak interactions violate both the C and P symmetries – neutrinos spin left-handedly, whereas their antiparticles (antineutrinos) exist only in right-handed form. Despite this maximal violation of C and P, it had been thought that they were always violated together so as to respect the combination CP.

However, the Cronin–Fitch experiment showed that this could not be exactly true. What is the connection between this abtruse property of elementary particles and the matter dominance of the universe? A possible answer was provided by Andrei Sakharov in 1967. He laid out three conditions that would enable a universe containing initially equal amounts of matter and antimatter to evolve into a matter-dominated universe, which we see today.

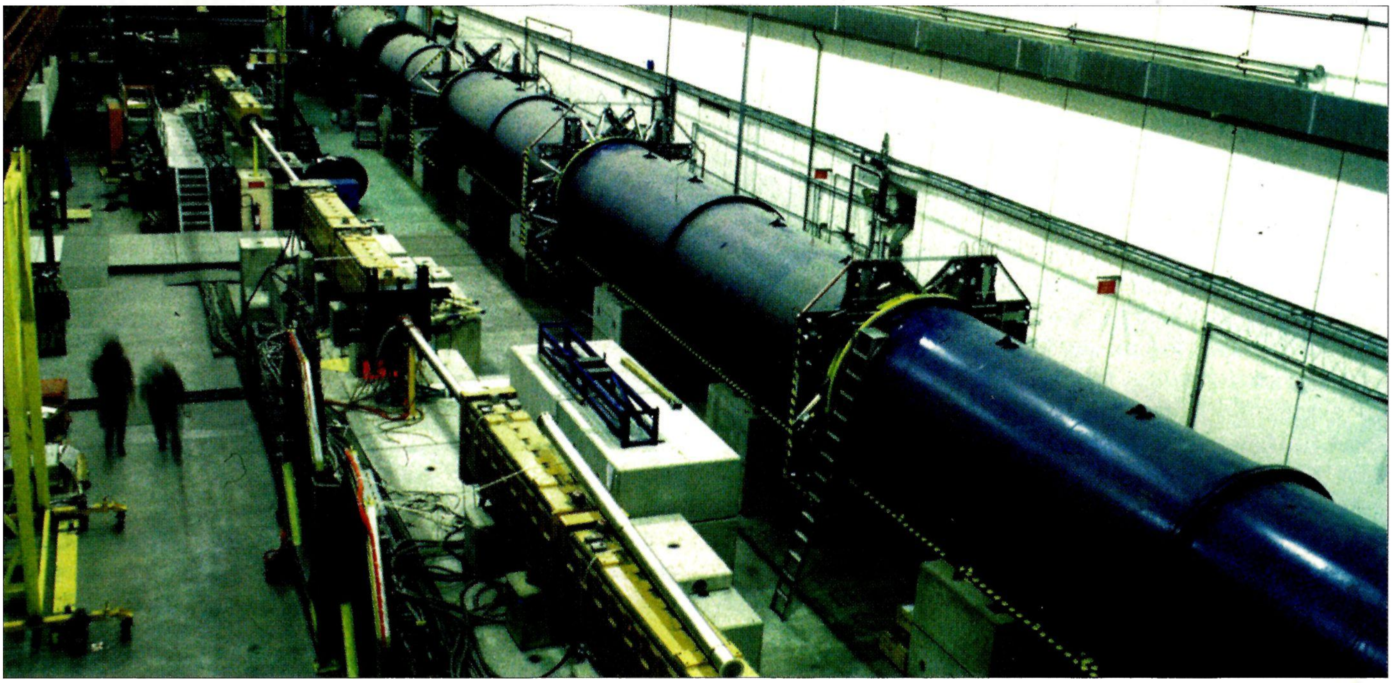
The first requirement was that the proton – the bedrock particle of nuclear matter – should be unstable. The second was that there would be interactions violating C and CP, as shown by Cronin and Fitch, that would open up the possibility that the universe's initial exact matter–antimatter symmetry could be upset. The third condition was that the universe would undergo a phase of extremely rapid expansion: otherwise, matter and antimatter particles, having equal masses, would be fated to pair up with equal densities.

