

Experiment sees the arrow of time - at last!

Article from physicsworld; see <http://physicsworld.com/cws/article/print/1327>

The classical laws of physics cannot distinguish between the past and the future, but now experiments at CERN have confirmed that time-reversal symmetry is broken in neutral kaons.



[CPLEAR](#)

Everyday experience tells us that it is impossible to travel backwards in time, no matter what science-fiction writers and movie directors tell us. However, this seemingly natural impossibility is actually one of the greatest mysteries in physics. Currently most physicists associate the irreversibility of time with the production of entropy in the warm macroscopic world. One consequence of this irreversibility - often called the "arrow of time" in thermodynamics - is the ageing process. In plain terms, one grows old because of the irreversible physical processes that occur during one's life. However, the fundamental classical laws of physics discovered by Galileo, Newton and Einstein do not distinguish between the future and the past. In other words, they appear to be symmetric in time.

One might naively expect that the thermodynamic arrow of time would be absent in the cold microcosmos of elementary particles, which most physicists believe to be

closed quantum mechanical systems. However, this is not the same as saying that time-reversal symmetry is preserved at the level of elementary particles. On the contrary, there is a different "arrow of time" that manifests itself in the fact that there is no symmetry in time between the process of matter transforming into antimatter and vice versa.

This arrow of time is one of the great mysteries in elementary particle physics. It is still unclear whether the arrow of time seen in particle decays is related to any sort of "ageing" process for particles. Therefore, understanding the nature of time-reversal symmetry, and its violation, appears essential in the elusive quest for a full understanding of the concept of time.

Most physicists believe that the violation of time-reversal symmetry is linked to the symmetry between matter and antimatter. Mathematically, this latter symmetry is expressed through a fundamental theorem stating that under the assumptions of locality (i.e. that interactions are local in space-time), Lorentz invariance (the laws of physics are the same in all reference frames) and unitarity (all probabilities always add up to one), all known quantum field theories possess a symmetry under the combined operation of CPT: C denotes the charge conjugation, which changes the quantum numbers of every particle into those of its antiparticle; P is a reflection operation known as parity, which turns an object into its mirror image and rotates it by 180° about an axis perpendicular to the mirror; and T denotes time reversal.

Therefore, assuming that CPT symmetry is always preserved, any violation of time-reversal symmetry should always be accompanied by a violation of CP symmetry and vice versa.

The laws of electrodynamics and the strong interaction preserve CP symmetry to great accuracy. However, it is known that weak interactions do not conserve CP symmetry. This was confirmed experimentally by Christenson, Cronin, Fitch and Turlay in 1964 when they measured rare (1-in-500) decays of long-lived kaons into pairs of pions. The neutral-kaon system is still the only system in which CP violation has been verified experimentally. Although this result implies that time-reversal symmetry should also be violated, it is nevertheless very important to demonstrate T violation directly, as such an experiment could allow us to test the CPT theorem itself, and thus shed light on the issue of entropy production in a particle system.

Such an independent measurement of T violation has now been provided by the CPLEAR collaboration at CERN, the European particle physics laboratory in Geneva. The test essentially amounts to a comparison of probabilities for the neutral kaon to transform into its antiparticle, the antikaon, and vice versa. The neutral kaon is a bound state of a down quark and an anti-strange quark, and has a strangeness quantum number of -1; its antiparticle has a strangeness quantum number of +1. Weak interactions are known not to conserve strangeness, so kaon can transform into antikaon in the course of time and vice versa.

In the CPLEAR experiment, headed by Panagiotis Pavlopoulos of the University of Basle in Switzerland, the neutral kaons are produced through the strong interactions in collisions of antiprotons with the protons in hydrogen atoms:

antiproton + proton \rightarrow kaon⁻ pion⁺ kaon⁰

or antiproton + proton \rightarrow kaon⁺ pion⁻ antikaon⁰

The strangeness of the neutral kaon - that is, whether it is kaon or antikaon- at the time of production can be "tagged" by the charge of the second kaon produced in the collision. The strangeness of the kaon at the moment of decay can be tagged through its decay products: kaon particles decay into a positron, negative pion and a neutrino, while antikaon particles decay into an electron, positive pion and anti-neutrino. (These decays are called semileptonic because some of the products are leptons and some are hadrons.) If there is an asymmetry, A_T , between the number of initial antikaon decaying into positrons and the number of initial kaon decaying into electrons, then, under certain assumptions that have been supported by the current data, this is a measure of the violation of time-reversal symmetry in the sense described above.

