A Necessary and Sufficient Condition in the Model of Kondepudi and Nelson for the Breaking of Chiral Symmetry

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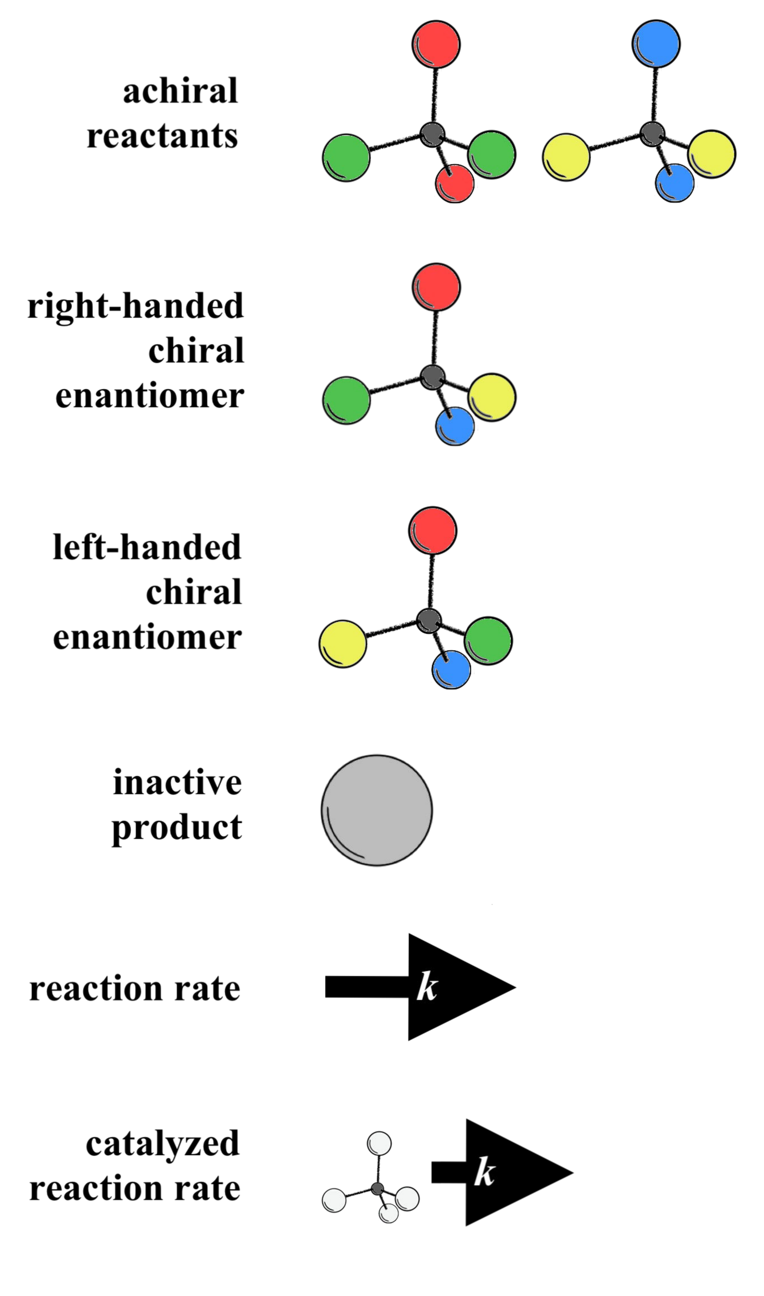
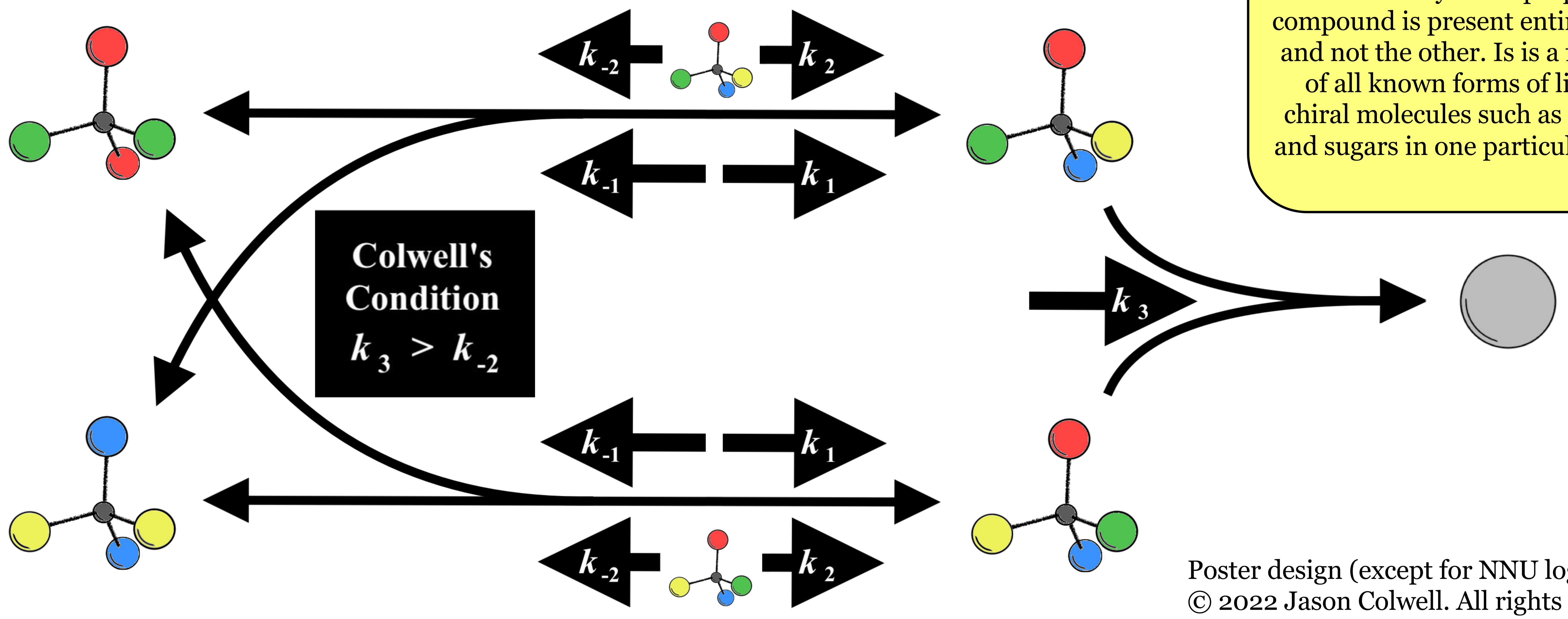


