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Diamagnetic anisotropy of the peptide group

(resonance structures/ring currents/polypeptides/protein structure/α helix)

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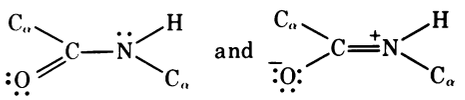
ABSTRACT **A simple theory of the diamagnetic anisotropy of noncyclic planar groups of atoms with resonance structures (mobile electrons) leads to the value -5.36×10^{-6} cm-g-sec electromagnetic units for the molar diamagnetic anisotropy of the peptide group.**

The observed diamagnetic anisotropy of proteins may be attributed in part to induced ring currents in the aromatic side chains of residues of phenylalanine, tyrosine, and tryptophan (1). It has been pointed out by Worcester (2), however, that polypeptides that do not contain aromatic residues, including poly(L-glutamic acid) (3), poly(γ-ethyl-L-glutamate) (4, 5), and poly(L-lysine hydrobromide) (6), also show magnetic orientation, which can be attributed to the diamagnetic anisotropy of the peptide groups, which are planar because of the resonance between two valence-bond structures (7):



Worcester assumed for the value of ΔK (the difference in molar magnetic susceptibility with the magnetic field normal to the plane of the group and that with the field in this plane) the unreliable value -8.8×10^{-6} cm-g-sec electromagnetic units, equal to that reported by Lonsdale (8) for the carboxylic ester group. An experimental value, from measurements on poly(γ-ethyl-L-glutamate) (5), is $-5.2 \pm 0.4 \times 10^{-6}$.

Over 40 years ago I formulated a quantitative theory of the diamagnetic anisotropy of aromatic molecules based upon the idea of induced ring currents (1). The Hamiltonian function for an electron with charge $-e$ in a constant magnetic field of strength H parallel to the z axis is

$$\mathcal{H} = \mathcal{H}^0 + \mathcal{H}' + \mathcal{H}'', \qquad [1]$$

in which $\mathcal{H}^0$ is the Hamiltonian function for zero field strength and $\mathcal{H}'$ and $\mathcal{H}''$ are given by

$$\mathcal{H}' = -(He/2mc)(xp_y - yp_x) \qquad [2]$$

and

$$\mathcal{H}'' = (H^2e^2/8mc^2)(x^2 + y^2). \qquad [3]$$

In the case that the potential function in $\mathcal{H}^0$ is cylindrically symmetrical about the z axis, the effect of $\mathcal{H}'$ vanishes, and the contribution of n electrons to the molar susceptibility is given by the Pauli expression

$$\Delta K = (nNe^2/4mc^2)\langle\rho^2\rangle, \qquad [4]$$

in which $\langle\rho^2\rangle$ is the mean value of $x^2 + y^2$ for the electrons. With the values of the constants introduced, this equation becomes

$$\Delta K = -4.243 \times 10^{-6}\langle\rho^2\rangle n, \qquad [5]$$

in which ρ is in Ångstrom units (10^{-10} m). In the benzene molecule we consider the six p_z electrons to be mobile. The value of $\langle\rho^2\rangle$ relative to an axis through the center of the ring is easily shown to be equal to $R^2 + \langle\rho^2\rangle$atom, in which R is the distance from the ring center to the carbon atoms and $\langle\rho^2\rangle$ atom is the value of $\langle x^2 + y^2\rangle$ relative to an axis through the nucleus of the atom. Because for the carbon atom each of the four orbitals of a completed sp^3 shell is occupied by one electron we expect the value of $\langle\rho^2\rangle$ atom to be the same for an x or y axis through the nucleus as for the z axis. Hence the value of ΔK would be determined solely by the term R^2 in Eq. 5, together with the factor 6 for the number of mobile electrons. With R = 1.39 Å, Eq. 5 then gives $\Delta K = -49.2 \times 10^{-6}$ for benzene. The experimental value, the average for benzene (−54), biphenyl (-2×54), terphenyl (-3×53), quaterphenyl (-4×54), and 1,3,5-triphenylbenzene (-4×54), is -54×10^{-6}, just 10% greater than the calculated value (1). Somewhat larger values, −59, −62, and -66×10^{-6}, respectively, are reported for 1,2,4,5-tetramethylbenzene, hexamethylbenzene, and hexaethylbenzene; the increases may reflect a small contribution of hyperconjugation to the alkyl groups. For condensed aromatic ring systems the theory was extended by calculating the currents along alternative paths in the molecule by consideration of the effect of the ponderomotive force on the equivalent network of electric conductors (1). The calculated values agree with the observed values to within about 5%.

For the peptide group the two resonating structures shown about involve the motion of one electron between the oxygen atom and the nitrogen atom, so that n is equal to 1. The dimensions of the group [carbon–oxygen 1.24 Å, carbon–nitrogen 1.32 Å, angle 125° (7)] correspond to 2.27 Å for the distance between the oxygen atom and the nitrogen atom, and hence to R = 1.135 Å. With these values Eq. 5 gives -5.47×10^{-6} for the diamagnetic anisotropy of the peptide group.

A correction should be made, however, for incomplete resonance in the peptide group. The two structures shown in the first paragraph do not contribute equally; instead, their contributions are in the ratio 60:40, as determined from the observed bond lengths (ref. 7, p. 498). The factor with which the calculated value of ΔK for complete resonance is to be multiplied to correct for incomplete resonance is $2ab$, in which a^2 and b^2 are 0.60 and 0.40, respectively, the contributions of the two structures, this factor thus being proportional to the coefficient of the resonance-energy integral in the expression for the energy of the molecule (ref. 7, p. 589). With this correction factor, 0.98, the calculated value of ΔK for the peptide group becomes -5.36×10^{-6}.

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The value assumed by Worcester (2), -8.8×10^{-6}, was reported by Lonsdale (8) for the ester group, —COOR; Lonsdale, however, made a simple error. She had determined the value of ΔK for pentaerythritol tetraacetate as -22.3×10^{-6}, which she corrected to -17.6×10^{-6} by subtracting the observed value for pentaerythritol. Because there are four acetate groups in the molecule, the value per group is -4.4×10^{-6}, rather than -8.8×10^{-6}. Her value for the carboxylic acid group in oxalic acid is -4.75×10^{-6}. The value calculated from the observed oxygen–oxygen distance and the ratio 85:15 of the two resonance structures (ref. 7, p. 276) is -4.01×10^{-6}.

An experimental value (5) for the anisotropy of a polypeptide chain with the α-helix structure is $2.6 \pm 0.2 \times 10^{-6}$ per amino acid residue, obtained from measurements of a solution of poly(γ-ethyl-L-glutamate). The contribution of the carboxylate groups to this value is determined by their orientation relative to the axis of the helix, which is not known. The planes of the peptide groups are parallel to the axis of the helix, and accordingly each of the groups contributes $5.36/2 = 2.68 \times 10^{-6}$ to the value of ΔK for the polypeptide. An experimental check of this value could be made by study of a polypeptide without resonating groups as side chains.

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