If a cosmological matter–antimatter asymmetry could be built up in this way, all of the remaining antimatter particles would annihilate later in the history of the universe, leaving behind matter particles and radiation, as observed today.

Sakharov's landmark paper provided the conceptual framework for generating a matter universe, but it has fallen to subsequent generations of physicists to explore specific mechanisms realizing his ideas, opening up some possibilities and excluding others. Key roles in this exploration are being played by recent experimental results from CERN and Fermilab, and new data from SLAC, KEK, Cornell, DESY and Frascati may soon be making important contributions.

The favoured theoretical framework for CP violation was provided

matter to the universe?



The kaon decay channel of the NA48 experiment at CERN – the latest study to provide a precision measurement of CP violation.

in 1973 by Kobayashi and Maskawa, who pointed out that CP violation would follow automatically if there were at least six quark flavours. Measurements in the neutral-kaon system and elsewhere are all consistent with this being the only source of CP violation, although they leave room for other sources, which inventive theorists continually propose.

GUT feeling

Also in 1973, Pati and Salam, and Georgi and Glashow, proposed grand unified theories (GUTs) containing new interactions that allowed for proton decay. Such decay would violate the conservation of baryon number – the total number of strongly interacting particles minus the number of antiparticles. So far, dedicated searches in such large underground detectors as Super-Kamiokande have not seen any evidence for this. However, the evidence that they have found for neutrino masses suggests that interactions that violate lepton number (the total number of weakly interacting particles minus the number of antiparticles) do exist. This is another key prediction of many GUTs, and may even play a role in generating the matter in the universe, as discussed later.

In 1978, CP violation and GUTs were combined by Yoshimura in a proposal for generating the matter asymmetry of the universe via the decays of massive particles. His idea was that, if they produced a CP-violating excess of quarks in their decays, this would evolve into the matter that we see in the universe today. Unfortunately, it was soon realized that the minimal GUTs originally proposed would yield too small an excess of quarks, so the GUT would need to be expanded to produce the amount of matter particles that are observed in the universe today: 10^{-9} of the number of photons.

It was suggested that the extra CP violation required might also generate a neutron electric dipole moment large enough to be detected. (Although a neutral particle, the neutron could contain an asymmetric distribution of equal and opposite positive and negative charge.) However, a long experimental campaign currently led by an experiment at ILL Grenoble limits this to less than 6×10^{-26} e cm, analogous to the Earth's surface being smooth and symmetric to less than 1 µm.

By then, theorists had developed new ideas. One idea was that the strong interactions might also violate CP. The fact that this has not been seen led to the postulation of the axion, which might be a component of the universe's dark matter.

Weak washout

The other surprise was that electroweak interactions could also change baryon number. This does not happen via the exchange of a specific particle. Instead it arises from coherent fields with non-trivial topological properties. These non-perturbative electroweak interactions provide both a challenge and an opportunity. The challenge is that they might "wash out" any matter density that is built up by GUT particles. The opportunity is that they might enable the matter density to be built up by the electroweak interactions alone.

One way to avoid the weak washout is to have the GUTs generate a net density of leptons, which the additional weak interactions would then recycle into baryons. One such scenario, proposed by Fukugita and Yanagida, relies on the decays of heavy right-handed neutrinos in the early universe. Some indirect support for this scenario comes from recent experimental hints that the known light neutrinos can mix (oscillate) and have masses, which could be due to mixing with such heavy neutrinos. At least some neutrino models that fit the neutrino data are also able to generate the matter in the universe. Another weighty implication of the new neutrino data?

As a GUTless alternative, perhaps the matter in the universe was generated when the cooling of the universe triggered a phase transition enabling quarks and the W and Z carriers of the weak force to acquire their masses from the Higgs boson? This electroweak mechanism would require the phase transition from a hot universe with massless particles to the present state with massive particles to have been abrupt, so as to meet Sakharov's third requirement.

