Ludmila V. Yakushevich

Nonlinear Physics of DNA

Second, Revised Edition

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Cover picture
The illustration is a drawing made by Nicolas Bouvier for Geneviève Almouzni, UMR 218 CNRS – Institut Curie

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data:
A catalogue record for this book is available from the British Library.

Bibliographic information published by Die Deutsche Bibliothek
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the Internet at <http://dnb.ddb.de>.

printed in the Federal Republic of Germany
printed on acid-free paper.

Composition Kühn & Weyh, Freiburg
Printing Strauss GmbH, Mörlenbach
Bookbinding Litges & Dopf Buchbinderei GmbH, Heppenheim

ISBN 3-527-40417-1

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Preface to the First Edition

This book is devoted to a new and rapidly developing field of science, which I call here the nonlinear physics of DNA. This is the first monograph on the subject, where various theoretical and experimental data on the nonlinear properties of DNA published in different journals on mathematics, physics and biology are gathered, systematized and analyzed. I will only point out a few reviews which preceded the book: by Scott [1], Zhou and Zhang [2], Yakushevich [3], and Gaeta and coauthors [4]. A collection of lectures given by participants at the International workshop in Les Hauches (France, 1994) [5], and selected sections in the monographs of Davydov [6] and Yakushevich [7] can also be mentioned.

Three events can be considered as having stimulated the appearance and rapid development of nonlinear DNA science. The first was the success of nonlinear mathematics and its application to many physical phenomena [8–10]. The second was the emergence of new results in studies of the dynamics of biopolymers leading to an understanding of the important role of the dynamics in the biological functioning of biopolymers [11–13]. The third event was the publication of a series of works of Davydov, where for the first time the achievements of nonlinear mathematics were applied to biology, and the hypothesis of the occurrence of solitons in biopolymers (namely, in alpha-helical proteins) was suggested [14].

The study of the nonlinear physics of DNA began in 1980 when Englander et al. [15] published the article 'Nature of the open state in long polynucleotide double helices: possibility of soliton excitations'. This was the first time the concept of nonlinear conformational excitations (or DNA solitons) imitating the local opening of base pairs was introduced. In the article the first nonlinear Hamiltonian of DNA was presented and this gave a powerful impulse for theoretical investigations. A large group of authors, including Yomosa [16, 17], Takeno and Homma [18, 19], Krumhansl and coauthors [20, 21], Fedyanin and coauthors [22–24], Yakushevich [25–27], Zhang [28], Prohofsky [29], Muto and coauthors [30–32], van Zandt [33], Peyrard [34, 35], Dauxois [36], Gaeta [37, 38], Salerno [39], Bogolubskaya and Bogolubsky [40], Hai [41], Gonzalez and Martin-Landrove [42] made contributions to the development of this field by improving the model Hamiltonian and its dynamical parameters, by investigating corresponding nonlinear differential equations and their soliton-like solutions, by consideration of statistical properties of DNA solitons and calculation of corresponding correlation functions. The results obtained by them formed a theoretical basis for the nonlinear physics of DNA.

The experimental basis of nonlinear DNA physics was formed by the results of experimental investigations on DNA dynamics and interpretations, some of them in the framework of the nonlinear concept. The most important results were obtained by Englander et al. [15] on hydrogen–tritium exchange in DNA, by Webb and Booth [43], Swicord and coauthors [44–46] on resonant microwave absorption (interpretations were made by Muto and coauthors [30] and by Zhang [47]), and by Baverstock and Cundall [48] on neutron scattering by DNA. All these results, however, admitted alternative interpretations (see the discussion in Ref. [3]), and only after publication of the work of Selvin et al. [49], where the torsional rigidity of positively and negatively supercoiled DNA was measured, was the reliable experimental basis for theoretical predictions given.

