Symmetry in Basic Physical Laws

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ABSTRACT: **Recent physical experiments suggest that chirality is not a purely chemical phenomenon, but seems to be an inherent feature of basic physical laws. A fundamental physical principle (the CPT theorem) connects asymmetry in space with the "arrow of time," and shows that such an arrow exists even on the level of mesons.**

KEYWORDS: **symmetry; CPT theory; parity; chirality; arrow of time; antimatter; particle decay**

INTRODUCTION

Asymmetry has been a major concern in chemistry since 1848 and Pasteur's pioneering work on crystallization. Chirality has been regarded as a typically chemical phenomenon, since it has commonly been believed that the basic laws of physics are totally symmetric.[1] This statement is true for all classical and quantum-mechanical phenomena, but recent theoretical and experimental research have shown that it is not applicable to the weak nuclear force (e.g., β-, K^0- or B^0-decay) (TABLE 1). In 2002, Y. Karyotakis and G. Hamel de Monchenault[2] published numerical results for symmetry violation in B-meson decay.

THE CPT THEOREM[3]

C, **P,** and **T** refer to different symmetry operations. The parity operation ($\hat{P}$) changes the sign of all spatial coordinates. This operation is essentially a point reflection of the particle, placed at the origin of a coordinate system. If the mirror image of a system and the system itself are physically indistinguishable, the system is called "parity invariant." The $\hat{C}$ operator (charge conjugation) transforms a particle into its anti-particle, and the $\hat{T}$ operator reverses time. A time-invariant process, such as a planet orbiting a star, is physically reasonable with time running either backwards and forwards; a time-variant process looks different if time runs backwards. An illustrative example for a time-variant process could be a ball dropping

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TABLE 1. Symmetry in basic physical processes

Interaction		Symmetry Conserved (+) or Violated (−)			
Gravity		+	+	+	+
Electromagnetism		+	+	+	+
Strong nuclear force		+	+	+	+
Weak nuclear force	β-decay	−	−	+	+
	K^0-decay	−	−	−	+
	B^0-decay	−	−	−	+

from a certain location (place A) on a table to the floor. If time runs now backwards, and the ball jumps onto the table, but comes to rest at a different place A', the process would be considered time-variant. Time variance does not say anything about whether it is possible for a process to run backwards in time; it just demands that the process would look different if time did run backwards.

The CPT theorem states that all interactions are invariant under the successive operation of $\hat{C}$, $\hat{P}$, and $\hat{T}$ and (that is, $\hat{C}\,\hat{P}\,\hat{T} = \hat{1}$). This theorem can be derived from very basic assumptions. An anti-particle can be described as a particle moving backwards in time ($\hat{C}\,\hat{P} = \hat{T}^{-1}$). The theorem demands that a process that violates CP symmetry has to be time-variant, in order to maintain CPT invariance.

BETA DECAY[4]

Soon after Lee and Yang[5] published their theoretical work predicting lack of parity conservation in the emission of particles (electrons) from nuclei, C.S. Wu presented experimental proof[6] confirming that prediction. The momentum vector of the electron ejected in β-decay can either point into the same direction as the spin of the atomic nucleus from which it is ejected or in the opposite direction. If $\hat{P}$ (simplified as a mirror reflection) is applied to the problem, the alignment of both vectors is inverted and so is the handedness of β-decay. If β-decay is a parity-invariant process, electrons have to leave the nuclei in equal amounts in both directions, aligned with the nuclear spin and the opposite direction; otherwise the process and its mirror image are different. By aligning the nuclear spins of a sample of ^{60}Co in an adiabatic demagnetization experiment, Wu was able to show that electrons from β-decay leave the nuclei preferentially in the direction that is opposite to the nuclear spin (left-handed) so that β-decay violates parity and is therefore a chiral process.

It was later shown that β-decay also violates charge conjugation (**C**) and that the combination of $\hat{C}$ and $\hat{P}$ (**CP**) is once again a good symmetry operation. According to the CPT theorem β-decay should therefore be invariant against time inversion.

KAON DECAY

After confirmation of parity violation in β-decay by Wu (1957), particle physicists were convinced that at least the joint transformation of parity and charge conjugation should be symmetric for all systems. Contradicting this assumption, Christenson *et* *al.*[7] reported, in 1964, the observation of a small CP-violation in the decay of the neutral kaon. Neutral kaons are mesons containing an anti-strange quark and a down quark ($\bar{s}$ d). The kaon K^0 and its antiparticle ($\bar{K}^0$) decay by weak interactions to the same final states, and form a pair, which oscillates between two different states:

$$|K_S^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) \text{ and } |K_L^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$$

decays into 2 pions with a characteristic time constant $\tau_S = 0.9\ 10^{-10}$ s, while K_L^0 decays into 3 pions ($\tau_L \approx 500\ \tau_S$) . The final states are distinguished by their CP quantum numbers.

