**Aβ_{5-x}** Peptides: N-Terminal Truncation Yields Tunable Cu(II) Complexes

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**ABSTRACT:** The Aβ_{5-x} peptides (x = 38, 40, 42) are minor Aβ species in normal brains but elevated upon the application of inhibitors of Aβ processing enzymes. They are interesting from the point of view of coordination chemistry for the presence of an Arg-His metal binding sequence at their N-terminus capable of forming a 3-nitrogen (3N) three-coordinate chelate system. Similar sequences in other bioactive peptides were shown to bind Cu(II) ions in biological systems. Therefore, we investigated Cu(II) complex formation and reactivity of a series of peptides and only slightly weaker than Aβ_{1-42} complexes could be achieved in Aβ_{1-39} and Aβ_{1-40} by adding appropriate amounts of the external imidazole ligand. The 3N Cu-Aβ_{1-39} complexes could be irreversibly reduced to Cu(I) at about −0.6 V vs Ag/AgCl and oxidized to Cu(III) at about 1.2 V vs Ag/AgCl. The internal or external imidazole coordination to the 3N core resulted in a slight destabilization of the Cu(I) state and stabilization of the Cu(III) state. Taken together these results indicate that Aβ_{1-39} peptides, which bind Cu(II) ions much more strongly than Aβ_{1-42} peptides and only slightly weaker than Aβ_{1-40} peptides could interfere with Cu(II) handling by these peptides, adding to copper dyshomeostasis in Alzheimer brains.

**INTRODUCTION**

Alzheimer’s disease (AD) accounts for approximately 50–70% cases of dementia, over 50 million people worldwide.1,2 Amyloid-β (Aβ) peptides are at the center of AD pathology. They compose amyloid plaques, a historic hallmark of the disease, and were more recently demonstrated to form neurotoxic oligomers.3,4 Aβ peptides are derived from the amyloid precursor protein (APP), which undergoes alternative proteolytic cleavage pathways in amyloidogenic and non-amyloidogenic processes. In the amyloidogenic pathway APP is cleaved by β-secretase (BACE1), a membrane-anchored aspartyl protease which cleaves APP before position 1 of the Aβ domain, and γ-secretase, a membrane-bound protease complex responsible for creation of the Aβ C-terminus.5-7 The Aβ_{1-40} and Aβ_{1-42} peptides formed in this pathway are further processed hydrolytically to N-terminally truncated species, which represent more than 60% of all Aβ species in AD brains. Aβ_{1-42} is the most abundant of these peptides.5-9 Another is Aβ_{1-40}, detected in Aβ deposits in brains of sporadic and familial AD victims and in transgenic mouse models.5-11 The origin of Aβ_{5-x} species (x = 38, 40, 42) is unclear. They were shown to be elevated in the course of application of inhibitors of BACE1 in experimental animals.5,12 This suggests direct alternative cleavage of APP, becoming possible when the main pathway is inhibited. They can also be produced by caspases, largely cellular apoptotic proteases implicated in AD neurodegeneration.13 Aβ_{5-x} peptides contain His in the second position (Xaa-His). Such Xaa-His arrangement creates a specific Cu(II) binding site distinct from both the dynamic ensemble of macrochelate species of Aβ_{1-39} peptides14,15 and the rigid ATCUN/NTS chelate system of Aβ_{1-39} peptides.16,18 The basic structure of Xaa-His-Zaa cupric complexes, derived from X-ray studies of Gly-His-Lys (GHK) and spectroscopic studies of many oligopeptides bearing various Xaa substitutions is three-coordinate, with the Xaa N-terminus, the Xaa-His peptide bond, and the His imidazole providing three nitrogen ligands arranged in a square-planar fashion around the Cu(II) ion (3N species). The fourth position can be occupied by a...
water molecule or other ligands, such as imidazoles or carboxylates from other peptide molecules, phosphate ions, etc.10–12 The amino acid residue directly following His (Zaa in Xaa-His-Zaa... sequences) cannot participate in the coordination for sterical reasons. The stability constants available in the literature indicate that the effective stability constants of Cu(II) complexes of Xaa-His-Zaa peptides are in the range of 1012–1013 M−1, slightly less than those of ATCUN/NTS motifs.18,21–23 We demonstrated, however, that at a sufficiently high concentration of the ternary ligand the effective stability constants of such a ternary XHZ-Cu(II)-L complex may be elevated by one or two orders of magnitude.20

In this work, we aimed to characterize Cu(II) coordination and electrochemical properties of resulting complexes, Aβ5−x peptides, by using Aβ5−16 as a suitable well-soluble model, analogously to Aβ1−16 and Aβ4−16 model peptides.15,16 Because of the presence of two metal binding regions in this peptide, one at the N-terminus and another at the His13-His14 couple, we also used shorter peptides, Aβ5−9 and Aβ5−12 as simplified models. For a better understanding of the role of Tyr10 in the studied processes, we also used a modified Aβ5−12Y10F (Aβ5−12F) peptide in some experiments (see Scheme 1 for sequences). Spectroscopic (UV-vis, CD, fluorescence) and potentiometric experiments were used to decipher and quantify the set of complex species formed in a broad pH range, while their redox properties were investigated using voltammetry (CV and DPV). Then, spectroscopic and reactivity of studied complexes. The obtained quantitative constants of such a ternary XHZ-Cu(II)-L complex may be elevated by one or 2 orders of magnitude.20

| Scheme 1. Sequences of Aβ5−x Peptides Studied in This Work* |
|---------------------------------------------------------------|
| Aβ5−9  | RHDSG−NH₂         |
| Aβ5−12 | RHDSGYEV−NH₂      |
| Aβ5−12F | RHDSGEFYEV−NH₂    |
| Aβ5−16 | RHDSGYEVHQQK−NH₂ |

“Residues whose side chains contribute to Cu(II) binding are highlighted in red (His) and blue (Tyr)."

**Experimental Methods**

**Materials.** N-α-9-Fluorenylmethoxycarbonyl (Fmoc) amino acids were purchased from Novabiochem. Triﬂuoroacetic acid (TFA), piperidine, and N,N,N′,N′-tetramethyl-O-(1H-benzotriazol-1-yl)uronium hexafluorophosphate (HTBU) were obtained from Merck. Triisopropylsilane (TIS), N,N-diisopropylethylamine (DIEA), 4-(2-hydroxyethyl)piperazine-1-ethanesulfonic acid (HEPES), CuCl₂, Cu(NO₃)₂·H₂O, NaOH, KOH, HCl, KNO₃, HNO₃, and imidazole were Sigma. The Tentagel S RAM resin was purchased from RAPP Polymere. Diethyl ether and dichlormethane (DCM) were from Chempuch. Acetonitrile and calibrated 0.1 M NaOH solution for potentiometry were from POCH, and dimethylformamide (DMF) was from Roth.

