Low frequency vibrational modes of 6-thiopurine in Ar matrices and composite films with graphene oxide : FTIR spectroscopy analysis and quantum mechanical calculations

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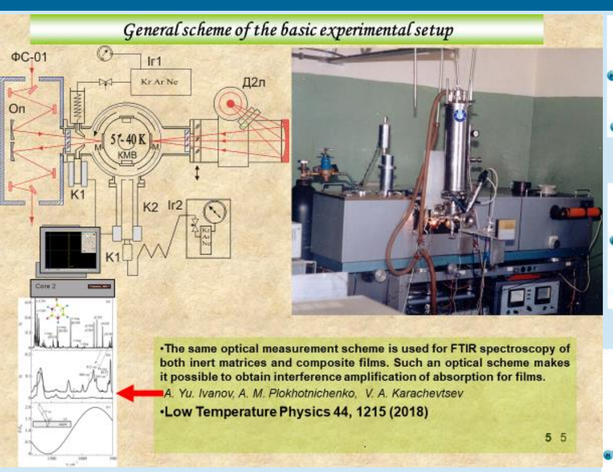
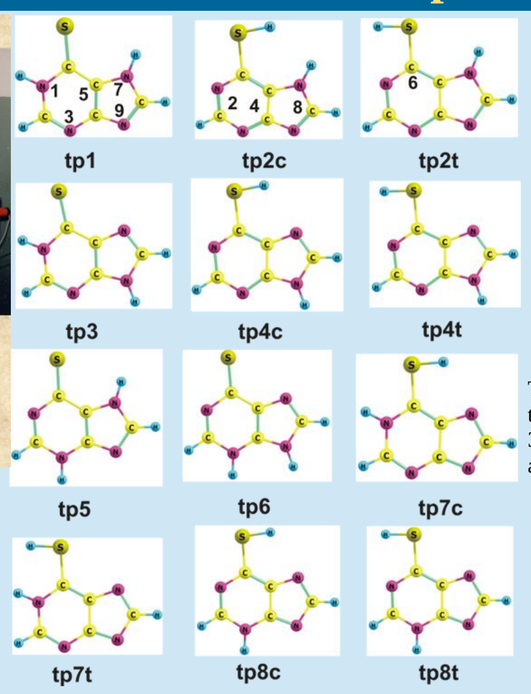
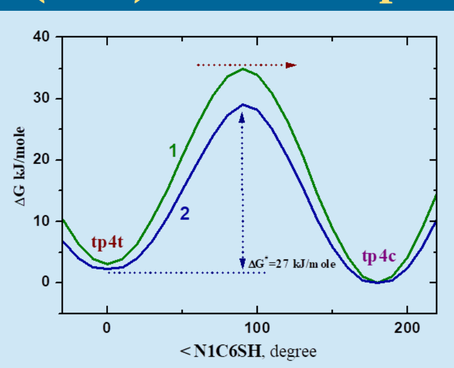
The study of the fundamental physical and chemical properties of the constituent parts of DNA and RNA in various physical conditions is a topical area of modern science. It is of great interest to study modified bases of nucleic acids, in particular sulfur or halogen derivatives. Some of these modified analog of the canonical DNA and RNA bases can be the basis for different drugs. For example, 6-thiopurine (6TP) and 5F-uracil (5FU) have shown effect on cell proliferation and are used in anticancer therapy, 5Cl, 5I- and 5Br-uracil are used in studies of mutagenesis and DNA radiation damage. Therefore, the study of interactions between these derivatives of nucleic acid bases and carbon nanoparticles are of great interest in terms of developing composite carbon nanostructures with various nanotechnological and biomedical functions.

