THE JOURNAL OF PHYSICAL CHEMISTRY B

Article

pubs.acs.org/JPCB

Changing the Direction of Intramolecular Electron Transfer in Oxidized Dipeptides Containing Tryptophan and Tyrosine

Olga B. Morozova,[†,‡] Robert Kaptein,[‡,§] and Alexandra V. Yurkovskaya*[,†,‡]

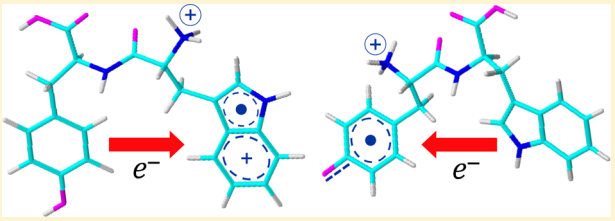
[†]International Tomography Center, Institutskaya 3a, 630090 Novosibirsk, Russia

[‡]Novosibirsk State University, Pirogova 2, 630090, Novosibirsk, Russia

[§]Bijvoet Center for Biomolecular Research, Utrecht University, Padualaan 8, NL-3584, The Netherlands

Supporting Information

ABSTRACT: Intramolecular electron transfer (IET) in the oxidized dipeptide Tyr-Trp was investigated in the pH range from 1.0 to 3.1 by the method of time-resolved chemically induced dynamic nuclear polarization. The results were compared with data obtained earlier for Trp-Tyr. Surprisingly, it was found that the direction of IET changes with the order of the amino acid residues in the peptide. For Tyr-Trp, the rate constant of electron transfer from tyrosine residue to tryptophanyl cation radical is below 1.2×10^4 s^{-1}, whereas for Trp-Tyr, the value of this rate constant is 5.5×10^5 s^{-1}. Conversely, for oxidized Tyr-Trp at pH range 2.1 and lower, electron transfer from tryptophan residue to tyrosyl radical is observed. The rate constant of this reaction is proportional to the concentration of protons in aqueous solution, and at pH 1.0 is equal to 6.5×10^5 s^{-1}. The change in direction of IET observed for oxidized Tyr-Trp dipeptide is presumably due to the positive charge at the N-terminal amino group of the peptide, which promotes electron transfer in the direction of the N-terminus.



INTRODUCTION

There is a growing interest in the role of amino acid radicals as intermediates in electron and hydrogen transfer processes in enzymology and photobiology.[1] Examples are the catalytic role of tyrosyl radical in ribonucleotide reductases,[2] and the intramolecular electron transfer (IET) from tryptophan (Trp) to flavins in DNA photolyases and blue-light photoreceptors.[3] Electron transfer has also been demonstrated in aqueous solutions of amino acids,[4] model peptides,[5−8] and proteins.[9] Thus, radicals of tyrosine (Tyr) and Trp play an important role in a number of biological processes. Detection of these transient radicals by electron paramagnetic resonance (EPR) or electron nuclear double resonance (ENDOR) is difficult because of their short lifetime. EPR spectra of highly reactive radicals could be obtained in frozen matrices, but under these conditions more stable secondary radicals are often detected, and kinetic data could not be compared to the data obtained for reactions in solutions. An alternative approach used here is the method of time-resolved chemically induced dynamic nuclear polarization (CIDNP). The advantage of this method is that it allows to separate contributions from geminate and bulk processes and to obtain information about the mechanism and rate constants of the reactions.[6−8]

In the present work, the method of time-resolved CIDNP was applied to IET reactions in the oxidized peptide tyrosine−tryptophan (Tyr-Trp) in the pH range from 1.0 to 3.1:

$$\mathrm{TyrOH{-}TrpNH^{+\bullet}} \underset{k_r}{\overset{k_f}{\rightleftarrows}} \mathrm{TyrO^{\bullet}{-}TrpNH} + \mathrm{H^+} \qquad (1)$$

The results were compared with those obtained earlier for Trp-Tyr. The structure of the peptides is shown in Chart 1. Since the typical pK_a values for terminal amino and carboxylic groups in peptides are ∼7.5 and ∼3.5,[10] respectively, in the pH range studied, the peptides carry positive charge at the amino group, whereas the carboxylic group is neutral. Radicals of the peptide were generated photochemically in the quenching of triplet-excited 2,2′-dipyridyl (DP, Chart 1). CIDNP kinetics obtained during this photoreaction were compared to that for the earlier studied Trp-Tyr.[6−8]