**Peptide Synthesis.** Aβ5−16 (RHDSGYEVHQQK−NH₂), Aβ5−12 (RHDSGYEV−NH₂), Aβ5−9 (RHDSG−NH₂) and Aβ5−12F (RHDSGEFYEV−NH₂) were synthesized by solid-phase peptide synthesis using a CEM Liberty microwave peptide synthesizer (Applied Biosystems) according to a Fmoc/tBu protocol with HTBU and DIEA as coupling reagents and 20% piperidine in DMF as a Fmoc removal agent.24 Tentagel S RAM resin was used as a solid phase. The peptides were cleaved from the resin in TFA/TIS/water (95:2.5:2.5 v/v/v) for 2 h. Then, the peptides were precipitated with cold diethyl ether, centrifugated, dissolved in water, and lyophilized. The crude peptides were purified by HPLC (Waters) following a detection at 220 nm/280 nm using a mix of eluting solvents A (0.1% (v/v) TFA in water) and B (0.1% (v/v) TFA in 90% (v/v) acetonitrile). The purification method was a gradient of eluents S–45% of B within 40 min, flow 2 mL/min. The mass of the pure peptides was further verified by ESI-MS. The concentrations of initial peptide stock solutions were determined by potentiometric titrations. Concentrations of secondary and subsequent stock solutions of Aβ5−12 and Aβ5−16 were determined using an extinction coefficient ε of 1375 M−1·cm−1 at 275 nm. For Aβ5−9 and Aβ5−10 ε values of 200 M−1·cm−1 at 258 nm and ε of 9032 M−1·cm−1 at 214 nm were used.25

**UV–vis, CD, and Fluorescence Spectroscopy.** The UV–vis spectra were obtained on a PerkinElmer spectrophotometer over the spectral range of 200–900 nm. The circular dichroism (CD) spectra were recorded over the range of 250–800 nm on a Jasco 815 spectropolarimeter. All spectroscopic measurements were performed at 25 °C in a 1 cm path length quartz cuvette.

**Potentiometry.** Samples containing 1 mM Aβ (Aβ5−9, Aβ5−12, Aβ5−16), or 0.9 mM Cu(II) or 1 mM Aβ (Aβ5−9, Aβ5−12, Aβ5−16) and 1.8 mM Cu(II) were titrated with a small portion of concentrated NaOH in the pH range 2.5–10.

**Kinetic Experiment.** Aβ5−9 was added to the sample containing 0.9 mM Cu(II) and 1 mM Aβ5−9 in 20 mM HEPES pH 7.4 to the final Aβ5−9 concentration of 1 mM. The changes in UV–vis spectra were monitored for 24 h.

Fluorescence spectra were registered using a Cary Eclipse spectrophotometer (Varian) with the excitation wavelength of 275 nm and detection of emission in the range of 280–400 nm. All fluorescence measurements were performed at 25 °C in a 1 cm path length quartz cuvette. The samples of 20 μM Aβ5−12 or 20 μM Aβ5−12/19 μM CuCl₂ were titrated with NaOH from pH 4.2 to 12.2.

The pK values were calculated using Hill equations eq 1 and eq 2:

(i) for a single process

\[ F = \frac{P_f + P_i \times 10^{(pH-pK_f)}}{1 + 10^{(pH-pK_f)}} \]  

(ii) for a two-step process

\[ F = \frac{P_f + P_i \times 10^{(pH-pK_1)}}{1 + 10^{(pH-pK_1)}} \times \frac{P_i \times 10^{(pH-pK_2)}}{1 + 10^{(pH-pK_2)}} \]
were performed separately to determine the protonation and Cu(II) stability constants of the studied compounds. 

**Voltammetry.** The electrochemical experiments were done in a three-electrode arrangement with Ag/AgCl as the reference, platinum wire as the counter, and glassy carbon electrode (GCE, BASi, 3 mm diameter) as the working electrode. The reference electrode was separated from the working solution by an electrolytic bridge filled with 4 mM HNO₃/96 mM KNO₃ solution. The GC electrode was sequentially mechanically polished with 1.0 and 0.3 μm alumina powder on a Buckler polishing cloth to a mirror-like surface. In order to remove the remaining powder, the electrode was sonicated for 1 min in deionized water. All electrochemical measurements were carried out in 96 mM KNO₃ solutions containing 4 mM HNO₃ solution at pH 7.4. The pH was adjusted by adding small volumes of concentrated KOH or HNO₃ solutions; the concentrations of peptides were 0.5 mM and the ligand-to-Cu(II) ratio was 1:0.8 in all cases (a small Cu(II) deficiency was applied to avoid the interference from uncomplexed Cu(II) cations). In ternary complex investigations imidazole was added to the Cu(II)–peptide complex up to 10 mM concentration. The pH was closely controlled before, during, and at the end of each voltammetric measurement. Oxygen was removed from the sample solution by passing argon for 5–10 min before all measurements, and an argon blanket was maintained over the solution during the experiments carried out at 25 °C.

Cyclic (CV) and differential pulse voltammetry (DPV) experiments were performed using the CHI 1030 potentiostat (CH Instrument, Austin, USA). For all presented CV curves, the scan rate (v) was 100 mV/s. The following parameters were used in DPV: pulse amplitude 50 mV, pulse time 100 ms.

### RESULTS AND DISCUSSION

**ΔpK₅₋₉ Complexes.** We first performed a set of pH-metric titrations of the studied peptides in the absence and presence of Cu(II) ions. The protonation constants calculated from these experiments are presented in Table 1. The assignments of proton exchanging groups mainly contributing to given protonation constants are based on previous studies of analogous peptides.⁶,¹⁶,²⁹,³⁰ The pK₅ values are typical for the respective groups and sufficiently well separated to make these assignments unambiguous.³¹

The potentiometric titrations performed at various Cu(II)/peptide ratios for ΔpK₅₋₉ indicated the formation of complexes having solely a 1:1 copper-to-peptide stoichiometry and differing by the number of bound/released hydrogen ions (Table 2). The CD and UV–vis spectra of Cu(II)–ΔpK₅₋₉ complexes are presented in Figures 1 and S1, respectively.

