ASYMMETRY: THE NON-CONSERVATION OF PARITY AND OPTICAL ACTIVITY

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Introduction.—The discovery that parity is not conserved in certain processes has aroused a great deal of interest, and within a year of the initial discoveries' being made, Lee and Yang were awarded the Nobel Prize for their work. Unfortunately, virtually all the papers and most of the review articles on this subject are only intelligible to those familiar with nuclear theory. It is the aim of this Review to present the underlying principles of the theory and experiments relating to this discovery in a manner which may be understood by scientists not specialised in this field. It is hoped that it may be of particular interest to chemists, who are familiar with the problem of asymmetry in a different context.

Parity.—The principle of parity states that the laws of Nature are invariant under space reflection, *i.e.*, that the mirror-image of a sequence of events is also a possible sequence of events; it also means that the mirror-image of an object is a possible object in Nature (as suggested by Dirac for elementary particles and again recently confirmed by the discovery of the antiproton and antineutron). In the parity operation P, the spatial co-ordinates are inverted through the origin, x, y, and z becoming $-x$, $-y$, and $-z$; a state designated by a wave-function which remains unchanged in sign under the operation P is said to have "even parity", and one which changes sign, "odd parity".

To illustrate the meaning of these terms, let us consider an example. A screw is an asymmetrical object; that is, it is not identical with its mirror-image (or one can express this by saying that a left-handed screw and a right-handed screw are non-superimposable). Under the reflection in Fig. 1, the direction is changed. If we imagine the screw to be moving with a momentum p, then after reflection it would have momentum $-p$.

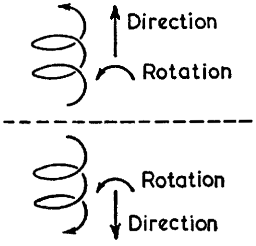

Fig. 1

Momentum is an example of a *polar vector* (length + direction); polar vectors change sign on reflection, *i.e.*, they have *odd parity*. On the other hand, the sense of rotation of the screw (or its spin, if we imagine it to be moving) is not changed by reflection. Spin is an example of an *axial vector* (surface + sense of rotation); axial vectors are unchanged by reflection and therefore have *even parity*.

Clearly, an object (like a screw) which is defined by a polar vector coupled with an axial vector, must be asymmetric with respect to the parity operation, since one vector changes sign, whereas the other does not. A quantity which is the product of a polar vector and an axial vector is called a *pseudoscalar*, and processes involving pseudoscalar quantities will not obey the law of parity. This is only another way of saying that an asymmetrical object or process cannot be described by symmetrical functions.

Elementary Particles, their Interactions, and Conservation Laws.—Of the elementary particles, the electron, proton, and neutron are fairly familiar to chemists. The electron (e^-) is a very light particle with a unit negative charge; the proton (p) is nearly 2000 times heavier, and has a unit positive charge. The corresponding anti-particles, with the opposite charges, are the positron (e^+) and the antiproton ($\bar{p}$). The neutron (n) has almost the same mass as the proton, but carries no charge, and its anti-particle, the antineutron ($\bar{n}$), differs only in having the opposite magnetic moment. Protons and neutrons (together called nucleons) make up the nuclei of atoms.

Before anything can be said about other elementary particles, their interactions must be briefly defined. These are of three kinds:

(a) *Nuclear interactions.* These involve very strong forces operating only at very small distances (*e.g.*, inside the nucleus) between pairs of nucleons: p–p, p–n, n–n.

(b) *Electromagnetic interactions.* These are the "normal" interactions, involving fairly strong forces. For example, the fact that charged particles attract or repel each other is explained by supposing that each particle produces an electromagnetic field, and that the interaction proceeds by the emission and absorption of photons.

(c) *Weak interactions.* These are so-called because the ratio of the strengths of the three types of interaction (nuclear, electromagnetic, and weak) is as $1:10^{-2}:10^{-12}$. An example of a weak interaction is β-decay. After an average life-time of twelve minutes, a neutron decays into a proton and an electron:

$$n \rightarrow p + e^-$$

Until recently, it was believed that six conservation laws were valid for all types of interaction, that is, conservation of energy, momentum, and angular momentum, and three symmetry laws: (i) Parity (P); (ii) charge conjugation (C), an operation which changes all particles into their anti-particles (*e.g.*, $e^{-} \rightarrow e^{+}$) and should not affect the symmetry of any possible physical process; and (iii) time-reversal (T), better defined as *reversal of direction of motion*; this requires that the reverse of a possible process in Nature should also be a possible process in Nature.