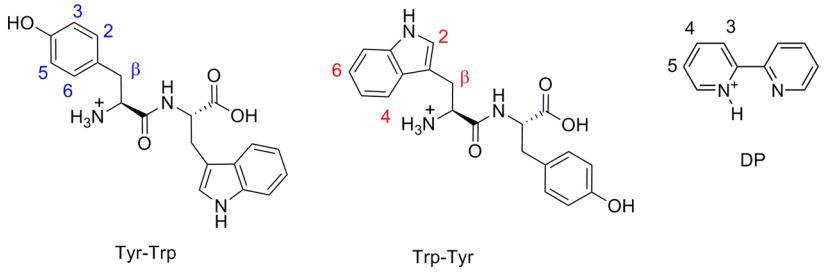
Below, "Trp-Tyr", "Tyr-Trp", "DP" are used as general abbreviations. For reactants and intermediates in various protonation states, designations are DPH^+, $DPH^{\bullet}$, $DPH_2^{+\bullet}$, TyrOH, $TyrOH^{+\bullet}$, $TyrO^{\bullet}$, TrpNH, and $TrpNH^{+\bullet}$.

EXPERIMENTAL SECTION

Time-resolved CIDNP experiments were carried out applying the standard protocol:[11] radiofrequency (RF) saturation pulses - laser pulse - evolution time τ - RF detection pulse - free induction decay. The first train of RF pulses completely destroys all Boltzmann polarization; consequently, only enhanced signals from the polarized reaction products formed during the variable delay τ appear in the CIDNP spectra. In all time-resolved measurements, the length of the detection RF pulse was 1 μs. The timing corresponds to the center of the RF pulse (i.e., 0.5 μs for $\tau = 0$) on all CIDNP plots in Figures 2−4.

Received: August 10, 2012
Revised: September 14, 2012
Published: September 14, 2012

Chart 1. Structures of the Peptides Tyr-Trp (left), Trp-Tyr (middle), and of the Dye DP (right)



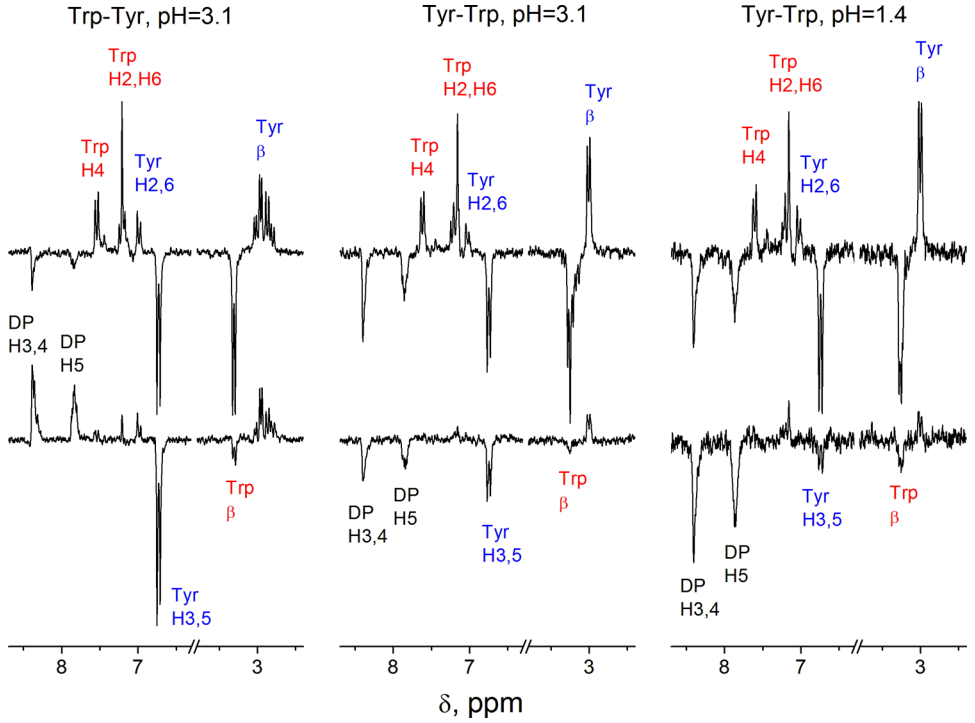


Figure 1. 200 MHz ^{1}H CIDNP spectra obtained in photoreactions of DP with the dipeptide Trp-Tyr at pH 3.1 (left), and with the dipeptide Tyr-Trp at pH 3.1 (middle) and 1.4 (right). Upper spectra were taken immediately after the laser pulse, lower spectra were taken at 100 μs after the laser pulse.