Abstract

The setting is a system containing achiral reactants which form a chiral compound. In 1983, Kondepudi and Nelson proposed a model for the breaking of chiral symmetry. The present article reduces the conditions for bifurcation to a single condition which is shown to be both necessary and sufficient. A number of other papers on this topic also propose models for the breaking of chiral symmetry. These are shown to be essentially special cases of the model of Kondepudi and Nelson, with the same necessary and sufficient condition. The central question of this line of research is: in a racemic mixture of a chiral compound, could an excess of one enantiomer over the other develop on its own? The answer is yes, if and only if a certain simple condition is satisfied. This answer should prove useful in further research, both theoretical and experimental, into the origin of life.

What is chirality?

A chiral molecule is one that is non-superimposable on its mirror image. Water is not chiral; reflecting the water molecule about any plane produces a new molecule which can be moved in space so that it is exactly the same as the original molecule. Naturally occuring amino acids, by contrast, are chiral; they exist in two distinctly different mirror-image versions. The two versions of a chiral molecule are called "enantiomers". One is called "right-handed", and the other "left-handed".



What is homochirality?

Homochirality is the property whereby a chiral compound is present entirely as one enantiomer and not the other. Is is a fundamental property of all known forms of life, whose cells keep chiral molecules such as amino acids, proteins and sugars in one particular enantiomeric form.

Why homochirality is important

Homochirality is an essential property of all known forms of life. Every amino acid in a protein is left-handed, and every sugar in a DNA chain is right-handed. When this property is disrupted -- that is, when chiral molecules of the wrong handedness are caused to exist and remain in a cell -- the cell ceases to function normally.

A shocking example of chirality

Introduced in 1957 in West Germany, the drug Thalidomide was promoted for relief of morning sickness in pregnant women. A chiral compound, one enantiomer has the desired effect, while the other is teratogenic, having toxic effects upon the unborn infant. An estimated 10,000 infants were affected, suffering birth defects such as severe deformation of the limbs. The drug was removed from the European market in 1961.

Symmetry-breaking and chemical evolution

The natural development of homochirality is essential to the theory of chemical evolution.

However, the laws of nature do not favor one enantiomer of a chiral molecule over the other. Chemical systems producing chiral compounds tend to produce left- and right-handed enantiomers in equal quantity. For homochirality to arise, this symmetry must somehow be broken. The most plausible model for such a phenomenon is the Kondepudi–Nelson model, proposed in 1983. In this model, the chiral compound is produced by an autocatalytic reaction. This way, a slight excess of one enantiomer increases the production rate of that enantiomer; the favored enantiomer might thus amplify its own greater concentration.

Nearly 150 articles have cited this work of Kondepudi and Nelson, but symmetry-breaking conditions have not been determined in general.

Until now.

Result

In 2022, Jason Colwell identified a simple necessary and sufficient condition for symmetry-breaking in the Kondepudi–Nelson system, and provided rigorous mathematical proof of the result.