It was observed that, in β-decay, the proton and electron produced could not account for the total energy, momentum, and angular momentum of the initial system, and Pauli suggested that another particle, the neutrino, was also produced. Since it is believed that the overall number of particles and anti-particles remains balanced, it is a neutrino (ν) which is emitted together with a positron, and an antineutrino ($\bar{\nu}$) with an electron:

$$\mathrm{n} \rightarrow \overset{+}{\mathrm{p}} + \mathrm{e}^{-} + \bar{\nu}$$

Thus the neutrino was postulated to explain an awkward experimental result, and although other evidence for its existence was soon forthcoming,[1] it has always seemed a very odd particle, bearing no charge and, it seems, little or no mass.

Another particle which had its origin in theory was the meson, postulated by Yukawa to explain the *nuclear* interactions (it is supposed that mesons are exchanged between nucleons as photons are between particles in electromagnetic interactions). The meson was required to be about 300 times heavier than the electron; this is the π-meson discovered by Powell. It decays to give a μ-meson (which has about 200 times the mass of an electron):

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu \, (\text{or } \bar{\nu}) \ldots\ldots\ldots\ldots\ldots (1)$$

which itself decays very rapidly to give an electron and two neutrinos:

$$\mu^{\pm} \rightarrow \mathrm{e}^{\pm} + \nu + \bar{\nu} \ldots\ldots\ldots\ldots\ldots (2)$$

Those particles lighter than the π-meson, *i.e.*, μ, e, and ν, are called leptons (light particles).

Finally, there are the *strange* particles, which are of two kinds: (*a*) Those heavier than nucleons. All decay to give either p or n, for example, the hyperon (Λ):

$$\Lambda \rightarrow \mathrm{p} + \pi^{-}$$

(*b*) Those intermediate in mass between nucleons and π-mesons, *e.g.*, the K-mesons. All weak interactions involve either leptons or strange particles.

The θ–τ Puzzle.—A few years ago few people questioned the validity of parity conservation or considered devising specific experiments to test it. For example, it was held that elementary particles cannot have electric dipole moments, since it can be shown that this would violate parity; Purcell and Ramsay[2] alone proposed actually to investigate this question. Wick,

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[1] For a recent review on the neutrino, see G. Lüders, *Naturwiss.*, 1958, **45**, 456.

[2] E. M. Purcell and N. F. Ramsay, *Phys. Rev.*, 1950, **78**, 807.

Wightman, and Wigner[3] pointed out that it was difficult to justify, theoretically, either the operation P or the operation C (charge conjugation) as exact symmetry laws; the disturbing possibility remained that they were only approximate and that the combined operation CP was the only exact symmetry law.

The θ ($\equiv K_{\pi 2}$) and τ ($\equiv K_{\pi 3}$) mesons have apparently identical masses and lifetimes,[4] which would normally indicate that they are the same particle, but analysis of the decay products

$$K^{\pm} \rightarrow \pi^{\pm} + \pi^{0} \qquad (\theta \text{ mode})$$
$$K^{\pm} \rightarrow \pi^{\pm} + \pi^{+} + \pi^{-} \quad (\tau \text{ mode})$$

indicates that one decay mode (θ) has even parity, and the other mode (τ) odd parity, since the π-meson has been assigned odd parity from other experiments. Hence they cannot be different modes of decay of one and the same particle—unless parity is not conserved.

It was this problem which led Lee and Yang[5] to examine the evidence for parity conservation and to conclude that, for weak interactions, there was in fact no such evidence, and to propose specific experiments designed to decide this question.

Parity Non-conservation.—One possibility is to measure the angular distribution of the electrons coming from the β-decays of oriented nuclei. If θ is the angle between the orientation of the parent nucleus and the momentum of the electrons, an asymmetry of distribution between θ and $(180°-\theta)$ would indicate a correlation of the spin (an axial vector) with the β-ray momentum (a polar vector), which can only be understood in terms of parity violation (cf. p. 49).