Tautomers of 6-thiopurine (6TP) in low temperature Ar matrices

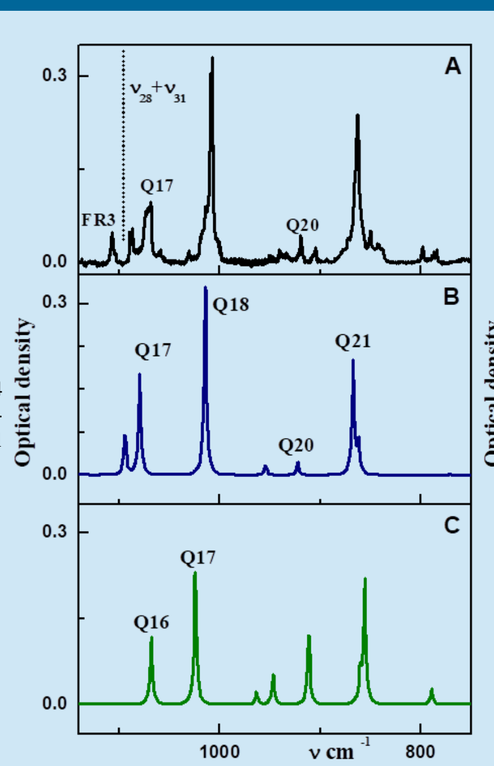




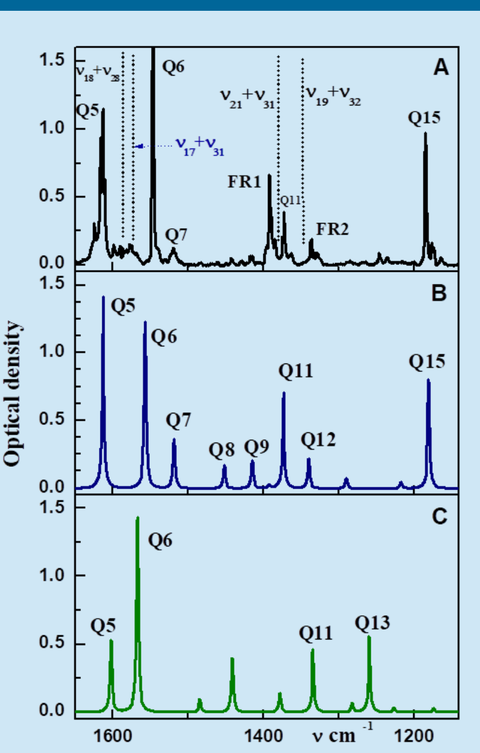
Numbering of atoms and all possible structures of 6TP isomers. The isomer names correspond to literature data



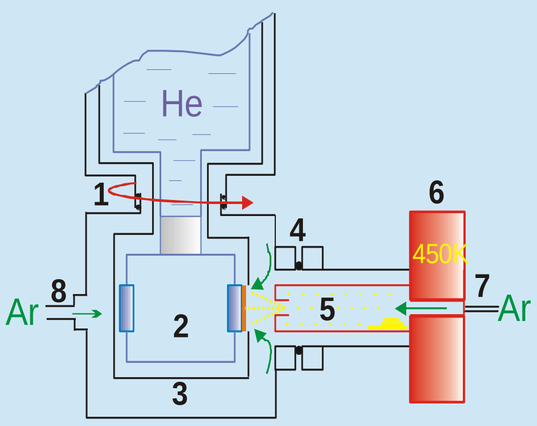
The profiles of the conformational barrier for tp4 thiol tautomer calculated by the DFT/B3LYP/6-31++G(d,p) and MP2/6-31++G(d,p) methods (curve 1 and 2) with step of 10° along dihedral angle N1C6SH.



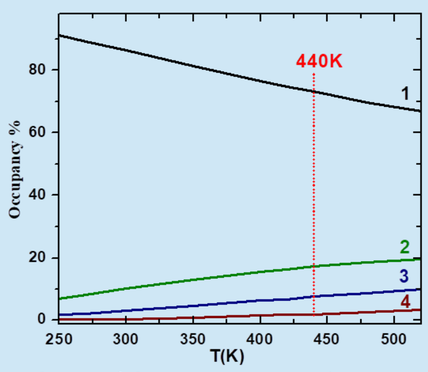
FTIR spectrum of 6-thiopurine in the range of stretching and bending vibrations of the ring and exocyclic groups (1700-1140 cm^{-1}) A) - Ar matrix, (T = 8K, M / S = 700). B) calculation by the DFT/B3LYP/6-311++G(df,pd) method for the tp1 tautomer C) calculation by the DFT/B3LYP/6-311++G(df,pd) method for the tp4c tautomer. FRi – combination mode changed by Fermi resonance. Dotted lines show the frequencies of possible combination bands.