**Figure 2** demonstrates the potentiometric species distribution compared to parameters derived from these spectra. The quantitative agreement of these results allowed us to calculate the spectroscopic parameters for individual complexes, as given in Table 3. The first complex formed is a 3N species with fi⁹ indicated the formation of complexes with the fourth equatorial site occupied by a water molecule. It

### Table 1. Protonation Constants (log βᵢ and pK₅ Values) of ΔpK₅₋₉, ΔpK₅₋₁₂, and ΔpK₅₋₁₆ (L) at I = 0.1 M (KNO₃), Determined by Potentiometry at 25 °C

| Species  | Log βᵢ | pK₅ | Assignment            | Coordination Mode |
|----------|--------|-----|----------------------|-------------------|
| ΔpK₅₋₉  |        |     |                      |                   |
| HL       | 7.37(1)| 7.37| Arg5 N-term.         |                   |
| H₂L      | 13.51(1)| 6.13| His6                 |                   |
| H₁₆L     | 16.67(1)| 3.17| Asp7                 |                   |
| ΔpK₅₋₁₂ |        |     |                      |                   |
| HL       | 10.08(1)| 10.08| Tyr10                |                   |
| H₂L      | 17.60(1)| 7.52| Arg5 N-term.         |                   |
| H₁₆L     | 23.84(1)| 6.25| His6                 |                   |
| H₁₄L     | 28.21(1)| 4.37| Gla11                |                   |
| H₁₃L     | 30.94(1)| 2.73| Asp7                 |                   |
| ΔpK₅₋₁₆ |        |     |                      |                   |
| HL       | 10.39(1)| 10.39| Tyr10/Lys16          |                   |
| H₂L      | 20.35(1)| 9.96| Tyr10/Lys16          |                   |
| H₁₆L     | 27.94(1)| 7.60| Arg5 N-term.         |                   |
| H₁₄L     | 34.61(1)| 6.67| His6/13/14           |                   |
| H₁₂L     | 40.92(1)| 6.31| Glu11                |                   |
| H₁₀L     | 46.43(1)| 5.50| Glu11                |                   |
| H₈L      | 50.35(1)| 3.92| Glu11                |                   |
| H₆L      | 52.83(1)| 2.48| Asp7                 |                   |

**Table 2. Stability Constants (log βᵢ and pK₅ Values) of Cu(II) Complexes of ΔpK₅₋₉, ΔpK₅₋₁₂, and ΔpK₅₋₁₆ (L) at I = 0.1 M (KNO₃), Determined by Potentiometry at 25 °C⁶

| Species  | Log βᵢ | pK₅ | Assignment            | Coordination Mode |
|----------|--------|-----|----------------------|-------------------|
| ΔpK₅₋₉  |        |     |                      |                   |
| CuL      | 9.48(1)|     | Asp7                 | 3N+H₂O            |
| CuH₁₆L   | 5.66(1)| 3.82| Tyr10/Lys16          | 3N+OH⁻            |
| CuH₁₃L   | 3.69(1)| 9.35| Equatorial H₂O       | 3N+OH⁻            |
| Total 3N | 2L     |     |                      |                   |
| +H₂O     |        | 3.61|                      |                   |
| ΔpK₅₋₁₂ |        |     |                      |                   |
| CuH₁₆L   | 23.72(3)|     | Asp7                 | 3N+H₂O            |
| CuH₁₃L   | 20.44(1)| 3.23| Tyr10/Lys16          | 3N+OH⁻            |
| CuL      | 15.76(1)| 4.69| Gla11                | 3N+H₂O            |
| CuH₁₃L   | 6.29(2)| 9.47| Tyr10/H₂O            | 3N+Tyr10 and 3N+OH⁻ |
| CuH₁₆L   | −3.76(2)| 10.05| H₂O/Tyr10            | 3N+OH⁻            |
| Total 3N | 2L     |     |                      |                   |
| +H₂O     |        | 3.66|                      |                   |
| ΔpK₅₋₁₆ |        |     |                      |                   |
| CuH₁₆L   | 46.00(2)|     | Asp7                 | 3N+H₂O            |
| CuH₁₃L   | 42.79(1)| 3.212| Tyr10/Lys16          | 3N+OH⁻            |
| CuL      | 38.62(1)| 4.169| Gla11                | 3N+H₂O            |
| CuH₁₃L   | 33.46(1)| 5.159| His13/14             | 3N+N              |
| CuHL     | 26.11(2)| 7.35| His13/14             | 3N+N              |
| CuL      | 16.43(3)| 9.68| Equatorial H₂O/     | 3N+3N/3N+OH⁻      |
|          |        |     | Tyr10/Lys16          |                   |
| CuH₁₆L   | 6.56(3)| 9.87|                      |                   |
| CuH₁₃L   | −3.38(2)| 9.94|                      |                   |
| CuL      | 31.50(1)|     |                      |                   |
| CuH₁₆L   | 25.37(1)| 6.134| His13/14 N⁻         | 3N+H₂O+2N         |
| CuH₁₃L   | 19.08(1)| 6.29|                      | 3N+H₂O+3N         |
| CuH₁₃L   | 10.15(1)| 8.93| Vál12/Gla11 N⁻      | 3N+H₂O+4N        |
| CuH₁₃L   | 1.05(1)| 9.1| Equatorial H₂O      | 3N+OH⁻+4N        |
| CuH₁₃L   | −9.4(1)| 10.45| Lys16/Tyr10         | 3N+OH⁻+4N        |
| CuH₁₆L   | −19.94(9)| 10.54|                    | 3N+OH⁻+4N        |
| Total 3N | 2L     |     |                      |                   |
| +H₂O     |        | 3.62|                      |                   |

βᵢ(CuHₓLᵧ) = [MₓHₙLᵦ]([L]⁻[H⁺]ⁿ). Standard deviations on the last digits provided by HYPERQUAD,²⁸ given in parentheses, represent statistical errors of constant determinations. Assignments are based on literature values.²⁹,³¹ Coordination modes are derived from the analysis presented below.
The additional split in the Table 3). These changes are due to the deprotonation of the band maximum, the change of its symmetry in CD, and Asp7 pKₐ.

It is not surprising, as the coordination of the Asp7 carboxylate does not affect the spectroscopic parameters (Tables 2 and 3). This event, recorded by potentiometry with the pKₐ of 3.82, does not affect the spectroscopic parameters (Tables 2 and 3). It is not surprising, as the coordination of the Asp7 carboxylate to the Cu(II) ion bound in the 3N core provided by Arg5 and His6 is excluded by the complete geometry. The elevation of Asp7 pKₐ by 0.65 pH units can be explained by lowering the overall molecular charge by Cu(II) coordination by one, compared to the unbound peptide.

The next recorded deprotonation occurred with the pKₐ of 9.35 and was associated by a significant blue shift of the d→d band maximum, the change of its symmetry in CD, and concomitant alterations in charge transfer bands (Figure 1, Table 3). These changes are due to the deprotonation of the coordinated water molecule.²⁰,²¹ The additional split in the d→d band, not observed in titrations of WHWSKNR-NH₂ and GHTD-NH₂ complexes,²⁰,²¹ is indicative of an additional interaction involving the coordinated hydroxyl anion, most likely with the cationic Arg side chain.