Samples were sealed in standard 5 mm Pyrex NMR tubes. ^{1}H CIDNP spectra were obtained after irradiation by a COMPEX Lambda Physik XeCl excimer laser (wavelength 308 nm, pulse energy up to 150 mJ) in the probe of a 200 MHz Bruker DPX-200 NMR spectrometer operating at 4.7 T.

L-Tyrosine-L-tryptophan and L-tryptophan-L-tyrosine were purchased from Bachem and used without further purification; DP, DCl, NaOD (30% solution in D_2O), and D_2O (99.9% enriched) were used as received from Sigma-Aldrich. All ^{1}H NMR measurements were performed in D_2O. The pH was adjusted by adding DCl or NaOD. No correction for the deuterium isotope effect on pH was made. Concentrations of reactants were 5×10^{-4} M (DP) and 2.5×10^{-3} M (peptides).

RESULTS AND DISCUSSION

In acidic solution, quenching of ^{T}DPH$^+$ (pK_a = 5.8[12]) by Trp and Tyr occurs via electron transfer with comparable rate constants.[13] Thus, in the quenching of ^{T}DPH$^+$ by the peptide Tyr-Trp, two types of the peptide radicals, with radical centers on Trp and Tyr residues are formed:

$$^T\mathrm{DPH}^+ + \mathrm{TyrOH{-}TrpNH} \xrightarrow{k_q^{Tyr}} \mathrm{DPH_2}^{+\bullet} + \mathrm{TyrO^\bullet{-}TrpNH} \quad (2)$$

$$^T\mathrm{DPH}^+ + \mathrm{TyrOH{-}TrpNH} + \mathrm{H}^+ \xrightarrow{k_q^{Trp}} \mathrm{DPH_2}^{+\bullet} + \mathrm{TyrOH{-}TrpNH}^{+\bullet} \quad (3)$$

Tyrosyl cation radical $TyrOH^{+\bullet}$ formed as a result of electron transfer quickly deprotonates (pK_a<−1[14]), whereas the radical $DPH^\bullet$ in acidic solution transforms into $DPH_2^{+\bullet}$ (pK_a = 8.5[12]). Electron transfer from the Trp residue leads to the formation of the cation radical $TrpNH^{+\bullet}$ (pK_a = 4.3 for free Trp,[15] and 4.6 < pK_a < 5.4 for Trp in the peptides[16,17]).

Previously we studied IET in the oxidized reverse peptide Trp-Tyr:

$$\mathrm{TrpNH}^{+\bullet}{-}\mathrm{TyrOH} \underset{k_r}{\overset{k_f}{\rightleftarrows}} \mathrm{TrpNH{-}TyrO^\bullet} + \mathrm{H}^+ \quad (4)$$

For this dipeptide it was found that $k_f = 5.5 \times 10^5$ s^{-1} and is not pH-dependent.[8] The rate constant k_r is proportional to the

dx.doi.org/10.1021/jp307956q | J. Phys. Chem. B 2012, 116, 12221−12226

proton concentration, and thus increases as the pH becomes lower:

$$\lg(k_r) = \lg(k_r^0) - \mathrm{pH} \quad (5)$$

where k_r^0 is the rate constant at pH 0. At pH 1.6, $k_r = 3.2 \times 10^5$ s^{-1} (ref 8).

Figure 1 shows CIDNP spectra obtained in the photoreaction of DP with Trp-Tyr at pH 3.1, and with Tyr-Trp at pH 3.1 and 1.4. Upper spectra were obtained immediately after the laser pulse, lower spectra at 100 μs after the laser pulse. CIDNP signals are observed for nonexchangeable protons, which have nonzero hyperfine couplings in the transient radicals, i.e., enhanced absorption for H2,6 and β protons of Tyr, and for H2, H6 and H4 of Trp, emission for H3,5 of Tyr, and β protons of Trp. The similarity of signal intensity patterns for both peptides shows that the primary photochemical processes are identical, and in the case of Tyr-Trp corresponds to reactions 2 and 3. The polarization of DP protons is formed in two types of radical pairs with opposite signs of Δg: $\Delta g > 0$ for the radical pair with tryptophanyl radical, $\Delta g < 0$ for the one with tyrosyl radical.[8] According to the rules for CIDNP,[18] in the pair with tryptophanyl radical, polarization of DP protons is negative, and in the pair with tyrosyl radical, it is positive. As we will see, this sign change in Δg makes the time-dependent CIDNP traces exquisitely sensitive to the direction of electron transfer. The resulting CIDNP sign for DP depends on two factors: (i) CIDNP enhancement factors in these two pairs determined by the magnetic properties of the radicals, and (ii) the proportion of radical pairs of each type, which reflects the ratio of the quenching rate constants of triplet-excited DP by Trp and Tyr. It is seen that in CIDNP spectra, detected immediately after the laser pulse, protons of DP are negatively polarized, meaning that CIDNP formed in the radical pairs where tryptophanyl radical predominates.