An experiment was carried out along these lines by Wu *et al.*,[6] using cobalt-60:

$$^{60}\text{Co} \rightarrow {}^{60}\text{Ni} + \text{e}^{-} + \nu$$

The nuclei of ^{60}Co were strongly polarised by cooling to 0.01°K in a strong magnetic field. If parity were conserved, the distribution of the emergent electrons should have been symmetrical, as shown by the mirror-reflection in Fig. 2. In fact, the angular distribution of the electrons was

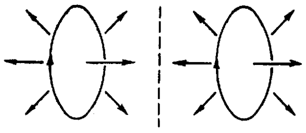

FIG. 2

asymmetrical, many more electrons emerging in the direction opposite

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[3] G. C. Wick, A. S. Wightman, and E. P. Wigner, *Phys. Rev.*, 1952, **88**, 101.
[4] R. Dalitz, *Phil. Mag.*, 1953, **44**, 1068.
[5] T. D. Lee and C. N. Yang, *Phys. Rev.*, 1956, **104**, 254.
[6] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *Phys. Rev.*, 1957, **105**, 1413.

to that of the nuclear spin, *i.e.*, the electrons were left-handed, as shown in Fig. 3.

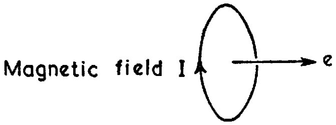

FIG. 3

The Two-component Neutrino Theory of Lee and Yang.—Even before experimental evidence was available, parity non-conservation was explained in terms of a new theory of the neutrino. Lee and Yang[7] suggested that, for a given momentum p, the neutrino has only *one* spin state, the spin always being parallel to p; the spin of the antineutrino is always antiparallel to its momentum. The spin and momentum automatically define the sense of the screw: the neutrino represents the spiral motion of a right-handed screw, and the antineutrino the spiral motion of a left-handed screw. (In four-component theories of the neutrino, both neutrinos and antineutrinos may be left- or right-handed.)

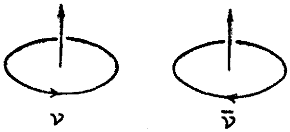

FIG. 4

Under space inversion P, one inverts the momentum of a neutrino, but not its spin direction. Since these must be parallel, inversion leads to a non-existent state by definition and parity is not conserved. (The inversion is as in Fig. 1.)

The operation charge conjugation C changes a particle into its antiparticle but does not change its spin direction or momentum; operation C on the neutrino leads to an antineutrino with its spin and momentum still parallel; this, by definition, is also a non-existent state. The theory is therefore not invariant under charge conjugation.

If the screw-like nature of the neutrino is to be an intrinsic property, the neutrino must necessarily have zero rest-mass. This was also the basis of a similar theory of Salam.[8] To see this point, let us suppose that we are on our way to the moon and that we are passed by a neutrino which, in some miraculous way, we are able to see. The neutrino has a velocity of, say, $0.8c$ (c=velocity of light) and is left-handed. We accelerate to $0.9c$ and pass this same neutrino, which will now appear to us as right-handed (*i.e.*, relative to us, we have carried out the parity operation on the

[7] T. D. Lee and C. N. Yang, *Phys. Rev.*, 1957, **105**, 1671.
[8] A. Salam. *Nuova Cim* 1957 **5**. 299

neutrino—inverted its momentum). If the neutrino had the velocity of light, then its handedness would be independent of the velocity of the observer, and since any finite rest mass would be infinite at this velocity, the neutrino must have zero rest-mass.

Landau[9] suggested that if parity non-conservation implied a fundamental asymmetry of space, this might lead to difficulties (however, cosmological asymmetry is compatible with Riemannian space-time of general relativity[10]). Landau therefore suggested the principle of combined inversion, in which space inversion (*P*) and transformation of a particle into its antiparticle (*C*) occur simultaneously.

Obviously parity does not hold, since combined inversion does not change charged particles into themselves. The principle of combined inversion leads again to the theory of the neutrino in which it is always polarised in its direction of motion (*i.e.*, its spin and momentum are parallel). It should be noted that the mirror-image of the neutrino cannot exist in the ordinary world, but would exist in the anti-matter world. From this theory it follows that, in π-meson decay (1), the μ-mesons will be completely polarised, in proportion to v/c (*i.e.*, the ratio of their velocity to that of light).

Further Experimental Evidence.—The decay processes (1) and (2) had already been considered by Lee and Yang[5]. If (1) violates parity conservation, the μ-meson will be polarised in its direction of motion. In (2), the angular distribution problem will then be very similar to that in β-decay, that is, the direction of the electrons will depend on the polarisation of the μ-mesons.