At still higher pH above 10 a further set of changes appeared in the CD spectra, with a characteristic strong negative feature at 500 nm. According to the literature, they are due to the replacement of the hydroxyl group by the deprotonated N of the imidazole ring, possibly resulting in imidazole-bridged oligomers.²¹,³²,³³

The potentiometric titrations did not provide evidence for the presence of a CuL-type complex. Such complexes were reported previously for simpler XHZ peptides by potentiometry, but with little support by independent direct techniques.

| Complex | Mode (species) | UV–vis | CD |
|---------|----------------|--------|-----|
| Cu(II)-| 3N+H₂O (CuL+CuH₅L) | 600 (47)²⁷ | 650 (0.17)²⁷ |
| Aβ₅₋₉ | 3N+OH⁻ (CuH₇L) | 555 (63)²⁷ | 546 (0.61)²⁷ |
| Cu(II)-| 3N+H₂O (CuH₇L+CuHL+CuL) | 600 (60)²⁷ | 650 (0.17)²⁷ |
| Aβ₅₋₁₂ | 3N/Tyr10 and 3N+OH⁻ (CuH₇L) | 548 (0.29)²⁷ | 470 (0.09)²⁷ |
| Cu(II)-| 3N+H₂O | 600 (60)²⁷ | 650 (0.17)²⁷ |
| Aβ₅₋₁₂ | 3N+OH⁻ (CuL+CuH-1L−) | 513 (0.05)²⁷ | 301 (0.39)²⁷ |
| Cu(II)-| 3N+H₂O | 605 (0.16)²⁷ | 553 (0.44)²⁷ |
| Aβ₅₋₁₆ | 3N+H₂O (CuH₇L+CuH₅L) | 506 (0.05)²⁷ | 470 (0.09)²⁷ |
| Cu(II)-| 3N+H₂O | 605 (0.16)²⁷ | 553 (0.44)²⁷ |
| Aβ₅₋₁₆ | 3N+H₂O (CuH₇L+CuH₅L) | 506 (0.05)²⁷ | 470 (0.09)²⁷ |
| Cu(II)-| 3N+H₂O | 605 (0.16)²⁷ | 553 (0.44)²⁷ |

Twice deprotonation. N<sup>α</sup>→Cu<sup>II</sup> charge transfer (CT). N<sup>α</sup>→Cu<sup>II</sup> CT. Tyr O→Cu<sup>II</sup> CT.

No such complex was detected for WHWSKNR-NH₂. It was also invisible for potentiometry in the study of GHTD-NH₂ complexes, due to insufficient stability at submillimolar peptide concentrations, but a spectroscopic titration with the peptide excess demonstrated its existence at pH 7.4.²¹ Here we used the same approach to detect it, as shown in Figure 3. The associated spectral changes were very similar to those observed for GHTD-NH₂, indicating the formation of a 3 + 1N complex, with the water molecule replaced by an imidazole nitrogen of the second peptide molecule. The conditional stability constant derived from this titration is provided in Table 4, and the spectral parameters of
CuH2L stoichiometry, but the same 3N coordination as the respective protonation events to individual groups, as provided with the data for Aβ5−9. The characteristic pKα sequence by residues 10−12, Tyr10 and Glu11 in Aβ5−12. Their characteristic pKα values about 10 and 4, respectively, together with the data for Aβ5−9, allowed us to directly assign the respective protonation events to individual groups, as provided in Table 1 and presented in Figure 4.

Accordingly, the lowest-pH complex of Aβ5−12 has the CuHL stoichiometry, but the same 3N coordination as the CuL complex of Aβ5−9, as seen in CD and UV−vis spectra, presented in Figures 5A and S2, respectively. The next two deprotonations under pH 5 did not affect the spectra and can be assigned to Asp7 and Glu11 carboxyl deprotonations. The spectra became more complicated above pH 8, where two overlapping deprotonations took place. In order to facilitate the analysis, we performed spectroscopic titrations of Cu(II)-Aβ5−12, the analog having Tyr replaced with Phe. The respective CD and UV−vis results are presented in Figures S5B and S3.

The pKα values for the 3N complex formation obtained from CD titrations were 3.77(1) and 3.51(2) for the formation of 3N complexes of Aβ5−12 and Aβ5−12F, respectively. The former value is in a good agreement with the potentiometry-derived value of 3.66. Based on the characteristic CT band at 400 nm, contrasted with Cu(II)-Aβ5−12F in the pH range 7−10 (Figure 6A) and CD titrations monitored at 370−380 nm (Figure 6B),

Table 5. Spectroscopic Parameters of Ternary Complexes of Cu(II)-Aβ5−x with Imidazole (Im) or Aβ5−x at 25 °C

| Ternary complex | Mode         | UV−vis    | CD           |
|-----------------|--------------|-----------|--------------|
|                 |              | λmax/nm   | (Δε/M0) cm−1|              |
| Cu(II)-Aβ5−9+   | 3N+NIm(5−9)  | 566 (79)  | 560 (+0.20)  |
| Aβ5−9           |              |           | 478 (−0.08)  |
|                 |              |           | 335 (+0.15)  |
|                 |              |           | 300 (−0.37)  |
|                 |              |           | 267 (+0.51)  |
| Cu(II)-Aβ5−16+  | 3N+NIm(1−16) | 575 (76)  | 564 (+0.22)  |
| Aβ5−16          |              |           | 482 (−0.07)  |
|                 |              |           | 337 (+0.17)  |
|                 |              |           | 298 (−0.37)  |
| Cu(II)-Aβ5−9+   | 3N+NIm      | 566 (75)  | 645 (−0.11)  |
| Im              |              |           | 551 (+0.17)  |
|                 |              |           | 478 (−0.08)  |
|                 |              |           | 332 (+0.11)  |
|                 |              |           | 296 (−0.35)  |
| Cu(II)-Aβ5−12+  | 3N+NIm      | 562 (81)  | 644 (−0.11)  |
| Im              |              |           | 550 (+0.17)  |
|                 |              |           | 478 (−0.11)  |
|                 |              |           | 333 (+0.13)  |
|                 |              |           | 297 (−0.40)  |
| Cu(II)-Aβ5−16+  | 3N+NIm      | 564 (70)  | 645 (−0.08)  |
| Im              |              |           | 553 (+0.19)  |
|                 |              |           | 478 (−0.06)  |
|                 |              |           | 330 (+0.12)  |
|                 |              |           | 297 (−0.35)  |

Table 4. Conditional Stability Constants (M−1) for Binary (K5−4) and Ternary (K5−4) for Cu(II) Complexes of Aβ5−x Peptides at pH 7.4

| Peptide         | K5−4       | K5−4       |         |
|-----------------|------------|------------|---------|
| Aβ5−9           | 5.75 × 1012| 870 ± 69   | 283 ± 50| 5200 ± 200|
| Aβ5−12          | 5.13 × 1012| 557 ± 36   | n.a.    | n.a.     |
| Aβ5−16          | 9.55 × 1012| 98 ± 27    | n.a.    | n.a.     |

K5−4 values were calculated from potentiometric data using the CI approach. Competitivity index (CI) was calculated for Cu(II), peptide, and ligand (Z) concentrations of 0.001 M. CI is the value of log KZCu such as the condition ∑αi([Cu(Li)]) = [CuZ] is fulfilled, where Z is a theoretical competitor. Aβ5−9 was calculated directly from spectroscopic titrations using eq 1.