The reactions studied here are, in principle, cyclic, i.e., initial compounds and reaction products are the same. In these reactions, cancellation of polarization occurs as a consequence of the spin-sorting nature of CIDNP at high magnetic fields: polarization due to geminate recombination is exactly opposite to that in the escaping radicals that end up in the same products. However, if the radical lifetime is long enough nuclear relaxation will reduce the polarization in the radicals, making the cancellation incomplete. Three types of reactions lead to polarization transfer from radical to diamagnetic products: (i) radical recombination by back electron or hydrogen transfer, (ii) degenerate electron exchange between the radical and its parent molecule, and (iii) the IET reaction.

CIDNP kinetics for different protons of Tyr, Trp, and DP, obtained in photoreactions of the peptide Tyr-Trp at different pH values from 1.0 to 3.1 are shown in Figures 2−4. Signals of H3,5 of Tyr, β protons of Trp, and H3,4 of DP were used for quantitative analysis.

In the pH range studied, degenerate electron exchange is operative only in the case of Trp residues[7] with a pseudo-first-order rate constant, which is a product of the second-order rate constant k_{ex} and peptide concentration C (asterisk denotes nuclear polarization).

$$^*\mathrm{TrpNH}^{+\bullet} + \mathrm{TrpNH} \xrightarrow{k_{ex}} {}^*\mathrm{TrpNH} + \mathrm{TrpNH}^{+\bullet} \quad (6)$$

The high efficiency of reaction 6 leads to a fast decay of Trp CIDNP (Figure 3), resulting in a low sensitivity of CIDNP kinetics of Trp to the rate of IET.

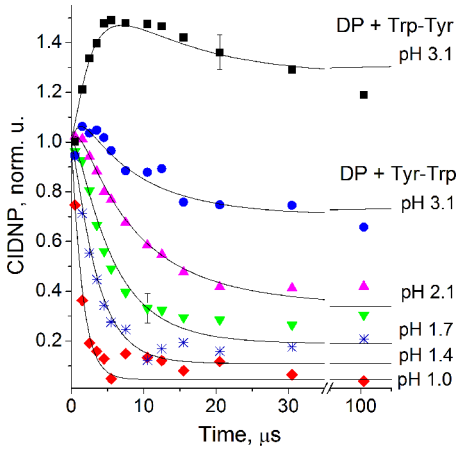


Figure 2. ^{1}H CIDNP kinetics for H3,5 of Tyr residue, obtained in photoreactions of DP with the peptides Tyr-Trp and Trp-Tyr at different pH values. Amplitude of polarization (emission) is plotted. Solid lines repesent model simulations. For all parameters of the simulations, see text. For details of the simulations, see Supporting Information.

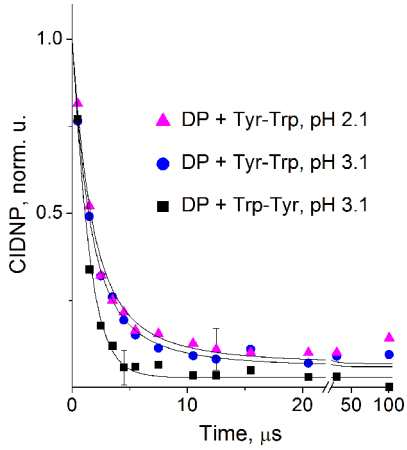


Figure 3. ^{1}H CIDNP kinetics for β protons of Trp residue, obtained in photoreactions of DP with the peptides Tyr-Trp and Trp-Tyr at different pH values. Amplitude of the polarization (emission) is plotted. Solid lines represent model simulations. For all parameters of the simulations, see text. For details of the simulations, see Supporting Information. Kinetic traces at some pH values were omitted to avoid overlap in the figure.