Besides theoretical results and experimental data an important contribution to the formation of the nonlinear physics of DNA was made by numerous applications where the nonlinear concept was used to explain the dynamical mechanisms of DNA function such as transitions between different DNA forms [50–52], long-range effects [53–55], regulation of transcription [56], DNA denaturation [34], protein synthesis (namely, insulin production) [57], and carcinogenesis [58].

Taking into account the interests of a wide range of readers who are mostly physicists, I began the monograph with a brief excursion into molecular biology, and presented in the first three chapters the main elements of the DNA structure, dynamics and function.

To enable comparison of linear and nonlinear approximations I have included a chapter devoted to the linear theory of DNA and described briefly therein the main results of theoretical and experimental studies in this field.

The nonlinear theory of DNA is presented in the monograph in detail. The main ideal and non-ideal nonlinear models are described in the framework of the approach based on the hierarchy of the DNA models. To enable comparison of the results of theory and of experiment, and especially of experiments on scattering by DNA, the chapter devoted to the statistics of nonlinear excitations in DNA is also included. In the final two chapters several examples of interpretations of experimental data on DNA dynamics and function in terms of the nonlinear concept are presented.

The material of the book is given in a fairly complete form. However, the reader is assumed to be familiar with the elements of physical theory, including classical mechanics and statistical physics.

In this monograph I have tried to give a description of the main theoretical and experimental data on the nonlinear physics of DNA.

I have tried to organize the material in such a way as to give a complete picture which is why the chapters on DNA structure, dynamics and functioning are included. But I should note that because of the very young 'age' of this field of science, many gaps still remain. As a consequence, some of the chapters which I think should be traditionally included in monographs on physics are absent. For example, I could not present any data on nonlinear quantum mechanical properties of DNA or on DNA nonlinear electrical properties because these questions have not been studied at all. One more example is the interaction of DNA with the environment. I could present here only rather limited information about this because until now only a few very simple approaches have been proposed.

In spite of the absence of some chapters, I decided, for two reasons, to conserve the rather general form of the title of the book. First, I am sure that these problems will be actively developed in the very near future and many gaps will disappear, and secondly I hope to involve physicists in this very promising field of science.

The most promising directions I think are associated with the study of inhomogeneous nonlinear models of DNA, because this will lead to new interesting relations between the physical nonlinear properties of DNA and its biological functioning. Another very promising direction is associated with the study of the interaction of DNA and external fields. Both studies can lead to the discovery of new mechanisms of regulation of fundamental biological processes such as transcription or replication. So, in future we shall have a chance to 'bridge' the nonlinear physics of DNA and medicine.

Many sections of the book are part of a course of lectures delivered to students of the Physical and Biological Departments of the Moscow State University and Pushchino State University (Russia). Selected chapters of the book were discussed widely during my travel with lectures at the Universities of Durham, Loughborough, Warwick, Surrey (England), at the Ecole Normale Superieure de Lyon (France), at the Universities of Salerno, Roma, Firenze and the Institute of Health (Italy).

I would like to express my gratitude to my colleagues Kamzolova S.G., Karnaukhov V.N., Komarov V.M., Sidorova S.G, Kun'eva L.F. and Mitkovskaya L.I. for their constant support and help in preparing the manuscript for publication. I would like also to thank my parents for the warmth and patience they have shown me during the whole period of writing the monograph.

Preface to the Second Edition

I am very much obliged to Dr. Michael Baer, a Senior Publishing Editor of Wiley, for the invitation to prepare the second edition of my book. This gave me an opportunity to add new interesting results that have been intensively discussed in recent years [59–65].

In the second edition of the book I have included new data on the distribution of electrostatic potential around DNA, on charge transfer along the double helix, on computer modeling propagation of nonlinear conformational waves along the DNA and the effects of thermal bath, random and real (native) sequence of bases and asymmetry on the propagation. I have also included a short description of supercoiling DNA as one of the possible types of internal motion in DNA and new impressive data on single molecule experiments which were the theme of a special workshop of CECAM in Lyon (France) in 2001 [66].