The CPLEAR collaboration, following a series of preliminary announcements at conferences since 1995, has now reported a final result for the asymmetry of $A_T = (6.6 \pm 1.3_{\text{stat}} \pm 1.0_{\text{syst}}) \times 10^{-3}$ (A Angelopoulos *et al.* 1998 *Physics Letters B* at press). The result demonstrates clearly a departure from time invariance in the semileptonic decays of neutral kaons.

Within the experimental accuracy of the CPLEAR experiment, the amount of T violation is found to be equal to the amount of CP violation observed in the neutral-kaon system, thereby providing a non-trivial consistency check of the validity of the CPT theorem to this level of accuracy.

An indirect demonstration of T violation, based on a phenomenological analysis of CP-violating amplitudes, was actually made at CERN in 1970 using data on the decay of long- and short-lived kaons into two neutral pions (K R Schubert *et al.* 1970 *Phys. Lett.* **B31** 658; 662). That analysis assumed unitarity: in other words, it was assumed that those kaons that disappeared had decayed into observable states. The CPLEAR experiment does not rely on this assumption and, most importantly, the result is the first direct observation of the T violation.

The violation of time-reversal symmetry in the neutral-kaon system has subsequently been confirmed by the [KTeV experiment at Fermilab](#) in the US. The KTeV collaboration, headed by Bruce Winstein of the University of Chicago, has reported preliminary results from an experiment on very *rare* events, the 1-in- 10^7 decay of a single kaon into electrons and pions. In such a process time-reversal violation manifests itself in a subtle way. Since changing the direction of time also reverses the direction of momentum of a particle, the KTeV team detect violation of T symmetry by comparing the rates of some decays with other decays in which the particles emerge in the "time-reversed" direction.

What the CPLEAR and KTeV collaborations have shown with their observation of T violation is that the transformation of matter into antimatter is asymmetrical in time compared with the reverse process. This might have far-reaching consequences for our understanding of the cosmos. For instance, it might help explain why the universe is made of matter rather than antimatter, despite the fact that it is thought that equal amounts of both were created in the big bang. However, the discovery of the violation of time-reversal symmetry does not tell us if entropy is produced in the microcosmos. In simple terms, these experiments do not answer the question: do kaons grow old? All indications currently point towards the validity of the CPT theorem for the neutral-kaon system. However, if kaons do grow old, this would constitute evidence of new fundamental interactions in nature not covered by the CPT theorem. A natural candidate for such interactions is gravitation. Indeed, in highly curved space-times the CPT theorem is known to fail, at least in its original formulation. The neutral-kaon system exhibits great sensitivity to such effects - indeed, the CPLEAR experiment has placed stringent bounds on these effects, which are close to the magnitude at which gravitational interactions might set in (R Adler *et al.* 1995 *Phys. Lett.* **B364** 239).

Other tests of fundamental symmetries should be possible in the near future. The DAFNE collider at the Frascati National Laboratories in Italy will provide further precision tests of CP and CPT violation by measuring the decays of ϕ -mesons (bound states of strange and anti-strange quarks). The AD project at CERN will test CPT in anti-atoms. And many tests of T, CP and CPT violation will be possible at the NA48 experiment at CERN, at "B-factories" at the Stanford Linear Accelerator Center in the US and the KEK Laboratory in Japan, and ultimately at the Large Hadron Collider at CERN.

These experiments are expected to shed more light on the microscopic origin of discrete symmetries within the Standard Model of particle physics and, perhaps, tackle fundamental issues on the nature of space-time and gravity.

About the author

Nick Mavromatos in the Department of Physics at Oxford University, UK.
Dec 1, 1998