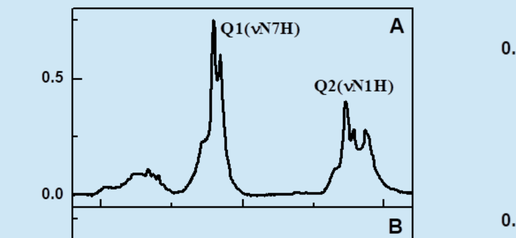
FTIR spectrum of 6-thiopurine in the range of stretching and bending vibrations of the ring and exocyclic groups (1140-750 cm^{-1}) A) - Ar matrix, (T = 8K, M / S = 700). B) calculation by the DFT/B3LYP/6-311++G(df,pd) method for the tp1 tautomer C) calculation by the DFT/B3LYP/6-311++G(df,pd) method for the tp4c tautomer. FRi – combination mode changed by Fermi resonance. Dotted lines show the frequencies of possible combination bands.



The general scheme of low-temperature setup based on liquid He cryostat: rotating vacuum seal (1), cryogenic block with cold mirrors and QCM (2), rotating nitrogen shield (3), flange with indium seal (4), Knudsen cell (5), electric heater of Knudsen cell (6), Ar flow through Knudsen cell (7), outside Ar flow (8)

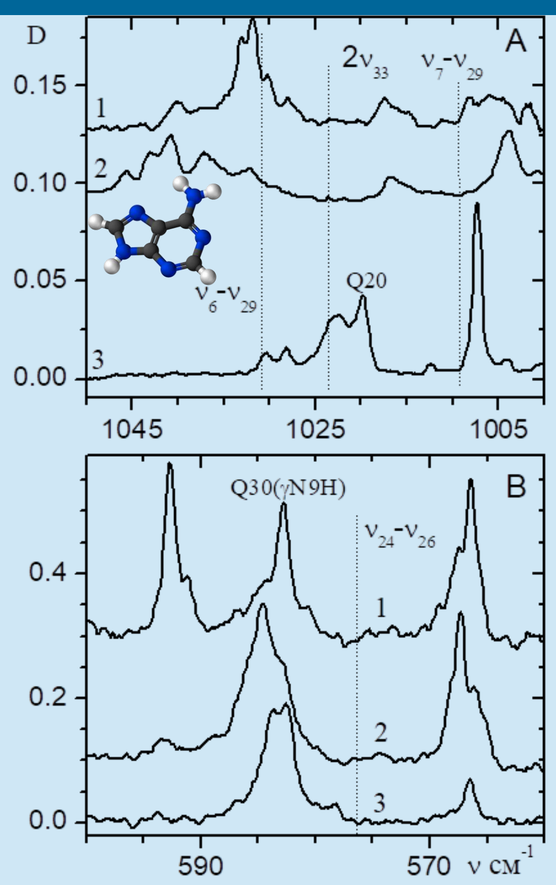


Population of the main tautomers (1 - tp1, 2 - tp4c, 3 - tp4t, 4 - tp3) 6-thiopurine at different temperatures of the gas phase (calculated by DFT/B3LYP/6-311 ++ G (df, pd) method.