Moscow, October 2003 Ludmila V. Yakushevich

Dedication

The author dedicates this book to the memory of the pioneer in nonlinear biophysics, Professor Alexandr Sergeevich Davydov.

1 DNA Structure

DNA is one of the most interesting and mysterious biological molecules. It belongs to the class of biopolymers and has a very important biological function consisting of the ability to conserve and transfer genetic information. In this book, we shall try to look at the DNA molecule from the physical point of view, that is we shall consider it as a complex dynamical system consisting of many atoms and having a quasi-one-dimensional structure with unusual symmetry, many degrees of freedoms, many types of internal motions, and specific distribution of internal forces.

In this chapter we describe briefly the main features of the DNA structure.

1.1 Chemical Composition and Primary Structure

Deoxyribonucleic acid or DNA is assembled from two linear polymers. The basic formula of each of the polymers is now well established. It consists of monomeric units called nucleotides (Figure 1.1). Each nucleotide consists of three components: sugar (furanose-derivative deoxyribose), heterocyclic (5-carbonic) base and phosphate (PO_4^-). The bases are of four different types. Two of them, adenine (A) and guanine (G), are purines, and the other two, thymine (T) and cytosine (C), are pyrimidines (Figure 1.2). The sugar is connected by a beta-glycoside bond to one of the four bases and forms one of four natural nucleosides: adenosine, guanosine, cytidine and thymidine. The nucleotide is formed by phosphorylation of the 3′- and 5′-hydroxyl groups of the sugar which is a component of the nucleoside.

Each of the polymers described above (they are often named 'strand') is characterized by its polarity (there is a 3′-end and a 5′-end) and the polarity-specified sequence of the bases borne by consecutive deoxyriboses, which is the carrier of the genetic information. Two strands associate to form DNA, the strands being arranged so that

1. they run parallel to each other but have opposite polarities (Figure 1.3);
2. the bases are inside and connected to one another by weak hydrogen bonds;
3. two bases connected by hydrogen bonds form the base pair and according to the rule of Chargaff [67] there are only two types of base pairs in DNA: A-T pairs and G-C pairs (Figure 1.4).

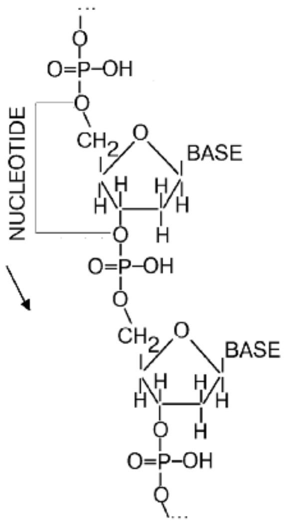

Figure 1.1 A fragment of polynucleotide chain. The direction of the chain is shown by the arrow.

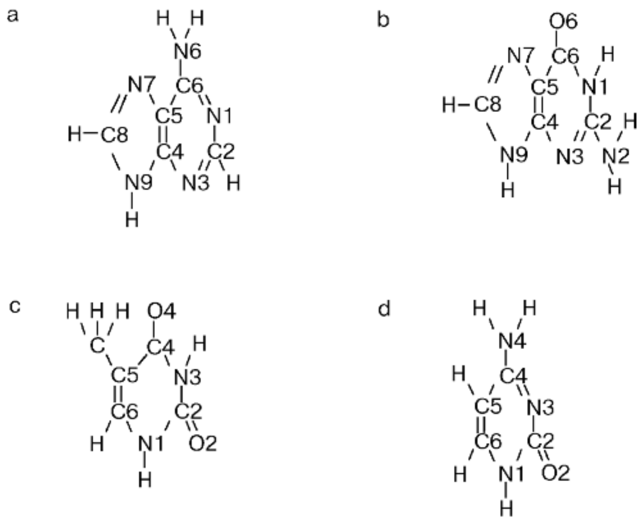

Figure 1.2 DNA bases: (a) adenine, (b) guanine, (c) thymine and (d) cytosine.