Aβ5−12 and Aβ5−12F Complexes. The extension of the sequence by residues 10−12, YEV, added two proton-exchanging side chains, Tyr10 and Glu11 in Aβ5−12. Their characteristic pKα values about 10 and 4, respectively, together with the data for Aβ5−9, allowed us to directly assign the respective protonation events to individual groups, as provided in Table 1 and presented in Figure 4.

Figure 3. Top: the titration of 0.8 mM Cu(II) and 1.0 mM Aβ5−9 at 25 °C and pH 7.4 with the excess of Aβ5−9, up to 15 mM, monitored by CD. Arrows mark the direction of changes. Bottom: the fit of the conditional stability constant of the CuL complex at spectral areas of maximum change: 635 nm (gray), 535 nm (green), and 315 nm (orange).

Figure 4. Species distribution calculated for 0.9 mM Cu(II) and 1.0 mM Aβ5−12 on the basis of constants presented in Tables 1 and 2, with selected spectroscopic parameters of Aβ5−12 overlaid.
we can assign the deprotonation event about pH 9 (8.89(3) from CD, 8.95(7) from UV−vis) to deprotonation and equatorial Cu(II) coordination of Tyr10 phenolate oxygen.36,37 This band disappears gradually above pH 9.5, in accord with another deprotonation, which can thus be assigned to the replacement of Tyr O− by the solution-derived OH− group, with pK้า = 9.92(5). At very high pH an imidazole bridged species is formed as in Cu(II)-Aβ5−19.

The comparison of pK้า values for uncoordinated Tyr, 10.08, coordinated Tyr, 8.89, and deprotonated water in Cu(II)-Aβ5−12, 9.92 vs 9.3 for Cu(II)-Aβ5−9 (average of potentiometric and spectroscopy calculations) and 9.62(3) in Aβ5−12F (from spectroscopy), allowed us to estimate the ratio of Cu(II) affinities of Tyr phenolate vs the hydroxyl group at pH 9 as ca. 8.3. The physiological relevance of this interaction is limited, however, as the Cu(II) occupancy by Tyr phenolate at pH 7.4 is 3% or less, estimated from potentiometric data compared to fluorescence titrations of Aβ5−12 and Cu(II)-Aβ5−12 (Figure S4).

**Aβ5−16 Complexes.** A further C-terminal peptide sequence extension by residues 13−16, VHHQK, added three proton-exchanging side chains, compared to Aβ5−12, His13, His14, and Lys16. As a result, the separation of contributions to potentiometric macroconstants of Tyr10 and Lys16 on one hand and of His6, His13, and His14 on another was not possible, due to overlapping protonation processes. The differences between the respective pK้า values, presented in Table 1, are close to statistical values for two and three equivalent groups, 0.6 and 0.48 pH units, respectively.31 All these values remain in their typical ranges.

Due to the presence of two distinct Cu(II) binding sites in Aβ5−16, the spectroscopic and potentiometric experiments were performed at the 1.8:1 Cu(II):peptide ratio, in addition to the 0.9:1 ratio used for shorter analogs. The CD titration for the 0.9:1 ratio is presented in Figure 7, the UV−vis titration in Figure S5, and the species distribution plots in Figure 8. The respective data for the 1.8:1 ratio are presented in Figures S6, S7, and S8.

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**Figure 5.** CD spectra recorded at 25 °C for 0.9 mM Cu(II) and 1.0 mM Aβ5−12 (A) or 0.9 mM Cu(II) and 1.0 mM Aβ5−12F (B) at pH values color coded on the graphs.

**Figure 6.** (A) Comparison of UV−vis spectra of Cu(II) complexes of spectra recorded at 25 °C for 0.9 mM Cu(II) and 1.0 mM Aβ5−12F (solid lines) or Aβ5−12 (dotted lines) at pH values indicated on the graph. (B) pH dependence of CD signals at 370−380 nm (red circles) or 635−655 nm (black squares) derived from CD spectra shown in Figure 5 for 0.9 mM Cu(II) and 1.0 mM Aβ5−12F (full symbols) or Aβ5−12 (open symbols).

**Figure 7.** PH dependence of CD spectra recorded at 25 °C for 0.9 mM Cu(II) and 1.0 mM Aβ5−16, at pH values color coded on the graph.

**Figure 8.** Species distribution calculated for 0.9 mM Cu(II) and 1.0 mM Aβ5−16 on the basis of constants presented in Tables 1 and 2, with selected spectroscopic parameters of Aβ5−16 overlaid.

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At the 0.9:1 ratio the CuH$_2$L and CuHL and CuHL complexes present at low pH correspond to the 3N complex. Its spectroscopic parameters with d–d bands at 600 nm at the UV–vis spectrum as well as at 506 and 605 nm at the CD spectrum are very similar to those observed for the 3N complexes of $\alpha$-$\beta_{5-9}$ and $\alpha$-$\beta_{5-12}$. The pK$_a$ values of formation of this complex calculated from spectroscopic and potentiometric data is 3.4–3.6. This spectroscopic species is superseded with another, comprising the CuH$_2$L and CuHL stoichiometries, which exhibited a 35 nm blue shift of the d–d band in the UV–vis spectra and significant changes in the CD pattern (see Table 3, Figure 7, and Figure S5). The pK$_a$ of this process derived from spectroscopy is 5.55. The only residues that can release a proton in this pH range are His13 and His14. These residues are essentially equivalent in the apopeptide, but their pK$_a$ values in the complex are 5.16 and 7.35. These features clearly indicate that His13 or His14 replaces the water molecule in the fourth equatorial coordination site. This observation is further supported by the lack of Tyr phenolate coordination (the absence of a 400 nm band) above pH 8 in Cu(II)-$\beta_{5-9}$-$\beta_{12}$ complexes. As a result the Cu(II)-independent Tyr10 and Lys16 deprotonations occur at pH 9.5–10, along with the third proton release, which must originate from the replacement of $\text{N}^{\text{Im}}$ by $\text{OH}^−$ in the fourth site. This replacement induces a small change in CD spectra as shown in Figure 8, indicating that the pK$_a$ for this process is ca. 9.65, about 0.3 log units higher than in Cu(II)-$\beta_{5-9}$. As for all other $\alpha$-$\beta_{5-9}$ peptides a major spectral change above pH 11 was noted, tentatively assigned to the formation of the imidazole bridged tetramer. The protonic equivalence of His13 and His14 and their similar distancing to the N-terminally coordinated Cu(II) ion suggests that the 3 + 1N complex is actually a mixture of His13 and His14 coordinated species, perhaps with a slight distance-wise preference for His13.