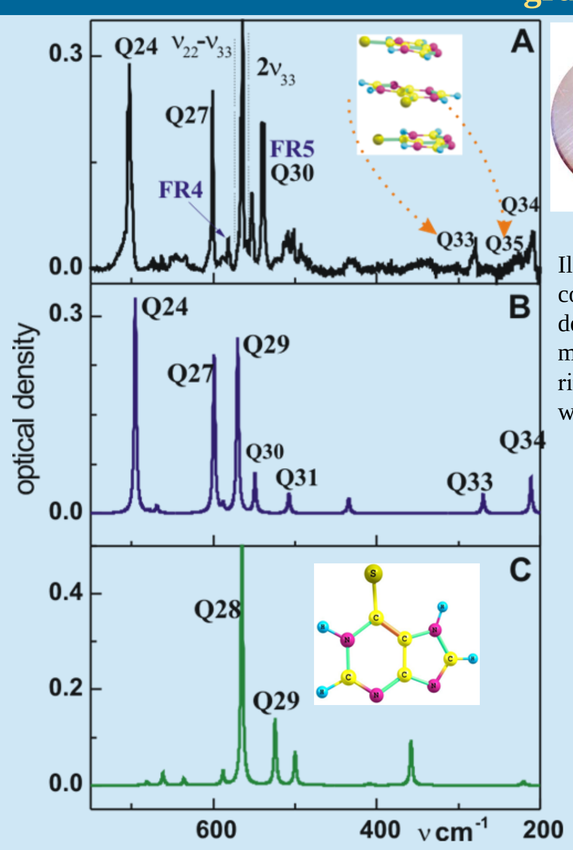


FTIR spectrum of 6TP in the region of stretching vibrations νNH (3500-3400 cm^{-1}) A) - experiment, Ar matrix, (T = 8K, matrix to sample ratio (M/S) = 700). B) - calculation by the DFT/B3LYP/6-311++G (df,pd) method for tp1 tautomer . C) - calculation for tautomers tp4t (curve 1) and tp4c (curve 2)

Low frequency region of the vibrational spectra of some nucleic acid bases in isolated state and composite films with graphene oxide (GO)



IR-Fourier spectra of adenine and **Fermi** resonant splitting: A) -- in-plane pendulum oscillation δ_{rock} NH2; B) -- out-of-plane oscillations γN9H in matrices: Ar (1), Kr (2), Ne (3). The dotted line shows the frequencies of possible combination oscillations.



FTIR spectrum of 6-thiopurine in the range of bending vibrations of the ring and exocyclic groups (750-200 cm^{-1}) A) - Ar matrix, (T = 8K, M / S = 700). Stacking structure is shown on this slide. B) calculation by the DFT/B3LYP/6-311++G(df,pd) method for the tp1 tautomer C) calculation for the tp4c tautomer. FRi – combination mode changed by **Fermi** resonance. Dotted lines show the frequencies of possible combination bands. Qi - mode number

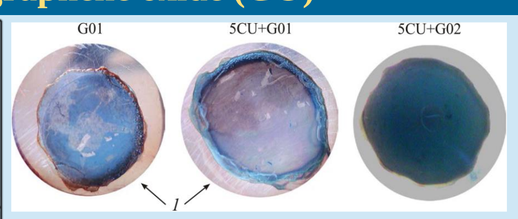


Illustration of a graphene oxide GO1 film and composite films 5CU +GO1 and 5CU+GO2 deposited by a drop method on copper mirrors. 1 is an annular residue ("coffee ring") caused by the phase boundary pinning while drying.

