

DNA from a solution on a solid substrate and examining it under an electron microscope; however, to study molecules in the solution, the melting process is usually observed indirectly, from the change of the viscosity of the solution or from the change of the light absorption ( $\lambda = 2600 \text{ \AA}$ ) upon heating in the melting region. The melting process is reversible—the helices come together upon cooling (usually the helices in the molten DNA molecules still remain somehow fastened to each other at several points), the hydrogen bonds become restored, and the two-helix polymer is again produced—the DNA is renatured.

The temperature width of the melting interval varies under various conditions from a fraction of the degree to several degrees. This indicates that the melting of DNA is a collective process (more frequently it is called cooperative); if the AT (or GC) pairs were to be dissociated independently, then the width of the melting interval would be  $4T^2/q = 160^\circ$  ( $q = 3500^\circ\text{K}$ —the heat of melting per link of DNA chain).

The theory of melting of the DNA molecule, based on statistical thermodynamics, should predict the temperature dependence of the fraction of the molten links, the average length of the molten sections, etc.

For molecules with links of the same type (the so-called homopolymer), the theory was considered on the basis of various models (for the literature see, for example<sup>[1]</sup>); comparison with the experimental value of the width of the melting interval of the homopolymer,  $\sim 1^\circ$ , makes it possible to find the energy of the two boundaries of the molten and helical sections:  $F_S = 3500^\circ\text{K}$ .

When low-molecular substances (metals, dyes, and also protanes) are added to a DNA solution, their molecules can settle on DNA molecules and strengthen the bond between the helices. In this case the melting curve shifts into the region of higher temperatures and broadens. The increase of the melting temperature and the broadening of the melting interval<sup>[2]</sup> are exactly the same as in the melting of solid solutions having a melting diagram of the "cigar" type. These experiments make it possible to find the heat of melting of one link of DNA,  $q = 3500^\circ\text{K}$ , and also the ratio of the concentrations of the introduced low-molecular substance on the molten and helical parts of the DNA.

Unlike the homopolymers—the low-melting-point poly-AT and high-melting-point poly-GC (melting temperatures  $T_{AT} = 65^\circ\text{C}$ ,  $T_{GC} = 105^\circ\text{C}$ , widths of the melting intervals  $\sim 1^\circ$ ), a real heterogeneous DNA, consisting of AT and GC pairs, melt at  $T = 90^\circ\text{C}$  (at a concentration of the AT pairs  $c = 1/2$ ) and has a broader melting interval ( $\sim 4^\circ$ ).

Recently, a theory of melting of real DNA was developed<sup>[3,4]</sup>. A simple algorithm has been proposed, which makes it possible to determine with the aid of the electronic computer the melting of DNA with arbitrary specified sequence of links<sup>[3]</sup>, and an analytic solution was obtained (at  $(T_{GC} - T_{AT})q/TATFS \ll 1$ ) for the problem of melting of DNA with random sequence of links<sup>[4]</sup>. According to the analytic solution,

the melting of heterogeneous DNA occurs at the average melting temperature of its links: the DNA melts in this case in large pieces (approximately with  $l = [FS T_{AT}/q(T_{GC} - T_{AT})]^2/c(1-c) \approx 400$  links each), and the large width of the melting interval is due to the inhomogeneity of the AT - GC composition in these pieces, and equals  $(T_{GC} - T_{AT})\sqrt{c(1-c)}/l$ . Owing to the large length of the molten sections, the relative enrichment of the molten part of the DNA of the low-melting-point AT component is small, of the order of  $1/\sqrt{l}$ . If a two-filament DNA is broken up into pieces with  $N$  links each, then the width of the melting interval increases by approximately  $(T_{GC} - T_{AT})\sqrt{c(1-c)}/\sqrt{N}$ .

An estimate shows that the surface energy  $F_S$  for a closed ring DNA is smaller by a factor of 2 than for a linear DNA; this agrees with the fact that the width of the melting interval for annular DNA is twice as large as for linear DNA<sup>[5]</sup>.

An electronic computer calculation<sup>[3]</sup>, while agreeing qualitatively with the analytic solution, makes the conclusions of the theory more precise and leads to better agreement with experiment.

Comparison of the experimental curves of the melting of DNA with the theory makes it possible to estimate the concentration of the defects on the DNA molecule, the deviation of the AT - GC sequence from random, etc.

<sup>1</sup>D. M. Crothers, and B. H. Zimm, *J. Mol. Biol.* **9**, 1 (1964).

<sup>2</sup>M. D. Frank-Kamenetskiĭ, *Dokl. Akad. SSSR* **157**, 197 (1964); *Molekulyarnaya biologiya* (Molecular Biology) **2**, 408 (1968).

<sup>3</sup>A. A. Vedenov, A. M. Dykhne, A. D. Frank-Kamenetskiĭ, and M. D. Frank-Kamenetskiĭ, *Molekulyarnaya biologiya* **1**, 313 (1967).

<sup>4</sup>A. A. Vedenov and A. M. Dykhne, *Zh. Eksp. Teor. Fiz.* **55**, 357 (1968). [*Sov. Phys. JETP* **28**, 187 (1969)].

<sup>5</sup>M. D. Frank-Kamenetskiĭ, A. D. Frank-Kamenetskiĭ, *Molekulyarnaya biologiya* **3**, (3) (1969).

#### A. S. Tibilov and A. M. Shukhtin, Generation of Radiation by Ion-ion Recombination

The cross section for the reaction of ion-ion recombination (IIR) by double collisions  $A^- + B^+ \rightarrow A + B^*$  at thermal velocities reaches values  $\sigma_{IIR} \approx 10^{-12} - 10^{-13} \text{ cm}^2$ . This reaction can proceed with selective population of the excited levels of the proposed neutral atoms. The position of the resonantly populated level, the width of the resonance, and also the magnitude of  $\sigma_{IIR}$  for a given pair of ions can be readily calculated. The IIR reaction can be regarded as a possible mechanism for creating inverted level population. It is particularly convenient for use in a scheme of a "collision laser," since the produced neutral atoms obtained in this case a kinetic energy  $\Delta E = 1 - 2 \text{ eV}$ , which practically exclude the inverse process. To obtain an amplifying medium based on the IIR mechanism, it is necessary to create conditions such that the role of the IIR in the population of the given levels predominates over the other mechanisms. Investigations have shown that such conditions occur

\*Mathematically, the problem is equivalent to the one-dimensional Ising model—a chain of interacting spins in a magnetic field, which depends in random fashion on the number of the link.

in a pulsed electric discharge in a mixture Na - H<sub>2</sub> (J ≈ 200 A/cm<sup>2</sup>).

The reaction  $H^- + Ne^+ \rightarrow H + Na(4S)$  leads to selective population of the Na(4S) level. The high degree of ionization of the Na in the discharge ( $n_{Na_0} < 10^9 \text{ cm}^{-3}$ , and  $n_{Na_+} \approx 10^{14} \text{ cm}^{-3}$ ), and the high values of the electron temperature cause the indicated reaction to become the main source of population of the ground and

lower excited levels of Na. The IIR turns out in this case to be quite an effective mechanism for producing inversion and the populations of the levels  $4S^2S_{1/2} - 3P^2P_{1/2,3/2}$  and the generation of simulated emission at these transitions with a large gain.

Translated by J. G. Adashko