Garwin, Lederman, and Weinrich[11] used scintillation counters to identify the mesons entering a block of material and the electrons emerging after a delay of not more than 2 microseconds. There is a large asymmetry for the electrons in (2), indicating that the μ-mesons are strongly polarised. As in β-decay, the electrons are left-handed.[12] (All experiments have shown electrons to be left-handed and positrons to be right-handed.)

There have been numerous further experiments on polarisation in β^--decay,[13–17] in which the asymmetry has, as predicted, been found

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[9] L. Landau, *Nuclear Physics*, 1957, **3**, 127.

[10] E. C. G. Stueckelberg, *Phys. Rev.*, 1957, **106**, 388.

[11] R. L. Garwin, L. M. Lederman and M. Weinrich, *Phys. Rev.*, 1957, **105**, 1415.

[12] J. I. Friedman and V. L. Telegdi, *Phys. Rev.*, 1957, **105**, 1681.

[13] H. Frauenfelder, R. Bobone, E. Von Goeler, N. Levine, H. R. Lewis, R. N. Peacock, A. Rossi, and G. de Pasquali, *Phys. Rev.*, 1957, **106**, 386.

[14] P. E. Cavanagh, J. F. Turner, C. F. Coleman, G. A. Gard, and B. W. Ridley, *Phil. Mag.*, 1957, **2**, 1105.

[15] E. Ambler, R. W. Hayward, D. D. Hoppes, R. P. Hudson, and C. S. Wu, *Phys. Rev.*, 1957, **106**, 1361.

[16] H. Frauenfelder, A. O. Hanson, N. Levine, A. Rossi, and G. de Pasquali, *Phys. Rev.*, 1957, **107**, 643.

[17] M. Deutsch, B. Gittelman, R. W. Bauer, L. Grodzins, and A. W. Sunyar, *Phys. Rev.*, 1957, **107**, 1733.

approximately equal to v/c; on μ-meson decay;[18–21] on the longitudinal polarisation of positrons from ^{58}Co, ^{66}Ga, and ^{13}N, [16,22–24] and unpolarised μ^+-mesons.[25,26] It has been pointed out that β-particles emitted by randomly oriented nuclei can be longitudinally polarised, which could be detected in double scattering,[27] and this has been observed.[28]

It was also suggested by Lee and Yang that β-decay should leave the nucleus partially polarised with respect to the β-ray momentum, and consequently any following γ-ray should be circularly polarised to an extent proportional to the cosine of the angle between the direction of the emission and the γ-proton. This has been shown to be the case by experiments on β–γ polarisation correlation.[29–31]

Of particular interest in connection with the question raised on p. 57 is the demonstration that the Bremsstrahlung due to longitudinally polarised ß-rays is circularly polarised. As the electrons emitted in β-decay slow down, they lose some of their energy by emitting γ-radiation, and this is called Bremsstrahlung (literally, brake-radiation). The circular polarisation of the *external* Bremsstrahlung (that produced after the electron has left the atom) has been calculated[32–34] and measured,[35–37] down to quite small energies.[38]

Current Theory and Experiment on Parity Non-conservation.—All the evidence cited so far relates to the first group of weak interactions (those involving leptons). The asymmetry of these processes can be ascribed to the special properties of the neutrino. However, neutrinos are not involved in

[18] A. Abashian, R. K. Adair, R. Cool, A. Erwin, J. Kopp, L. Leipuner, T. W. Morris, D. C. Rahm, A. M. Thorndike, W. L. Whittemore, and W. J. Willis, *Phys. Rev.*, 1957, **105**, 1927.

[19] J. M. Cassels, T. W. O'Keeffe, M. Rigby, H. M. Wethrell, and J. R. Wormald, *Proc. Phys. Soc.*, 1957, *A*, **70**, 543.

[20] M. H. Alston, W. H. Evans, T. D. N. Morgan, R. W. Newport, P. R. Williams, and A. Kirk, *Phil. Mag.*, 1957, **2**, 1143.

[21] C. Castagnoli, C. Franzinetti, and A. Manfredini, *Nuovo Cim.*, 1957, **5**, 684.

[22] H. Postma, W. H. Huiskamp, A. R. Miedema, M. J. Steenland, H. A. Tolhoek, and C. J. Gorter, *Physica*, 1957, **23**, 259.

[23] S. Frankel, P. G. Hansen, O. Nathan, and G. M. Temmer, *Phys. Rev.*, 1957, **108**, 1099.