Unfortunately, the Higgs boson has not yet shown up at CERN's LEP electron–positron collider, implying that it weighs more than about 100 GeV and that the electroweak phase transition was too weak to allow the matter of the universe to be generated this way.

However, the door is not yet closed. For example, a supersymmetric scenario, with new "sparticles" partnering the known particles, might provide a suitable abrupt transition, and also contain additional CP-violating effects that could generate a suitable matter density. These supersymmetric options suggest that LEP, which is now operating at higher energy, might produce a Higgs boson this year or the next. If LEP is lucky, this could also have weighty implications for the universe.

CP in the laboratory

One of the great attractions of such GUTless models is the possibility that they could be tested in laboratory experiments on CP violation. This exciting prospect has been underlined by the recent confirmation, by the KTeV experiment at Fermilab and by NA48 at CERN, of direct CP violation – the decay of neutral kaons into two pions – first measured by the NA31 experiment at CERN . The magnitude of the effect is surprisingly large.

Another possible observation of CP violation has recently been reported by the CDF collaboration at Fermilab in the decays of neutral B particles, each giving a J/psi and a neutral kaon. A large effect is expected in the Standard Model, and this is the most likely interpretation of the CDF data, although a null result cannot yet be excluded completely.

CP violation in the decays of B mesons is the primary objective of the experiments BaBar and BELLE at the B factories, which are starting to take data at SLAC in Stanford and KEK in Japan. Their first task will be to seek confirmation of CP violation in the reaction probed by CDF and to search for CP violation in the decays of neutral Bs into pion pairs.

Also in the hunt will be HERA-B at DESY, the revamped CLEO detector at Cornell and experiments at Fermilab's Tevatron collider. Even if these experiments turn out to agree with the orthodoxy of the Standard Model, there is scope for follow-on experiments that might be sensitive to subtle effects indicating new physics that might be related to a mechanism for generating the matter in the universe.

CP violation provides a uniquely subtle link between inner space, as explored by experiments in the laboratory, and outer space, as explored by telescopes measuring the density of matter in the universe.

One such experiment is LHCb, which is scheduled to start taking data at CERN's LHC collider in 2005. BTeV, another next-generation B experiment, is under consideration for the Tevatron. There are plenty of other opportunities for future experiments to probe CP violation and cast light on the origin of the matter in the universe. One is provided by rare neutral kaon decays, for example, producing a neutral pion together with a neutrino and an antineutrino or an electron–positron pair. The measurements of direct CP violation in decays into two pions leave room for large supersymmetric contributions to CP violation, which could cast light on supersymmetric scenarios for the origin of matter.

Another opportunity is the continued search for the neutron electric dipole moment, which might be able to reach the sensitivity required to test GUT models for the origin of matter.

Future violations

In the longer term, there are enticing opportunities to search for CP violation in neutrino oscillations, which could explore aspects of the models based on the decays of heavy neutrinos. Studies are under way on "neutrino factories" based on the decays of muons in storage rings (*CERN Courier* July p22). These provide well defined neutrino and antineutrino beams with both electron and muon flavours, which provide opportunities to search for CP-violating effects in the oscillations of neutrinos and antineutrinos. Looking further ahead, if the problems of controlling the muon beams can be solved, muon colliders could study Higgs bosons in unparalleled detail.

Supersymmetric models capable of generating matter in the universe raise the possibility that the decays of Higgs bosons might reveal novel violations of CP symmetry.

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I am sure that this dialogue between theory, experiment and cosmology will culminate in a theory of the origin of the matter in the universe, based on the far-reaching ideas proposed by Sakharov in 1967. This would be an achievement comparable in significance to the emerging theory of the formation of structure in the universe, based on inflation and dark matter. Microphysics and macrophysics are now yoked together, pulling scientific explorers across the untracked expanses of the cosmos.

John Ellis, *CERN.*