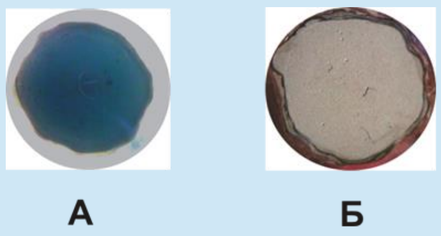
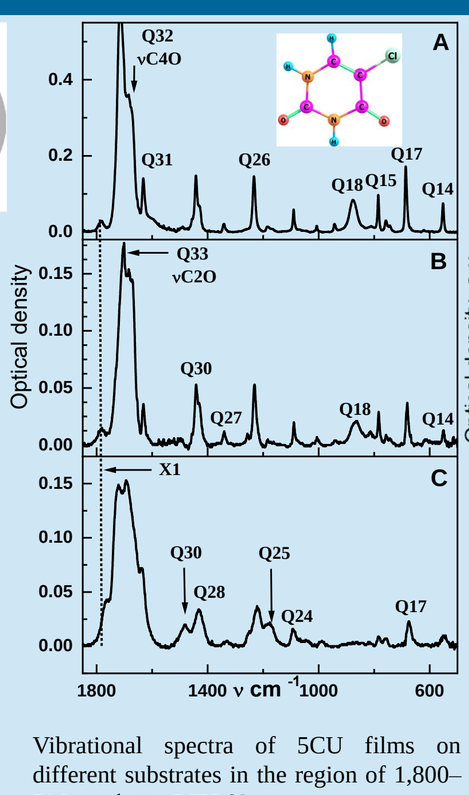
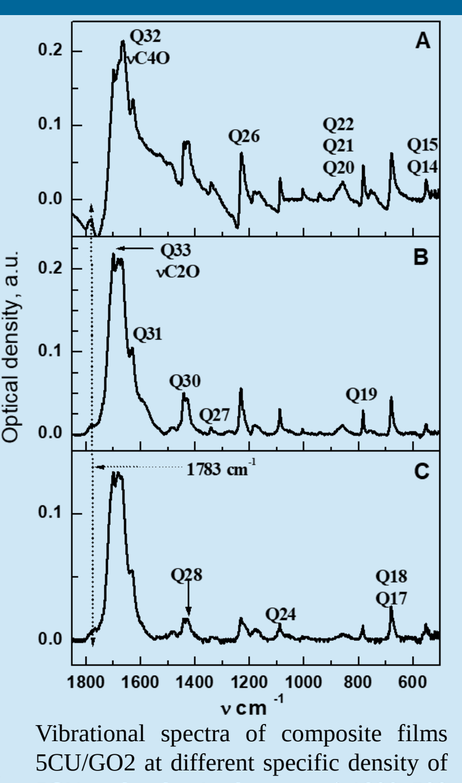


Image of the composite film 5CU/GO (A) and the composite film 5BU/MoS2 (B), which were applied by the drop method on mirrors. Film B shows a ring-shaped deposit ("coffee ring") caused by pinning of the phase interface during drying.



Vibrational spectra of 5CU films on different substrates in the region of 1,800–500 cm^{-1}: (a) 5CU film on a copper mirror after heating (T = 295 K); (b) 5CU film C after heating (T = 295 K); (c) 5CU film on GO1 after deposition (T = 10 K). The specific density of the 5CU molecules is approximately 45 · 10–6 g/cm² for film (a) and 15 · 10–6 g/cm² for films (b) and (c)



Vibrational spectra of composite films 5CU/GO2 at different specific density of 5CU molecules in the area of 1800–500 cm^{-1}: (a) specific density 50 · 10–6 g/cm²; (b) 25 · 10–6 g/cm²; (c) 12 · 10–6 g/cm². The spectrum of control film GO2 was subtracted from the spectra of composite films

Conclusions

1) It was found that 6-thiopurine molecules can be fixed in low-temperature matrices at sublimation temperatures of 440-450 K without thermal decomposition. It was determined that the population of minor N9H-thiol forms is 19 ± 5% when the evaporation temperature is 440 K.
2) In the entire spectral range of 3500-200 cm^{-1}, the 9 bands of the vibrational spectrum of the cis-N9H-thiol form of 6-thiopurine, which do not overlap with the bands of the basic thione tautomer, have been assigned.
3) In the region of bending vibrations, a splitting of the spectral bands caused by the Fermi resonance is found. Five combination bands enhanced by resonance were revealed. The combination bands in the low-frequency region include librational modes. The matrix leads to the noticeable increase of the frequency of the "butterfly" modes of the 6-thiopurine rings.
4) In all experiments, the biomolecules/GO composite films demonstrated resistance to thermal cycling between 10 K and room temperature.
5) It has been established that the interaction between the nucleic acid bases and GO structures most noticeably affects the out-of-plane bending vibrations (γ) of NH groups.
6) The possibility of creating stable biomolecules/GO composite structures that can be used for further research in nanophysics and nanomedicine is shown.

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