The influence of IET on CIDNP kinetics of the participating species, electron donor and electron aceptor, is as follows. Since the IET reaction shortens the lifetime of the electron acceptor radical, it leads to CIDNP cancellation for the electron acceptor, which manifests itself in the decay of CIDNP. For the electron donor, the IET reaction serves as an additional source of radicals that are not polarized. For the donor, nuclear polarization is formed in a second-order termination reaction of its radicals with dye radicals, which leads to an increase of CIDNP intensity of the donor in time. In the case of reversible IET, each residue, Trp or Tyr, can be either donor or acceptor. The IET reaction also changes the proportion of radical pairs of the dye radicals with either the tryptophanyl or tyrosyl radical formed after quenching of triplet DP. Since these radical pairs lead to opposite DP polarizations, the CIDNP kinetics of DP reflects the direction and efficiency of IET.

dx.doi.org/10.1021/jp307956q | J. Phys. Chem. B 2012, 116, 12221−12226

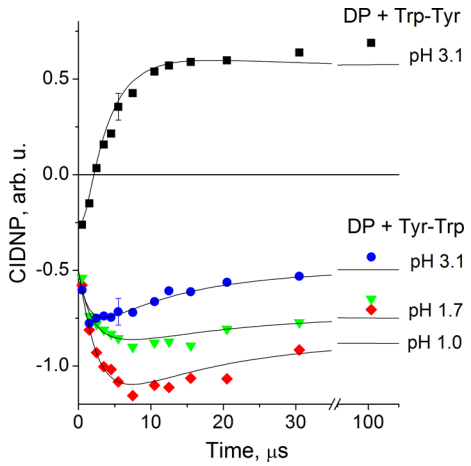


Figure 4. ^{1}H CIDNP kinetics for H3,4 of DP, obtained in photoreactions of DP with the peptides Tyr-Trp and Trp-Tyr at different pH values. Solid lines represent model simulations. For all parameters of the simulations, see text. For details of the simulations, see Supporting Information. Kinetic traces at some pH values were omitted to avoid overlap in the figure.

CIDNP kinetics for the earlier studied Trp-Tyr peptide was obtained at pH 3.1 for comparison (Figures 2–4). Under these conditions, reaction 4 could be treated as irreversible with $k_f = 5.5 \times 10^5$ s^{-1} (ref 8), which is manifested in the initial growth of the signal of Tyr (Figure 2) and the CIDNP sign change for DP from emission to enhanced absorption (Figure 4; Figure 1, lower left spectrum). The most pronounced difference between the two peptides is observed for DP CIDNP at pH 3.1 (Figure 4). For Trp-Tyr, there is a sign change, while for Tyr-Trp the polarization remains negative. Also, for Tyr-Trp, no initial growth is detected in CIDNP kinetics of Tyr. These observations point to a low efficiency of IET from Tyr to the tryptophanyl radical in the oxidized Tyr-Trp peptide, which was confirmed by excellent coincidence of experimental and simulated kinetics for Tyr-Trp at pH 3.1 in which IET was not taken into account.

It was expected that a low pH will accelerate the reverse reaction 1. To test this, kinetic measurements were performed in the pH range from 2.1 to 1.0. Lowering of the pH resulted in acceleration of CIDNP decay for Tyr, and increase of the negative polarization for DP (Figure 4), which reflects an increase of the rate constant k_r of the reverse reaction 1 with increasing proton concentration (eq 5).

To determine k_r at different pH values and to obtain the upper limit of k_f, CIDNP kinetics of the peptides were simulated using an approach suggested by Fischer and coauthors[19] and modified to take into account the reversible IET.[8] According to this approach, a system of equations is solved that describes the time dependence of the concentrations of radicals derived from DP, Trp, and Tyr, polarization in these radicals, and polarization in corresponding diamagnetic molecules. The equations include the parameters k_f and k_r, which are varied to get the best fit of the simulated CIDNP kinetics of DP, Tyr, and Trp to the experimentally detected ones. Details of the simulation procedure are given in the Supporting Information. The product of initial radical concentration and the second-order radical termination rate constant k_tR_0 (at each pH), k_{ex} (for all pH values), and the vertical scaling factor were also fitting parameters. The product k_tR_0 is determined by irradiation conditions and was found to be approximately 3×10^5 s^{-1} with slight variation for different kinetic curves. For k_{ex}, the best-fit value is 4×10^8 M^{-1}s^{-1}.