$$K_S^0 \rightarrow 2\pi \ :\ \mathbf{CP}|K_S^0\rangle = +1|K_S^0\rangle \text{ and } \mathbf{CP}|2\pi\rangle = +1|2\pi\rangle$$

$$K_L^0 \rightarrow 3\pi \ :\ \mathbf{CP}|K_L^0\rangle = -1|K_L^0\rangle \text{ and } \mathbf{CP}|3\pi\rangle = -1|3\pi\rangle$$

Although the kaon oscillates between two states, after a sufficient amount of time ($t \ll \tau_s$) we expect all kaons to be in the K_L^0 state, and only decays from that state into three pions should be observable. But Christenson *et al.* occasionally observed a decay producing two pions! Therefore, a CP-violating decay process has to exist for K_L^0 . The CP-violation in kaon decay is a tiny effect—only one of about 500 long-lived kaons decays to two pions, which is equal to an asymmetry factor A of approximately 0.002. But it gave the first experimental suggestion that matter and anti-matter may behave differently.

B-MESON DECAY

The standard model of particle physics would be consistent with a much bigger asymmetry in B-meson decay than that observed in kaon decay (values for A close to unity have been predicted), but another theory predicts an asymmetry of similar size. So analysis of B-meson decay can be used to test both theories. The B-meson ($\bar{b}$ d) forms a particle–antiparticle pair (B) similar to the kaon. Particle physicists are interested in one particular type of decay of the B-meson, since the amount of CP-violation responsible for the asymmetry can be deduced directly from it:

$$B \rightarrow J/\Psi + K_S^0$$

(J/Ψ is a single particle, the vector meson $c\bar{c}$.) The standard model of particle physics uses the Cabibbo-Kobayshi-Maskawa matrix V_{CKM} to describe processes involving the weak interaction. V_{CKM} is a 3×3 unitary matrix whose nine components measure the strength of transitions of quarks from down-type quarks (with charge −1/3) to up-type quarks (with charge +2/3). Because of the unitarity of the matrix, only 4 of the 9 components can be treated as independent parameters. One of these parameters is known as the complex Kobayashi-Maskawa phase. This phase is the only possible way to incorporate CP-violation into the standard model: A CP-transformation changes V_{CKM} into the complex conjugate matrix V_{CKM}^* —a process that would not

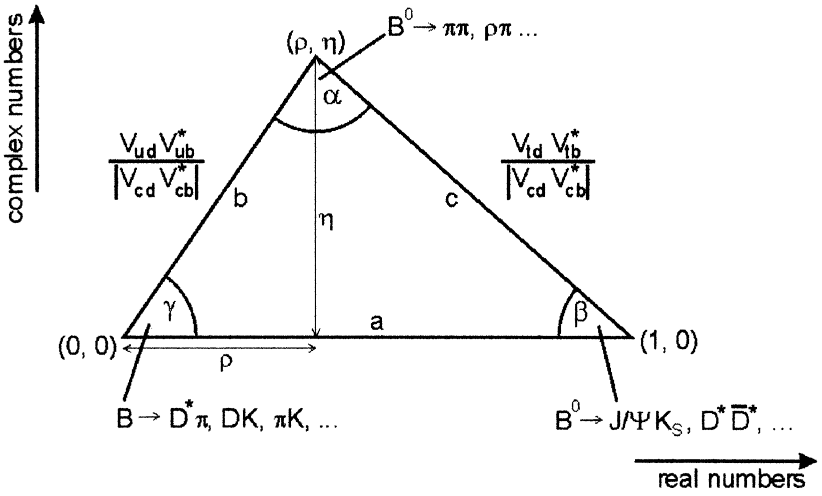

FIGURE 1. The components of V_{CKM} are connected by the unitary relation $V_{ik}{}^{*} V_{ij} = \delta_{kj}$. With $k = 3$ and $j = 1$ the unitarian relation transforms to: $V_{ub}{}^{*} V_{ud} + V_{cb}{}^{*} V_{cd} + V_{tb}{}^{*} V_{td} = 0$. This equation can be represented with the unitary triangle in the complex plane. The figure shows the normalized unitary triangle ($V_{cb}{}^{*} V_{cd} = 1$) after a rotation to align $V_{cb}{}^{*} V_{cd}$ with the real axis. Now the apex of the triangle has the coordinates ρ and η, where the value of η can be used to quantify the asymmetry in time.

change a matrix with real coefficients. A good approximation of the V_{CKM} is the Wolfenstein parametrization[8] with four independent parameters (λ, A, ρ, and η).

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ut} \\ V_{cl} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\cdot\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\cdot\eta) & A\lambda^2 & 1 \end{bmatrix}$$

Using the Wolfenstein parameterization, one of the unitary relations can be geometrically represented in form of a triangle in the complex plane—the so called unitary triangle (FIG. 1).

