Can neutral currents be detected in chemical systems?

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Manifestations of neutral currents in molecular systems might be observed in chemical detectors with symmetry breaking. The minimum characteristic dimensions of the corresponding experiments are estimated.

The possibility of observing neutral currents in macroscopic processes has recently been the subject of an active discussion.[1] One manifestation of neutral currents in chemical conversions might be a difference between the interaction energies of electrons of atomic orbitals with the nucleus in a chiral molecule and in its mirror isomer. The theoretical estimates of the difference $\Delta E = E_L - E_D$ (the L and D molecules are the left-hand and right-hand mirror isomers) lie in the range[2,3] 10^{-15}–10^{-20} eV. This energy nonequivalence could, in principle, lead to a difference between the rate constants of reactions involving the isomers. We call this difference the "advantage factor" (AF) of one of the isomers species in chemical reactions. An advantage factor can give rise to a state of an organic medium with a broken mirror symmetry. Attempts to detect this effect through measurements of the optical activity of the products of chemical reactions have resulted in a multitude of artifacts. The reason, as we have shown previously,[4,5] is that the effect of interest (theoretically,[2,3] AF$\approx 10^{-13}$–10^{-18}) cannot be built up to a measurable level in a chemical reaction because of the inescapable noise of various types. In this letter we will briefly discuss the possibility of detecting neutral currents by means of chemical detectors which are tuned in a special way, i.e., which use chemical systems capable of spontaneous symmetry breaking.

For definiteness, we single out from the many arrangements that have been proposed[5–7] one which was proposed back in 1953 by Frank[8]: $S + L \xrightarrow{k_L}$, $S + D \xrightarrow{k_D} 2D$, $L \xrightarrow{k_a} + D \rightarrow S'$, where S and S' are achiral molecules, and k_i are the rate constants of the corresponding reactions. As a measure of the observable asymmetry we adopt the chiral polarization[6] $\eta = (L - D)/(L + D)$, where L and D are the numbers of mirror isomers in the system. The evolution of the chiral polarization is described by the equation[5]

$$\eta = \epsilon(1 - \eta^2) + k\theta(\eta - \eta^3), \tag{1}$$

where $\theta = L + D$, $k = k_a/(k_L + k_D)$, and $\epsilon = (k_L - k_D)/(k_L + k_D)$ is a measure of the advantage factor. The symmetric state is unstable, and one of the two states $\eta_s = 1$, $\eta_s = -1$ arises in the system. Under actual experimental conditions, these events would occur only when the parameters of the system reach the critical level, and the condition $|\eta_s| < 1$ is satisfied, but an appropriate choice of the parameters can put η_s at any level required for detection. How do we use this system to detect neutral currents? It is easy to see that the appearance of a chiral polarization of this detector is neither a measure of the advantage factor nor even evidence that neutral currents are

affecting the chemical conversions. The symmetry breaking occurs spontaneously with either $\epsilon \neq 0$ or $\epsilon = 0$, because of the development of the original fluctuation of the chiral polarization, η_{0f}. Since η_{0f} is a random quantity, we cannot, in a single test, determine whether the symmetry is broken because of the advantage factor or independently—regardless of whether this factor is present. An experimental measure of the advantage factor could be introduced only in a series of measurements with a detector of this sort, by exploiting the fact that in the case $AF = 0$ the probabilities for finding the detector in the η_s and $-\eta_s$ states are identical, while with $AF \neq 0$ these probabilities depend on the advantage factor. It follows from system (1) that the evolution of the system toward the states $\eta_s = 1$ and $\eta_s = -1$, which is determined roughly by the initial sign of $\dot{\eta}$, i.e., by the ratio of η_{0f} and the advantage factor, leads to $\eta_s = 1$ if $\eta_{0f} > -\epsilon\xi$ or $\eta_s = -1$ if $\eta_{0f} < -\epsilon\xi$ (for definiteness, we are adopting $\epsilon > 0, \xi \sim 1$). If η_{0f} is a random quantity belonging to some distribution with a standard deviation σ_η, then the probability for finding the detector in the states $\eta_s = 1$ and $\eta_s = -1$ can be estimated roughly from

$$\omega = W(+1) - W(-1) \approx \begin{cases} \epsilon / \sigma_\eta & \text{for } \epsilon < \sigma_\eta \\ 1 & \text{for } \epsilon \geqslant \sigma_\eta \end{cases}.$$

The exact expression for ω is[5,7]

$$\omega = \mathrm{Erf}(\epsilon / \sigma_\eta). \tag{2}$$

The fluctuations of the chiral polarization are determined by the amount of chiral material in the detector[7]: $\sigma_\eta = \theta^{-1/2}$. We thus have $\omega = \mathrm{Erf}(\epsilon\sqrt{\theta}) \sim \epsilon\sqrt{\theta}$ (for small ϵ), and an experimental measure of the advantage factor is the minimum amount of chiral material required for an experiment in which it is possible to obtain a statistically reliable difference between the probabilities for observing the states of the detector with the opposite signs of the chiral polarization: $AF_{expt} \sim \theta^{-1/2}$. Since $\epsilon\sqrt{\theta}$ is the signal-to-noise ratio for the detector, the result (2) is not a consequence of the particular model which we have selected; it must hold for a variety of methods for devising such detectors. The upper limit on the experimentally observable value of the advantage factor is essentially determined by the amount of raw material available to the experimentalist. We emphasize that we are not talking about the amount of material present in the detector at a given instant but the total amount of material which can be used in a series of experiments. Let us look at some numbers. If 10^3 kg of chiral material (10^4 moles or 10^{28} particles) is used in an experiment, then with $AF \approx 10^{-15}$ the probability that the polarization of the detector will be due, specifically to the advantage factor in a single test is $\omega \approx 10^{-1}$, and the advantage factor can be detected in a statistically reliable way in a series of 10^2 experiments, in which the total amount of material used would be 10^{30} molecules (10^6 moles). An advantage factor $AF \approx 10^{-17}$ can be observed reliably in a system which uses material at a rate of 10^3 kg/s in an experiment lasting 1 yr ($\theta = 10^{34}$ molecules). The simple law $\epsilon\sqrt{\theta}$ thus suggests an experimental procedure and a quantitative measure of the manifestation of neutral currents in molecular systems which use chemical detectors with symmetry breaking.

These estimates can be used to draw an important conclusion regarding the neces-

sary scale of the experiment as a function of the magnitude of the advantage factor due to the neutral currents. The specific physical characteristics of a device to detect this advantage, factor, the experimental conditions, and the experimental "purity" require further study.

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