The experiments performed at the Cu(II) excess indicate that the 3N complex is formed in a fashion similar to that at the 1:1 ratio, but it is followed by the additive formation of a novel spectral band (∼579 nm) with the pK$_a$ of 5.90. This complex is analogous to that observed before for Cu(II)-$\alpha$-$\beta_{5-12}$ and corresponds to an independent formation of the second Cu(II) ion at the His13 and His14 residues. As expected, the binding of the second Cu(II) ion at His13/His14 prevented the entry of His13/His14 $\text{N}^{\text{Im}}$ to the coordination sphere of the N-terminal 3N complex.

**Ternary Complexes.** To further investigate the role of the fourth equatorial site in Cu(II) coordination of $\alpha$-$\beta_{5-9}$ peptides, we performed CD titrations of Cu(II)-$\alpha$-$\beta_{5-9}$/CuH$_2$L and Cu(II)-$\alpha$-$\beta_{5-12}$/CuH$_2$L complexes with imidazole (Im). The respective CD spectra and titration curves are provided in Figure 9.

The addition of Im resulted in a blue-shift of d–d bands of Cu(II)-$\alpha$-$\beta_{5-9}$/CuH$_2$L from 600 to 550 nm as shown in Figure 9A and 9B, respectively. These changes were accompanied by a 10 nm blue-shift and an increase of intensity of CT bands at 340 and 300 nm. No changes in the d–d bands and only a slight effect in CT signals were noticed during the analogous titration of Cu(II)-$\beta_{5-12}$ (see Figure 9C), even at the final 250-fold excess of Im over Cu(II).

The effects seen for Cu(II)-$\alpha$-$\beta_{5-9}$/CuH$_2$L complexes were analogous to those seen previously for Im titrations of all Xaa-His peptides studied by us recently, including WHWSKNR-NH$_2$, GHTD-NH$_2$, and GHK$^{10,21,58}$ and are consistent with the replacement of the equatorially coordinated water molecule in the3N coordination mode ($\text{N}^{\text{Im}}, \text{N}^\text{Im}, \text{N}^\text{−}$) dominant at pH 7.4, with the Im nitrogen, forming the ternary
Figure 10. CV (A–F) and DPV (G–I) curves of 0.5 mM Aβ$_{5-9}$ (A, D, G), Aβ$_{5-12}$ (B, E, H), and Aβ$_{5-16}$ (C, F, I) recorded in the absence (dashed line) or the presence of 0.40 mM Cu(II) and 5.0 mM imidazole, pH 7.4.

Table 6. Properties of Redox Processes from CV and DPV Curves of Aβ$_{5-x}$ Binary and Ternary Complexes$^4$

| Complex | Cu(II)/Cu(I) | Cu(II)/Cu(III) |
|---------|--------------|----------------|
| $K_{T}$ | $E_{CV}^{RED}$ | $E_{CV}^{OX}$ | $E_{DPV}$ | $I_{DPV}$ (μA) | $E_{CV}^{OX}$ | $E_{DPV}$ | $I_{DPV}$ (μA) |
| Cu(II)-Aβ$_{5-9}$ | $-0.579(5)$ | $-0.025(1)$ | $-0.453(5)$ | $-1.318(4)$ | $1.297(2)$ | $1.184(4)$ | $2.77(5)$ |
| Cu(II)-Aβ$_{5-9}$Im | $-0.576(1)$ | $0.011(4)$ | $-0.492(1)$ | $-1.490(7)$ | $1.094(5)$ | $1.024(2)$ | $2.918(9)$ |
| Cu(II)-Aβ$_{5-12}$F | $-0.633(5)$ | $0.054(3)$ | $-0.540(1)$ | $-1.473(6)$ | $1.269(5)$ | $1.158(2)$ | $3.02(5)$ |
| Cu(II)-Aβ$_{5-12}$ | $-0.669(1)$ | $-0.062(2)$ | $-0.523(2)$ | $-1.037(5)$ | $1.159(2)$ | $1.018(2)$ | $0.469(5)$ |
| Cu(II)-Aβ$_{5-12}$Im | $-0.647(3)$ | $0.008(3)$ | $-0.516(1)$ | $-1.000(6)$ | $0.955(4)$ | $0.863(2)$ | $0.145(1)$ |
| Cu(II)-Aβ$_{5-16}$ | $-0.680(4)$ | $0.200(5)$ | $-0.557(2)$ | $-0.434(5)$ | $1.058(4)$ | $0.938(3)$ | $0.065(4)$ |
| Cu(II)-Aβ$_{5-16}$Im | $-0.688(2)$ | $0.093(2)$ | $-0.560(6)$ | $-0.383(7)$ | $0.973(1)$ | $0.876(6)$ | $0.052(2)$ |

$^4$E values are given in V vs Ag/AgCl.

3N+1N (N$^{im}$, N$^{imid}$, N$^+$ + N$^{im}$) complex. The same effects were observed for titrations of 3N complexes with the excess of the parent peptide for GHTD-NH$_2$ and GHK$_{21,38}$ and Aβ$_{5-9}$ in this work. The much less pronounced response of Cu(II)-Aβ$_{5-12}$ compared to Cu(II)-Aβ$_{5-16}$ to Im can be readily explained by the intramolecular 3 + 1N coordination in this complex, employing His$_{13}$/His$_{14}$ residues. Nevertheless, a slight change of intensity of the CT band at 304 nm, along with the absence of changes in $d-d$ bands can be ascribed to the forced replacement of the intramolecular ligand by external Im. The conditional stability constants ($K_{T}$) for Im binding to Cu(II)-Aβ$_{5-x}$ complexes were obtained by global fitting of multiple titration curves according to eq 3:

$$K_{T} = \frac{[CuL(Im)]}{[CuL][Im]}$$

where L is the Aβ$_{5-x}$ peptide from the initial binary Cu(II) complex.