It was found that for k_f in the range from 0 to 1.2×10^4 s^{-1}, the pH-dependence of lg K = lg(k_f/k_r) is linear with slope equal to 1 with a high degree of accuracy. At higher k_f, the dependence became nonlinear. The best linearity with slope equal to 1 was found at $k_f \sim 6 \times 10^3$ s^{-1}. The results of the best-fit simulations are summarized in Table 1. Because of the uncertainty of k_f, the dependence lg(k_r) instead of lg K is plotted in Figure 5 together with that obtained for reaction 4 in our previous work.[8]

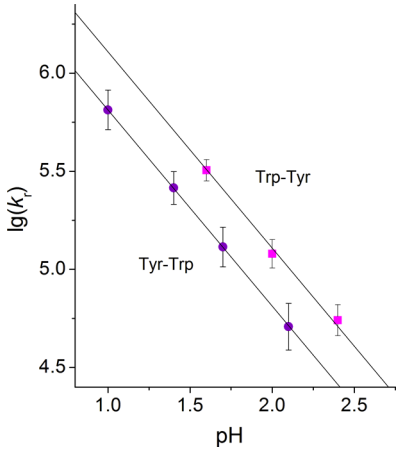


Figure 5. pH-dependence of the decimal logarithm of the rate constant of IET from Trp residue to tyrosyl radical in the oxidized peptides Tyr-Trp and Trp-Tyr.

The pH-dependence of IET rate constant in reverse direction, k_r, obeys the following equations for reactions 1 and 4, respectively:

$$\lg(k_r(1)) = 6.81 - \text{pH} \quad (7)$$

$$\lg(k_r(4)) = 7.11 - \text{pH} \quad (8)$$

At a given pH, $k_r(1)$ is smaller than $k_r(4)$ by a factor of $10^{7.11-6.81} = 2$.

Table 1. Rate Constants k_f and k_r of IET[a] in the Oxidized Peptides Tyr-Trp and Trp-Tyr (s^{-1})

Tyr-Trp			Trp-Tyr[b]		
pH	k_f	k_r	pH	k_f	k_r
1.0	$<1.2 \times 10^4$	$(6.5 \pm 1.5) \times 10^5$	1.6	$(5.5 \pm 0.5) \times 10^5$	$(3.2 \pm 0.4) \times 10^5$
1.4		$(2.4 \pm 0.5) \times 10^5$	2.0		$(1.2 \pm 0.2) \times 10^5$
1.7		$(1.2 \pm 0.3) \times 10^5$	2.4		$(5.5 \pm 1.0) \times 10^4$
2.1		$(5.1 \pm 1.4) \times 10^4$			

[a]For definitions of k_f and k_r, see eqs 1 and 4. [b]Data taken from ref 8.

dx.doi.org/10.1021/jp307956q | J. Phys. Chem. B 2012, 116, 12221–12226

The equilibrium constant K is related to the difference of reduction potentials of tryptophanyl and tyrosyl radicals, $\Delta E = E(\mathrm{TrpNH^{+\bullet}/TrpNH}) - E(\mathrm{TyrO^{\bullet},H^{+}/TyrOH})$:

$$\Delta E = 0.059 \times \lg K \tag{9}$$

The formula for the pH-dependence of the reduction potential of one-electron oxidized Trp is as follows:[17]

$$E(\mathrm{TrpNH^{+\bullet}/TrpNH}) = E_0(\mathrm{TrpNH^{+\bullet}/TrpNH}) + 0.059 \times \lg \frac{[\mathrm{H^+}]}{K_a^{\mathrm{Trp}} + [\mathrm{H^+}]} \tag{10}$$

where $E_0(\mathrm{TrpNH^{+\bullet}/TrpNH})$ is the reduction potential at pH 0, and K_a^{Trp} is the ionization constant for the Trp cation radical ($4.6 < \mathrm{p}K_a^{\mathrm{Trp}} < 5.4$ for Trp in the peptides[16,17]). For one-electron oxidized Tyr,[4]

$$E(\mathrm{TyrO^{\bullet}, H^{+}/TyrOH}) = E_0(\mathrm{TyrO^{\bullet}, H^{+}/TyrOH}) + 0.059 \lg(K_a^{\mathrm{Tyr}} + [\mathrm{H^+}]) \tag{11}$$

where $E_0(\mathrm{TyrO^{\bullet},H^{+}/TyrOH})$ is the reduction potential at pH 0, and $\mathrm{p}K_a^{\mathrm{Tyr}} = 10.1$ for the phenolic proton in free Tyr and Tyr in peptides.[17]