[24] F. Boehm, T. B. Novey, C. A. Barnes, and B. Stretch, *Phys. Rev.*, 1957, **108**, 1497.

[25] G. Culligan, S. G. F. Frank, J. R. Holt, J. C. Kluyver, and T. Massam, *Nature*, 1957, **180**, 751.

[26] L. A. Page and M. Heinberg, *Phys. Rev.*, 1957, **106**, 1220.

[27] L, J. Tassie, *Phys. Rev.*, 1957, **107**, 1452.

[28] A. de-Shalit, S. Kuperman, H. J. Lipkin, and T. Rothem, *Phys. Rev.*, 1957, **107**, 1459.

[29] H. Schopper, *Phil. Mag.*, 1957, **2**, 710.

[30] H. Appel and H. Schopper, *Z. Physik*, 1957, **149**, 103.

[31] F. Boehm and A. H. Wapstra, *Phys. Rev.*, 1957, **106**, 1364; 1957, **107**, 1202, 1462.

[32] K. W. McVoy, *Phys. Rev.*, 1957, **106**, 828.

[33] C. Fronsdahl and H. Uberall, *Phys. Rev.*, 1958, **111**, 580.

[34] K. W. McVoy, *Phys. Rev.*, 1958, **111**, 1484.

[35] M. Goldhaber, L. Grodzins, and A. W. Sunyar, *Phys. Rev.*, 1957, **106**, 826.

[36] S. Galster and H. Schopper, *Phys. Rev. Letters*, 1958, **1**, 330.

[37] A. Bisis and L. Zappa, *Phys. Rev. Letters*, 1958, **1**, 332.

[38] S. Galster and H. Schopper, *Nuclear Phys.*, 1958, **6**, 125.

strange-particle decay, and Lee and Yang's two-component theory apparently leaves the θ–τ puzzle, which gave it birth, unsolved. Moreover, parity is not conserved in hyperon decay,[39,40] a process also not involving neutrinos.

At a time when the situation was rather confused, there came the result of a crucial experiment. For reasons that cannot be explained here, it follows from Lee and Yang's theory* that the electron and the antineutrino, which emerge together, should have the same helicity (*i.e.*, handedness). Since the electron is always left-handed, the antineutrino should be left-handed also, and both the positron and the neutrino should be right-handed. It was conclusively shown[41] in the decay of ^{152m}Eu that the neutrino is left-handed, and this result is supported by other experiments on electron–neutrino angular correlation.[42,43]

A new universal theory of weak interactions has been suggested[44–46] in which parity non-conservation is no longer restricted to processes involving neutrinos, and which successfully explains virtually all the experimental results. Although the fundamental asymmetry now no longer resides in the neutrino, but in a Hamiltonian, the theory still yields a two-component neutrino (but a *right*-handed one).

The new theory makes a number of predictions, which are already being tested: (i) Weak interactions should be invariant under time-reversal (probable but not yet certain[47]). (ii) That one in 8000 of π-mesons should decay directly to an electron without going through a μ-meson. Such decays have now been found.[48,49] (iii) That one in 16×10^{-3} hyperons should undergo β-decay:

$$\Lambda \rightarrow \overset{+}{\mathrm{p}} + \mathrm{e}^- + \bar{\nu}$$

Isolated cases of such decays have recently been observed.[50,51]

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*For those familiar with the symbols, the interaction turned out to be *A* and *V*, not *S* and *T*, as was first thought.

[39] F. S. Crawford, M. Cresti, M. L. Good, K. Gottstein, E. M. Lyman, F. T. Solnitz, M. L. Stevenson, and H. K. Ticho, *Phys. Rev.*, 1957, **108**, 1102.

[40] F. Eisler, R. Plano, A. Prodell, N. Samios, M. Schwartz, J. Steinberger, P. Bassi, V. Borelli, G. Puppi, G. Tanaka, P. Woloshek, V. Zuboli, M. Conversi, P. Franzini, I. Manell, R. Santangelo, V. Silvestrini, D. A. Glaser, C. Graves, and M. L. Perl *Phys. Rev.*, 1957, **108**, 1353.

[41] M. Goldhaber, L. Grodzins, and A. W. Sunyar, *Phys. Rev.*, 1958, **109**, 1015.

[42] K. H. Lauterjung, B. Schimmer, and H. Maier-Leibnitz, *Z. Physik*, 1958, **150**, 657.

[43] W. B. Herrmannsfeldt, R. L. Burman, P. Stahelin, J. S. Allen, and T. A. Braid, *Phys. Rev. Letters*, 1958, **1**, 61.