The $K_{T}$ values are provided in Table 4. The strongest ternary complex was formed for Cu(II)-Aβ$_{5-9}$ followed by Cu(II)-Aβ$_{5-12}$. The lower $K_{T}$ for the latter could be caused by steric hindrance from additional residues in the Aβ$_{5-12}$ sequence. Such effect is evident in the 3-fold lower $K_{T}$ for the second Aβ$_{5-9}$ molecule, compared to Im. A further 5-fold lowering of $K_{T}$ for Cu(II)-Aβ$_{5-16}$ compared to Cu(II)-Aβ$_{5-12}$ is apparently a combination of additional hindrance and the competition from the intramolecular His$_{13}$/His$_{14}$ binding. The comparison of $K$ values presented in Table 4 indicates that this interaction increases the overall Cu(II) affinity of Aβ$_{5-16}$ by 1.8 times. This value is in excellent agreement with that derived from the 0.33 pH units shift of OH$^-$ coordination (Aβ$_{5-9}$ vs Aβ$_{5-16}$, 2.1 times). Therefore, the lowering of Im affinity to Cu(II)-Aβ$_{5-16}$ is a combination of competition between Im and His$_{13}$/His$_{14}$ and the increased hampering of Im access to the Cu(II) binding site.

Additionally, we performed a titration of Cu(II)-Aβ$_{5-9}$ with Aβ$_{1-16}$ (SI, Figure S9). Partial precipitation of the ternary complex limited the accuracy of the $K_{T}$ determination, which was estimated as 5200 M$^{-1}$ (Table 4). This high stability compared to other ternary complexes of Cu(II)-Aβ$_{5-x}$ can be attributed in part to the presence of three His imidazole ligands in Aβ$_{1-16}$ available for the binding, and in part to intermolecular interactions between the Cu(II)-Aβ$_{5-9}$ pep-
tides. We also attempted the study of the Cu(II)-Aβx−16 + Aβ16 system, but it was precluded by poor solubility of the ternary complex and the apparently weak interaction.

**Voltammetry.** For further characterization of Aβx−8 peptides, their binary Cu(II) complexes, and ternary complexes with Im, we performed a series of electrochemical experiments using cyclic voltammetry (CV) and differential pulse voltammetry (DPV). The CV results for Aβx−9, Aβx−12, and Aβx−16 are presented in Figure 10, with auxiliary CV results for Aβ5−12F provided in Figure S10. All apo-peptides were electrochemically inactive in the studied range of potentials (initially scanning from 0.5 V toward the negative direction, Figure 10A—C, black, blue, green, dashed lines; gray dashed line in Figure S10A), except for broad peaks observed at 0.6−0.9 V for Aβx−12 and Aβx−16 (Figure 10E—F, H—I, blue and green dashed lines) assigned to the Tyr10 phenol ring oxidation to a thermodynamically unstable tyrosyl radical subsequently converted into orthoquinone.40−42 Aβx−9 and Aβ5−12F were redox silent in this range, as expected (Figure 10D, G; Figure S10B).

The 3N Cu(II)-Aβx−x complexes yielded irreversible reduction peaks in voltammograms recorded from +0.5 V to −0.8 V (Figure 10A—C, Figure S11, black, blue, and green solid lines and Figure S10A, gray solid line, see Table 6 for CV and DPV-derived potentials). A significant separation between the cathodic and anodic peaks suggests a slow electron transfer and/or a reorganization of the complex structure upon Cu(II) reduction. This can be explained by the incompatibility of the planar 3N chelate of Aβx−x peptides with geometrical preferences of Cu(I) ions, as pointed out previously by Hureau et al. in their Cu(II)-GHK study.19 The cathodic peak of Cu(II)-Aβx−16 had an altered shape, appeared at the most negative potential, and had the lowest peak current (Figure 10C green solid line, Table 6). These effects are compatible with the formation of the 3 + 1N coordination structure supplanted by the His-13/His-14 imidazole nitrogen.

The Cu(II)-Aβx−x complexes can generate a Cu(II)/Cu(III) redox couple at potentials around 1 V and higher (Figure 10D—I (black, blue, and green solid lines) and Figure S10B (solid gray line)). For binary Cu(II)-Aβx−x complexes with Tyr-containing peptides, the Cu(II)/Cu(III) redox signal was preceded by Tyr10 oxidation peaks of decreased intensity and shifted to more positive potentials relative to apopeptides, in agreement with the literature.41 The lack of Cu(III)/Cu(II) reduction peaks in the studied complexes may be attributed to the catalytic oxidation of peptide ligands via the electro-generated (highly oxidizing) Cu(III) species according to an EC (electrochemical-chemical) mechanism. In addition to the Tyr phenolic ring, His imidazoles in Cu(II)-Aβx−16 can also be oxidized by Cu(III) at such potentials, (E° ≈ 1.25 V for l-His89 and ~1.0 V for His in Aβ/2/Aβ1647). The use of faster scan rates (0.5−5 V/s) did not improve the reversibility of the studied process (data not shown). The EC mechanism explains the irreversibility of these Cu(II)/Cu(III) couples, in contrast to the reversible Cu(II)/Cu(III) process in Aβ5−8 and Aβ5−10F complexes.44 The potentials of Cu(II)/Cu(III) peaks for Aβx−x complexes appeared in the following decreasing order: Cu(II)- Aβx−16 > Cu(II)-Aβx−12 > Cu(II)-Aβ5−12F > Cu(II)-Aβ5−8 (see Table 6 for values). Additionally, the intensity of the oxidation current increased in the same sequence.

Finally, electrochemical measurements for ternary Im complexes of Cu(II)-Aβx−x were done (Figure 10A—I, gray, orange, and red solid lines). A 12.5-fold Im excess over Cu(II) excess was used to ensure full saturation of Cu(II) with Im for Cu(II)-Aβ5−9 and Cu(II)-Aβx−12 and 50% saturation for Aβ5−16 according to equilibrium titrations. No significant changes in the voltammetric signature were noticed in the range of negative potentials (Figure 10A—C, Figure S11), but according to CV and DPV curves registered in the 0.2−1.3 V potential range (Figure 10D—I), the Im addition shifted both the Cu(II)/Cu(III) and Tyr10 oxidation toward less positive potentials. This is in accord with the presence of the 3 + 1N coordination of Cu(II) in the ternary complex, which stabilizes Cu(III) better.45 The largest shifts in electrochemical responses occurred for Cu(II)-Aβx−9Im and Cu(II)-Aβx−12Im in relation to the binary complexes. In contrast, a weaker interaction between Cu(II)-Aβx−9 and imidazole due to the presence of the autoternary complex resulted in a smaller change in redox activity of this chelate. Still, the potentials of formation of Cu(III) species are probably too high to have a biological relevance.