CP-violation requires that the area of that triangle be non-zero. The size of two of the sides of the triangle can be deduced from various known B-meson decay rates. The interpretation of these measurements is limited by theoretical uncertainties, but the measurement of the angle β—from time-dependent CP-violating asymmetries in the decay of the B-meson—is free from such uncertainties. With the knowledge of angle β, the parameter responsible for CP-violation can be calculated. During 2002, the BABAR experiment at the Stanford Linear Accelerator Center (SLAC) and the BELLE experiment at the KEK Laboratory (Japan) have reported[2] the first observations of CP-violations in the B-meson system yielding the value sin2β = 0.78 ± 0.08.

CONCLUSIONS

The reported value for CP-asymmetry ($\sin 2\beta = 0.78$) validates the standard model of particle physics and rules out the idea of super weak interactions. The equation for the asymmetry factor $A(t)$, which is proportional to $\sin 2\beta$, has also a time-dependent factor. $A(t)$ oscillates therefore on a psec timescale following so the $B^0 \bar{B}^0$ mixing with a maximum value[2] for $|A_{\max}| \approx 0.4$ and offering another explanation for the observed matter anti-matter imbalance in the universe. So far, chemistry has focused only on the properties of matter, but physicists have recently been able to produce anti-hydrogen in greater quantities.[10] From the chemist's point of view, the most important consequence of that achievement may be the chance to compare the chemistries of hydrogen and anti-hydrogen. It is generally believed that both forms of matter will behave in the same way. Yet, the K- and the B-meson experiments suggest that matter and anti-matter can behave differently, raising the question as to whether such differences might influence the chemistries of hydrogen and anti-hydrogen.

Further, if the CPT theorem is correct, CP-asymmetry demands time variance, which also has been experimentally validated[11] in appropriate systems. The "arrow of time"[12] is commonly believed to manifest itself as entropy only in many-particle systems. The K^0-experiments suggest that an arrow of time may also exist also on a subatomic level. One possible response to this situation is to wonder whether questions such as irreversibility and chirality—traditionally thought to arise only at the macroscopic (or chemical) level, and to be specifically chemical—could have their origin at the level of mesons and quarks, that is to say, in fundamental physical laws. If so, this would be an example of the reduction of chemistry to physics.

[*Editor's note*: Since the origins of irreversibility and chirality in relatively macroscopic systems can be understood quite satisfactorily without invoking broken symmetry of underlying physical laws (see papers by Prigogine and by King, in this volume), another interpretation, and a more plausible one, is that the types of symmetry breaking that are well-studied in chemical systems also may be involved in microphysical processes that are currently experimentally inaccessible to physicists. In a sense, this might be considered a reduction of physics to chemistry.]

REFERENCES

1. Ulanowicz, R.E. 2002. On the ordinality of causes in complex autocatalytic systems. **988:** this volume.
2. Karyotakis, Y. & G. Hamel de Monchenault. 2002. A violation of CP symmetry in B meson decays. Europhysics News **33.** <http://www.europhysics.com/full/15/article4/article4.html>
3. Kostelecky, A. 2002. Background information on Lorentz and CPT violation. <http: //media4.physics.indiana.edu/~kostelec/faq.html>
4. Myneni, K. 1984. Symmetry destroyed: the failure of parity. <http://ccreweb.org/documents/parity/parity.html>
5. Lee, T.D. & C.N. Yang. 1956. Question of parity conservation in weak interactions. Phys. Rev. **104:** 254–258. <http: //prola.aps.org/abstract/PR/v104/i1/p254_1>
6. C. S. Wu *et al.* 1957. Experimental test of parity conservation in beta decay. Phys. Rev. **105**: 1413–1415. <http: //cornell.mirror.aps.org/abstract/PR/v105/i4/p1413_1>
7. Christenson, J.H. 1964. Evidence for the 2*pi* decay of the K^0_2-meson. Phys. Rev. Lett. **13**: 138–140. <http: //cornell.mirror.aps.org/abstract/PRL/v13/i4/p138_1>

8. WOLFENSTEIN, L. 1983. Parametrization of the Kobayashi-Maskawa matrix. Phys. Rev. Lett. **51**: 1945–1947. <http: //cornell.mirror.aps.org/abstract/PRL/v51/i21/p1945_1>
9. KAMIEN, R.D. 2001. Chirality. <http: //dept.physics.upenn.edu/~kamien/chiralweb/>
10. JORGENSEN, L.V. 2002. Why is antihydrogen interesting? <http: //athena.web.cern.ch/athena>
11. PERRICONE, M. 1998. The time machine. Fermi News. **21**: 1–3. <http://www-fmi.final.gov/MI_Fermi_News/FermiNews98-10-30.pdf>
12. CALLENDER, C. 2001. Thermodynamic asymmetry in time. *In* Stanford Encyclopedia of Philosophy. <http: //plato.stanford.edu/entries/time-thermo/>