[44] R. P. Feynman and M. Gell-Mann, *Phys. Rev.*, 1958, **109**, 193.

[45] E. C. G. Sudarshan and R. E. Marshak, *Phys. Rev.*, 1958, **109**, 1860.

[46] J. J. Sakurai, *Nuovo Cim.*, 1958, **7**, 649.

[47] M. A. Clark, J. M. Robson, and R. Nathans, *Phys. Rev. Letters*, 1958, **1**, 100.

[48] T. Fazzini, G. Fidecaro, A. W. Merrison, H. Paul, and A. V. Tollestrup, *Phys. Rev. Letters*, 1958, **1**, 247.

[49] G. Impeduglia, R. Plano, A. Prodell, N. Samios, M. Schwartz, and J. Steinberger, *Phys. Rev. Letters*, 1958, **1**, 249.

[50] F. S. Crawford, M. Cresti, M. L. Good, G. R. Kalbfleisch, M. L. Stevenson, and H. K. Ticho, *Phys. Rev. Letters*, 1958, **1**, 377.

[51] P. Nordin, J. Orear, L. Reed, A. H. Rosenfeld, F. T. Solnitz, H. D. Taft, and R. D. Tripp, *Phys. Rev. Letters*, 1958, **1**, 380.

The Induction of Optical Activity by Physical Agents.—In their Review on asymmetric transformation and induction, Turner and Harris[52] confined themselves to chemical effects. Attempts to induce optical activity by physical agents—attempts which go back to the times of Pasteur[53]—are too numerous to be reviewed in full, but some of the more important work will be mentioned. Curie[54] criticised the view that a magnetic field alone could induce optical activity and suggested that a combination of a magnetic field and an electric field was necessary (*i.e.*, an axial vector and a polar vector). In 1894 van't Hoff[55] stated that the direct formation of asymmetric products might take place in reactions induced by circularly polarised light, and this was soon given a practical basis by the discovery of the Cotton effect.[56] Much of the early unsuccessful experimental work was discussed by Bredig,[57] who pointed out the importance of studying a reaction in which the primary reaction centre is actually the carbon atom which becomes asymmetric.†

A small rotation (0·05°) was first obtained by the use of circularly polarised light by Kuhn and Braun in 1929.[58] In the following year[59] rotations of $-1{\cdot}04°$ and $+0{\cdot}78°$ were obtained by the partial photochemical decomposition of ethyl α-azidopropionate $CH_3{\cdot}CH(N_3){\cdot}CO_2C_2H_5$ with circularly polarised light of wavelength 2800—3200 Å. It should be noted that these and similar successful experiments[60,61] do not in fact constitute true asymmetric synthesis: there is a net asymmetric synthesis because of *asymmetric decomposition.*

Karaganis and Drikos[62] obtained rotations of up to 0·2° by the reaction of unsymmetrical triarylmethyl radicals with chlorine, in the presence of circularly polarised light. Later[63] they showed that when the racemic triaryl chloride formed in the reaction was irradiated with circularly polarised light of the same wavelength, no optical activity was produced, and that the chloride did not decompose at this wavelength. Similarly, Davies and Heggie[64] obtained rotations of 0·04—0·05° in the reaction of trinitrostilbene with bromine or chlorine in the presence of circularly

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[52] E. E. Turner and M. M. Harris, *Quart. Rev.*, 1947, **1**, 299.

[53] L. Pasteur, *Revue Scientifique*, 1884, 7, 3.

[54] P. Curie, *J. Physique*, 1894, **3**, 409.

[55] J. H. van't Hoff, "Lagerung der Atome im Raume", Braunschweig, 1894.

[56] A. Cotton, *Ann. Chim. Phys.*, 1896, **8**, 347.

[57] G. Bredig, *Z. angew. Chem.*, 1923, **36**, 456.

†Optically active molecules often have axial symmetry, but as the word "dissymmetry" (as used by Pasteur and W. H. Mills) is not generally employed now, the word "asymmetry" has been retained. The Reviewer thanks a Referee for drawing his attention to this point.

[58] W. Kuhn and E. Braun, *Naturwiss.*, 1929, **17**, 227.

[59] W. Kuhn, and E. Knopf, *Naturwiss.*, 1930, **18**, 183; *Z. phys. Chem.*, 1930, *B*, **7**, 292.