**Cu(II) Exchange and Biological Relevance.** The stability of a complex is a key property in considering its biological relevance, as biological fluids are teeming with small molecules and proteins ready to compete for copper. Aβ peptides are essentially extracellular, and their toxicity is exerted mostly in synapses. Not much is known quantitatively about the fast-changing composition of synaptic cleft fluid. Therefore, we are forced to make educated guesses regarding Cu(II) complexation by Aβ peptides. The Aβx−x family peptides bind the Cu(II) ion with log Kx = 10.04 (x = 16) and 10.43 (x = 40).46 Much higher Cu(II) affinities were determined for Aβx−8 family peptides, log Kx = 13.53 (x = 16),46 and 14.18 (x = 9).47 The affinities of binary Cu(II)-Aβx−x peptides are closer to Cu(II)-Aβx−9, log Kx = 12.76 (x = 9), and 12.98 (x = 16). However, unlike Aβx−9, the Aβx−8 peptides can elevate their Cu(II) binding capability via ternary complexes, which is a feature shared with other Xaa-His peptides.17,20,21,37

Figure 11 presents the evolution of log Kx of ternary Im and Aβx−16 complexes of Cu(II)-Aβx−9 and Cu(II)-Aβx−16 calculated using the data presented in Tables 1, 2, and 4.

This simulation clearly shows that in the presence of a ~1 mM amount of external imidazole-bearing ligands Aβx−9 can become a stronger Cu(II) chelator than the longer Aβx−x species. Furthermore, at ca. 30 mM Im the Cu(II) binding ability of Aβx−16 equals that of Aβx−16 and that of Aβx−9.

![Figure 11. Theoretical evolution of log Kx of ternary complexes Cu(II)-Aβx−9/Im, Cu(II)-Aβx−16/Im, and Cu(II)-Aβx−9/Aβx−16 calculated using the data presented in Tables 1, 2, and 4.](https://dx.doi.org/10.1021/acs.inorgchem.0c01773)
matches Aβx−9. While the actual role of Aβx−x peptides in brain copper metabolism remains speculative, we postulate that the longer species serve to mop up the excess of Cu(II) ions from the synaptic cleft, and Aβx−9, as product of Aβk−40 cleavage by nephrilysin may participate in the export of copper across the blood–brain barrier.48,49 Aβx−x peptides are normally only very minor contributors to the overall β-amyloid pool but our results indicate that these peptides, when multiplicated as a result of therapeutic intervention, may interfere with the synaptic and extrasynaptic Cu(II) handling. The affinity of the Cu(II)-Aβx−9/Aβx−16 complex, much higher than that of imidazole, points at a possibility of strong, specific interactions with larger ligands that can be recruited from the Aβ family or other synaptic proteins. Despite the similar overall affinity, Cu(II)-Xaa-His and Cu(II)-Xaa-Zaa-His (ATCUN) complexes differ in the Cu(II) exchange kinetics, with Cu(II)-Xaa-His complexes reported as much more labile.50 They could thus interfere with proper Cu(II) delivery. In particular, Aβx−9, which most likely could be generated by nephrilysin analogously to Aβx−9, could theoretically intercept Cu(II) ions faster than the ATCUN peptides and release them off target, e.g. intracellularly, causing oxidative stress in brain cells.59

In order to directly find out how Aβx−x and Aβx−x peptides could compete for Cu(II) ions, we contacted them directly, by forming the Cu(II)-Aβx−9 complex at pH 7.4 and then contacting it with equimolar Aβx−9. The reaction was then followed for 24 h, as presented in Figure 12.

By comparing its course with the spectra presented above and with those published previously by Bossak-Ahmad et al., one can clearly see that the process of Cu(II) transfer from Aβx−9 to Aβx−16, along the gradient of affinities, is mediated by the formation of the ternary 3N+Aβ(4−9) complex. Interestingly, however, the overall process, measured at the maximum of Cu(II)-Aβx−x absorption, was very slow, taking more than 24 h to complete. Even more interestingly, the reaction had not one, but two slow steps. The first one, taking the first 2.5 h of incubation and characterized by an isosbestic point at 621 nm, was apparently the formation of the ternary complex, which then re-equilibrated into the final 4N Cu(II)-Aβx−x species with the isosbestic point at 578 nm. This experiment shows that the formation of ternary complexes can stabilize the Cu(II)-Aβx−x complexes not just thermodynamically, but also kinetically. Taking into account the milliseconds to seconds to minutes time scale of chemical processes in the synapses, such slow equilibrations between Aβx−x and Aβx−x indicate that ternary Cu(II)-Aβx−x complexes with external ligands, including other Aβ peptides, may indeed interfere with copper brain physiology.

Electrochemical properties of Cu(II)-Aβx−x complexes may further contribute to the impairment of brain copper metabolism by enabling the Cu(II)/Cu(I) cycle in the high-affinity Cu(II) pool, not accessible to much weaker Cu(II)-Aβx−x complexes. In this fashion the overproduction of Aβx−x peptides could also enhance the oxidative stress and reactive oxygen species (ROS) generation, normally ascribed to Cu(II)-Aβx−x species.51–53 On the other hand, the oxidation of Cu(II) ions in Aβx−x complexes to Cu(III) is even less likely than in Aβx−x complexes, but the presence of imidazole shifted the oxidation potential of the Cu(II)/Cu(III) couple toward less positive potential values, thus slightly increasing the probability of this reaction in vivo. Taken together, our results indicate that Aβx−x peptides, which bind Cu(II) ions much more strongly than Aβx−x peptides and only slightly more weakly than Aβx−x peptides,16,47 could interfere with Cu(II) handling by these peptides, adding to copper dyshomeostasis in Alzheimer brains, especially in the presence of auxiliary imidazole ligands, such as His side chains in other peptides and proteins.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.inorgchem.0c01773.

pH dependence of UV–vis spectra for Cu(II)-Aβx−x samples, fluorescence titrations of Aβx−12 and Cu(II)-Aβx−12, spectroscopic results and species distribution for 1 mM Aβx−16 and 1.8 mM Cu(II), spectroscopic titration of Cu(II)-Aβx−9 with Aβx−16, CV for Aβx−12, Cu(II)-Aβx−12, and DPV for Aβx−/Cu(II)/Im over 0.2 to −0.8 V potential range (PDF)

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Figure 12. Course of reaction of 1 mM Cu(II)-Aβx−9 with 1 mM Aβx−9 at pH 7.4 (20 mM HEPES) at 25 °C: (A) evolution of d-d bands; (B) reaction traces at 526, 578, and 621 nm.
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Notes
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