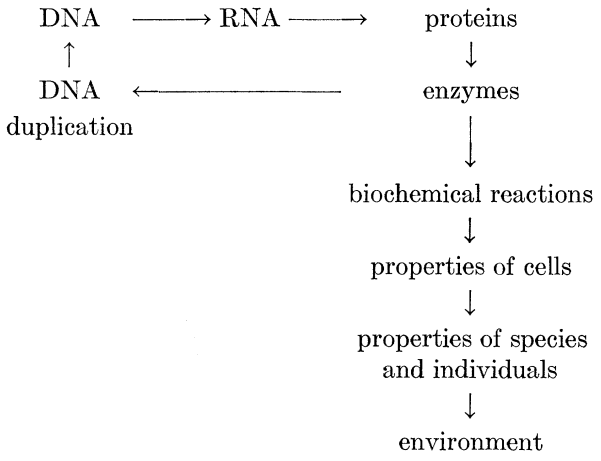
groove of DNA contains an extra "copy" of the proton–electronpair code (see Fig. 2) which may serve as a template for a third helix leading to the formation of messenger-RNA. For a more detailed discussion of this problem, we will refer to another paper.[23]

It seems hence clear that RNA serves as an intermediate between DNA and the proteins, so that DNA regulates RNA which in turn controls the protein synthesis. Since even the enzymes which catalyze the DNA duplication are produced in this way, one obtains the following diagram:



which may be characterized as the "growth cycle." Actually, there is a "feedback" mechanism at several of the other links in the diagram.

6. SUMMARY

Let us now summarize the main points discussed in this paper. Deoxyribonucleic acid (DNA) is considered as the hereditary substance and, according to Watson–Crick's model, the genetic message is contained in a proton–electronpair code which is situated well hidden and shielded in the middle of a double helix. The code consists actually of two complementary pieces of "lock and key" type which together have a great deal of stability. The genetic information is transferred to the cell by means of the formation of messenger-RNA but, during the transcription procedure, the code is not opened up at all, and the message is instead read in an extra "copy" which nature has provided in the deep groove of the double helix. In the replication process, the code is opened only momentarily to find the correct partners for the doubling of the genetic message. All these precautions give the genetic code an unusual stability and explain its ability to preserve a genetic message intact over thousands of years.

In this paper we have pointed out that, since the protons are not classical particles but "wave packets" obeying the laws of modern quantum theory, the genetic code cannot—in spite of all precautions—be 100% stable. Due to the quantum-mechanical "tunnel effect," there is always a small but finite probability that the protons will change place, alter the genetic code, and give rise to mutations. This implies also that this transfer of protons over a distance of about 10^{-8} cm may be one of the driving forces in the evolution of living organisms on the earth. Since the replication procedure forces the protons to "choose sides" and gives a new DNA molecule with the genetic code in a nonstationary state, there will always be a time-dependent process leading to a loss of genetic information through proton leakage which manifests itself at the next replication. The cell loses thus the ability to synthesize all the enzymes necessary for the metabolism and it seems hence likely that the time-dependent proton tunneling may be the primary cause of the phenomenon of aging. Since the proton tunneling further leads to somatic mutations, the phenomenon may also be responsible for the occurrence of spontaneous tumors and cancer.

It is evident that a model of these biological phenomena where all the emphasis is put on the DNA molecule must be somewhat oversimplified, since there are certainly also other cell constituents which play an important role in these connections. We believe, however, that the picture serves a meaningful purpose as a first approximation.

[23] P.-O. Löwdin, Technical Note 85, Uppsala Quantum Chemistry Group, 1962 (unpublished).

Discussion on the Proton-Tunneling Hypothesis for Dielectric Relaxation in Ice

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This may be of interest in relation to the suggestion of P. O. Löwdin [Proceedings of the Stanford Symposium on Quantum Aspects of Polypeptides and Polynucleotides, March 25–29, 1963 (unpublished)] that a proton-tunneling process may be critically involved in genetic mechanisms.

The late W. M. Latimer, who with W. H. Rodebush first pointed out the general significance of hydrogen bond interactions [J. Am. Chem. Soc. **42**, 1419 (1920)] made specific suggestions [Chem. Rev. **44**, 59 (1949)], which can be tested, in relation to the possible mechanism of the dielectric polarization process in ice. He noted that the activation energy for dielectric relaxation, then only crudely known, was in the range of 9–12 kcal/mole, and recognized that this would require an excitation process with a corresponding energy, if proton tunneling is involved. He observed that excitation to the first vibrational level of an $O - H$ stretching mode, which might logically be a prerequisite to tunneling, requires an energy in that range. Now, if excitation to the first vibrational level is a rate limiting process, the activation energy for D_2O should be only about $2^{-\frac{1}{2}}$ of the value with H_2O, so an experimental test was conceived. About then, new experimental results of high precision on both H_2O and D_2O appeared [R. P. Auty and R. H. Cole, J. Chem. Phys. **20**, 1309 (1952)], revealing the activation energies in H_2O and D_2O crystals to be 13.2 and 13.4 kcal/mole, respectively. In the light of the above argument, these data are now considered to show that the dielectric polarization in ice process does not involve proton tunneling. The obvious and probable mechanism, for which this activation energy appears a reasonable value, is dipole reorientation.

The rationale of the above may be that a symmetrical potential barrier would be required for an appreciable tunneling rate. This is not the case in ice, unless a proton is removed from the water molecule to which another proton, hydrogen-bonded to it, is about to jump. Proton tunneling is apt to be more important in the conduction process in ice, which may occur by the symmetrical processes

$$(1)\ \mathrm{HOH} + \mathrm{OH^-} \rightarrow \mathrm{HO^-} + \mathrm{HOH}$$

$$(2)\ \mathrm{H_2OH^+} + \mathrm{HO_2} \rightarrow \mathrm{H_2O} + \mathrm{HOH_2^+}\,.$$

Auty and Cole suggested that proton tunneling may be one of the conduction mechanisms in ice. Eigen has discussed this further.