[60] S. Mitchell, *J.*, 1930, 1829.

[61] J. A. Berson and E. Brown, *J. Amer. Chem. Soc.*, 1955, **77**, 450.

[62] G. Karaganis and G. Drikos, *Naturwiss.*, 1933, **21**, 607; *Z. phys. Chem.*, 1934, *B*, **26**, 428.

[63] G. Karaganis and G. Drikos, *Praktika*, 1936, **9**, 177; *Chem. Zentr.*, 1936, **I**, 3298.

[64] T. L. Davies and R. Heggie, *J. Amer. Chem. Soc.*, 1935, **57**, 377, 1622.

polarised light. The racemic dibromide could not be made optically active by exposure to circularly polarised light, and in the experiments with chlorine the wavelengths used were in a region in which the dichloride does not absorb. All these experiments therefore appear to represent true asymmetric syntheses. (It is not clear whether this also applies to the work of Radulescu and Moga.[65])

No explanation has been offered for these results; possibly they involve a metastable intermediate, formed by absorption of the circularly polarised light, which has a slightly preferred configuration (*e.g.*, a triarylmethyl radical which is not planar).

Optical Activity and Parity Non-conservation.—The type of fundamental asymmetry suddenly encountered amongst elementary particles inevitably recalls the spatial asymmetry responsible for optical activity. In Fig. 5 we have an example of the simplest type of such asymmetry, the central carbon atom in glyceraldehyde having four different substituents arranged spatially as if in the corners of a tetrahedron.

Fundamentally, this is a very similar situation to that in Fig. 1. A vector has two components; an object will be asymmetric in *n*-dimensional space if it has $(n + 1)$ "properties". Thus a triangle (which requires three properties for definition, *e.g.*, three lengths, two lengths and one angle, etc.) is asymmetric in a plane (two dimensions); a screw (a polar vector and an axial vector), and a carbon atom with four different substituents, are asymmetric in 3-dimensional space.

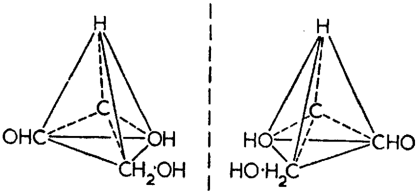

FIG. 5

It is natural to ask whether there is any connection between asymmetry at the molecular level and asymmetry at the level of elementary particles. Could optical activity be produced by polarised β-radiation? A dynamic interaction between molecules and high-energy electrons would have to be mediated by secondary effects of lower energy (since the interaction is negligibly small if the energy levels are far apart). We have already seen that polarised β-rays give rise to circularly polarised Bremsstrahlung and that, in the energy range required for photochemical asymmetric synthesis,

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[65] D. Radulescu and V. Moga, *Bul. Soc. chim. Romania*, 1939, **1**, 18; *Chem. Abs.*, 1943, **37**, 4070.

measurable asymmetry is still present. One possible pathway is therefore the following:

Longitudinally polarised β-rays → Circularly polarised light → Optically active molecules

Other secondary effects (*e.g.*, magnetic interaction) might conceivably produce optical activity. However, the sum of such effects would be very small, in terms of percentage of molecules actually effected; possibly too small to be detected experimentally. One worthwhile experiment would be to see whether there is any difference in the absorption by D- and L-isomers of the circularly polarised Bremsstrahlung from β-rays.

The question arises if some other pathway is possible. Optical isomers are identical in all physical and chemical properties except the transmission of plane-polarised light. That is to say, it is merely a matter of probability (*i.e.*, entropy) that a 50/50 mixture of the isomers is formed in chemical reactions, and to shift this balance to 51/49 or even 100/0‡ does not require any *energy* in principle (the idea of an entropy exchange in a reaction during irradiation will be considered elsewhere[66]). It requires some kind of transmission of information regarding form, and this transmission need not be by way of a dynamic interaction. An analogy in physics would be the so-called "exchange forces", which are not forces in the ordinary sense at all. The Pauli exclusion principle introduces a correlation in the behaviour of particles which, though its effects are similar to the effects of forces, has no explanation in dynamic terms. In other words, how does an electron joining an orbital know the spin quantum number of the electron already in that orbital?[67] The difficulty in answering this question shows that an effect cannot be ruled out simply because one cannot suggest an exact mechanism which can be easily visualised—as we have already seen in the case of asymmetric synthesis. That one asymmetry may lead to another is not only philosophically reasonable but in conformity with the second law of thermodynamics; certainly symmetry by itself cannot give rise to asymmetry.