In the pH range studied, $K_a^{\mathrm{Trp}}, K_a^{\mathrm{Tyr}} \ll [\mathrm{H^+}]$, and $E(\mathrm{TrpNH^{+\bullet}/TrpNH})$ is pH-independent, whereas $E(\mathrm{TyrO^{\bullet},H^{+}/TyrOH})$ decreases by 0.059 V per pH unit, providing that the difference in reduction potentials of tryptophanyl and tyrosyl radicals increases with pH accordingly:

$$\Delta E = \Delta E_0 + 0.059\ \mathrm{pH} \tag{12}$$

where ΔE_0 is the difference of the reduction potentials at pH 0.

Having only the upper limit of k_f and, therefore, the upper limit of K for the oxidized peptide Tyr-Trp, we can determine a lower value for $\Delta(\Delta E) = \Delta E(4) - \Delta E(1)$ by which ΔE for the oxidized Trp-Tyr exceeds that for oxidized Tyr-Trp in the pH range studied:

$$\Delta(\Delta E) = 0.059 \times \lg \frac{K(4)}{K(1)} \tag{13}$$

Combining eq 13 with eqs 7 and 8 and using the values of $k_f(4) = 5.5 \times 10^5\ \mathrm{s^{-1}}$ and $k_f(1) = 1.2 \times 10^4\ \mathrm{s^{-1}}$, we obtain the minimal $\Delta(\Delta E) = 0.059 \times (\lg(5.5 \times 10^5) - \lg(1.2 \times 10^4) - 7.11 + 6.81) = 0.08$ V, which is constant in the pH range studied.

From the values of k_f and pH-dependencies of k_r (eqs 7 and 8), we obtain that $\lg(K(4)) = 0$ at $\mathrm{pH} = 7.11 - \lg(5.5 \times 10^5) \approx 1.4$, and $\lg(K(1)) = 0$ at $\mathrm{pH} > 6.81 - \lg(1.2 \times 10^4) \approx 2.7$ for oxidized Tyr-Trp. This means that at $1.4 < \mathrm{pH} < 2.7$ at equilibrium conditions, the dominating oxidized form of each peptide is that with the radical center located on the C-terminal residue.

CONCLUSION

Time-resolved CIDNP is very useful for determination of mechanisms and absolute rate constants of fast radical reactions. The technique was used in a quantitative analysis of IET in the oxidized peptide Tyr-Trp. Earlier CIDNP kinetics detected in photoreaction of DP with the peptide Trp-Tyr in acidic aqueous solution for the protons of all reacting species proved to be very sensitive to the rate and direction of IET in the oxidized dipeptide. Simultaneous simulation of the kinetics for the protons of DP, Trp residue, and Tyr residue provided the rate constants of IET in both directions, from Tyr residue to tryptophanyl cation radical, and from Trp residue to neutral tyrosyl radical. Particularly, the sign of the dye polarization, which is negative in the pair with tryptophanyl radical and positive in the pair with tyrosyl radical, reflects the ratio of the two types of the peptide radicals with the radical centers at one of the two residues. Therefore, CIDNP kinetics of the dye (which is not involved in IET itself) is a sensitive indicator of the efficiency and the rate of IET. For the oxidized peptide Tyr-Trp studied here, it was established that the rate of IET from Tyr residue to tryptophanyl cation radical is more than an order of magnitude lower than that for oxidized Trp-Tyr. The rate constants of IET in the opposite direction, which increase with decrease of pH, are comparable in magnitude for both oxidized peptides. Thus, the direction of reversible IET in Tyr and Trp containing one-electron deficient dipeptides at low pH depends strongly on the order of the amino acids in the sequence. To the best of our knowledge, it is the first report of IET involving tyrosyl and Trp residues that leads to highly irreversible formation of tryptophanyl radical. This effect is tentatively attributed to the positively charged N-terminal amino group of the peptide, which affects ΔE at the different order of the residues and promotes IET in the direction of N-terminal residue. This work underscores the important influence of charges on both the rate and the direction of IET in peptides and proteins.

ASSOCIATED CONTENT

Supporting Information

Modeling of CIDNP kinetics in the photoreaction of DP with Tyr−Trp. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*Tel. +7 383 3331333; fax +7 383 3331399; e-mail: yurk@tomo.nsc.ru.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the program of the Russian Government "Measures to Attract Leading Scientists to Russian Educational Institutions" (Grant No. 11.G34.31.0045), RFBR (Project No. 11-03-00296), Program of the Division of Chemistry and Material Science RAS (Project 5.1.1), and the program of the President of Russia to support the leading scientific schools (No. NSch-2429.2012.3).

REFERENCES

(1) Stubbe, J.; van der Donk, W. A. *Chem. Rev.* **1998**, *98*, 705−762.
(2) Graeslund, A.; Sahlin, M. *Annu. Rev. Biophys. Biomol. Struct.* **1996**, *25*, 259−286.
(3) Heelis, P. F.; Okamura, T.; Sancar, A. *Biochemistry* **1990**, *29*, 5694−5698. Kim, S.-T.; Heelis, P. F.; Sancar, A. *Methods Enzymol.* **1995**, *258*, 319−343.
(4) Jovanovic, S. V.; Harriman, A.; Simic, M. G. *J. Phys. Chem.* **1986**, *90*, 1935−1939.
(5) Faraggi, M.; DeFelippis, M. R.; Klapper, M. H. *J. Am. Chem. Soc.* **1989**, *111*, 5141−5145. Prutz, W. A.; Land, E. J. *Int. J. Radiat. Biol.* **1979**, *36*, 513−520.

(6) Morozova, O. B.; Yurkovskaya, A. V.; Tsentalovich, Y. P.; Forbes, M. D. E.; Sagdeev, R. Z. *J. Phys. Chem. B* **2002**, *106*, 1455−1460.
(7) Morozova, O. B.; Yurkovskaya, A. V.; Vieth, H.-M.; Sagdeev, R. Z. *J. Phys. Chem. B* **2003**, *107*, 1088−1096.
(8) Morozova, O. B.; Yurkovskaya, A. V.; Sagdeev, R. Z. *J. Phys. Chem. B* **2005**, *109*, 3668−3675.
(9) Butler, J.; Land, E. J.; Pruetz, W. A.; Swallow, A. J. *Biochim. Biophys. Acta* **1982**, *705*, 150−162. Pruetz, W. A.; Butler, J.; Land, E. J.; Swallow, A. J. *Biochem. Biophys. Res. Commun.* **1980**, *96*, 408−414.
(10) Saprygina, N. N.; Morozova, O. B.; Gritsan, N. P.; Fedorova, O. S.; Yurkovskaya, A. V. *Russ. Chem. Bull., Int. Ed.* **2011**, *60*, 2579−2587.
(11) Morozova, O. B.; Kiryutin, A. S.; Sagdeev, R. Z.; Yurkovskaya, A. V. *J. Phys. Chem. B* **2007**, *111*, 7439−7448.
(12) Tsentalovich, Y. P.; Morozova, O. B.; Yurkovskaya, A. V.; Hore, P. J.; Sagdeev, R. Z. *J. Phys. Chem. A* **2000**, *104*, 6912−6916.
(13) Tsentalovich, Y. P.; Morozova, O. B. *J. Photochem. Photobiol. A: Chemistry* **2000**, *131*, 33−40. Tsentalovich, Y. P.; Morozova, O. B.; Yurkovskaya, A. V.; Hore, P. J. *J. Phys. Chem. A* **1999**, *103*, 5362−5368.
(14) Bent, D. V.; Hayon, E. *J. Am. Chem. Soc.* **1975**, *97*, 2612−2619.
(15) Posener, M. L.; Adams, G. E.; Wardman, P.; Cundall, R. B. *J. Chem. Soc., Faraday Trans. 1* **1976**, 2231−2239.
(16) Jovanovic, S. V.; Simic, M. G. *Free Radical Biol. Med.* **1985**, *1*, 125.
(17) DeFelippis, M. R.; Murthy, C. P.; Proiman, F.; Weinraub, D.; Faraggi, M.; Klapper, M. H. *J. Phys. Chem.* **1991**, *95*, 3416.
(18) Kaptein, R. *J. Chem. Soc. Chem. Comm.* **1971**, 732−733.
(19) Vollenweider, J. K.; Fischer, H. *Chem. Phys.* **1988**, *124*, 333−345.