A non-energetic interaction for the induction of optical activity by polarised β-radiation was first suggested by Vester.[68] The experimental difficulties in the investigation of this problem are numerous. A reaction is required with an intermediate whose lifetime is long enough for it to receive the required information (asymmetric configuration) but not so long that it loses it again before reacting. The reaction should be one whose velocity is increased but whose mechanism is little affected by high-energy β-rays. A difficulty here is that ionisations are mainly produced by electrons towards the end of their paths, when their velocity has been reduced,

‡The entropy of mixing is certainly not more than about 2 kcal./mole.

[66] F. Vester and T. L. V. Ulbricht, to be published.

[67] H. Margenau, "The Nature of Physical Reality", McGraw-Hill, New York, 1950.

[68] F. Vester, Seminar at Yale University, 7th February, 1957.

and asymmetry may have been reduced by scattering (Coulomb scattering should not affect the polarisation of particles with near-relativistic velocities,[69] and this has been confirmed by experiment[16,18,35,70]).

Experiments have been carried out[71,66] with a number of chemical systems, including the synthesis of 1-chloroethyl ethyl ether. Unfortunately this has a low specific rotation, but the reaction has the advantage of being a simple one with an ionic mechanism little affected by high-energy electrons[72] and yielding a liquid product whose rotation could be measured directly. Control experiments were carried out in the absence of radiation, and with unpolarised electrons from a linear accelerator. No consistent effect outside the margin of error was observed under a variety of conditions with β-sources (^{32}P, ^{90}Y, Sr–^{90}Y, ^{152}Eu) in the range of 25–3000 mc, indicating that an effect cannot be demonstrated in this system. Ideally, the optical activity due to the secondary effects discussed (which may be calculated, *e.g.*, for Bremsstrahlung[66]) should be just detectable; then significantly greater optical activity than this would constitute evidence for a non-energetic effect.

If optical activity could be produced by polarised β-radiation, it would be tempting to speculate whether the optical activity that asymmetric radiation (from cosmic rays, natural radioactivity, etc.) might have produced on Earth was associated with the origin of life. From a thermodynamic point of view, life represents a strange phenomenon: order emerging out of apparent chaos and resisting the otherwise universal tendency of entropy to increase.[73,74] In the ordered structure of living systems, optical purity plays a very important part,[75] and the widespread occurrence of D-amino-acid oxidase is not in the least surprising.[76]

It has been shown by Havinga[77] that a compound which is easily racemised may be spontaneously resolved during crystallisation; one isomer begins to crystallise first, racemisation occurs in the solution now richer in the other isomer, and finally, unequal quantities of the *dextro*- and the *lævo*-isomer may be obtained. This is certainly a suggestive experiment, and, if we assume that optical activity was required for the origin of life (of course, we do not know this), represents the most satisfying explanation for the origin of optical activity by chance. Other such explanations do not bear close examination; for example, the optical activity which might be produced by local statistical variation amongst that number of molecules present in a small cell is very much smaller than

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[69] T. D. Lee, personal communication.

[70] J. Henitze, *Z. Physik*, 1958, **150**, 134.

[71] F. Vester, T. L. V. Ulbricht, and H. Krauch, *Naturwiss.*, in the press.

[72] H. Krauch and F. Vester, *Naturwiss.*, 1957, **44**, 491.

[73] E. Schrödinger, "What is Life?", Cambridge University Press, 1944.

[74] L. von Bertalanffy, "Das Biologische Weltbild," A. Francke, Bern, 1949.

[75] W. Kuhn, *Experientia*, 1955, **11**, 429.

[76] H. A. Krebs, in "The Enzymes", Part II, i, page 499, edited by J. B. Sumner and K. Myrback, Academic Press, New York, 1952.

[77] E. Havinga, *Chem. Weekblad*, 1941, **38**, no. 46; *Biochim. Biophys. Acta*, 1954, **13**, 171.

that which might result from asymmetric radiation. Essentially, our conclusions depend on what mechanism for the origin of life we propose, and at the present time this is the subject more of philosophy than of science.

The author thanks Sir Robert Robinson and Professors T. D. Lee, H. C. Longuet-Higgins, and Sir Alexander Todd for their interest and encouragement, and Dr. F. Vester for numerous discussions. This paper was written during the tenure of an Imperial Chemical Industries Limited Fellowship at Cambridge.