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A Two-Color Fluorescent Lithium Ion Sensor

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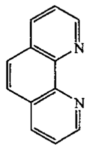
Introduction

The development of fluorescent metal ion sensors is a vigorous research area.[1−13] Lithium ion sensors are currently in demand for biomedical applications[14,15] and for monitoring ion transport in lithium ion batteries.[16−18] Although neglected relative to Ca^{2+}, several Li^{+} sensors have been reported.[19−24] Hiratani et al. have demonstrated the selectivity of 2,9-disubstituted 1,10-phenanthroline derivatives based on **4** for Li^{+}.[25−27] These molecules, upon excitation at 298 nm, exhibited fluorescence enhancement in the ultraviolet spectrum upon Li^{+} complexation. Here, we report that increasing the aromatic nature of 1,10-phenanthroline **1** through dipyrido[3,2-*a*:2′3′-*c*]phenazine (DPPZ, **2**) to benzodipyrido[3,2-*a*:2′3′-*c*]phenazine (BDPPZ, **3**) coupled with butyl substituents **5** yields a fluorescent sensor molecule that visibly changes color upon Li^{+} complexation.



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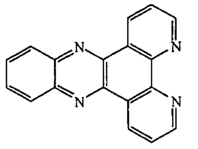

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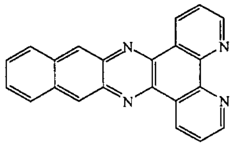

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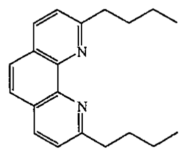

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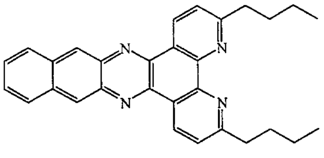

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The BDPPZ ligand **3** has been synthesized by others,[28−31] but 3,6-derivatives have not been reported. The more extended aromatic character of BDPPZ **3** results in longer wavelength absorption and emission compared to that of 1,10-phenanthroline **1** and DPPZ **2** (Figure 1).

Experimental Section

Materials. Fluorescence studies were performed on a 8100 SLM-AMINCO spectrofluorometer. UV−vis absorption spectra were acquired on a Cary 500 Scan UV−vis−NIR spectrophotometer. ^{1}H and ^{13}C NMR were recorded on a 300 MHz Bruker spectrometer at room temperature. 1,10-Phenanthroline, potassium bromide, *n*-butyllithium, manganese(IV) oxide, magnesium sulfate, 2,3-diaminonaphthalene, lithium perchlorate, sodium perchlorate, and potassium perchlorate were obtained from Aldrich Chemicals and used as received. Coumarin 153 was obtained from Lambda Physik. Fluorescence quantum yields were obtained using a Coumarin 153 solution in methanol ($\Phi = 0.42$, excitation at 410 nm) as a standard.

Synthesis and Characterization: 2,9-Dibutyl-1,10-phenanthroline (4). The molecule was synthesized by a modification of Dietrich-Buchecker's method.[32]1,10-Phenanthroline was dissolved in diethyl ether and cooled to −78 °C. To this solution was added 2 equiv of *n*-BuLi, and the reaction was allowed to proceed at −78 °C for 6 h. The resulting mixture was washed with water and then extracted with dichloromethane. The organic extracts were collected and oxidized with 99% pure MnO_2 for 24 h. The solution was filtered and dried with $MgSO_4$, and the solvents were evaporated off. The resulting amber residue was purified by column chromatography using a 4:1 hexane/dichloromethane solution. The product was collected as an off-white solid in a 67% yield. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 8.13−8.10 (d, 2H, $J = 8.3$ Hz), 7.68 (s, 2H), 7.51−7.48 (d, 2H, $J = 8.3$ Hz), 3.22−3.20 (t, 4H, $J = 8.2$ Hz), 1.94−1.84 (m, 4H, $J = 8.0$ Hz), 1.56−1.44 (m, 4H, $J = 7.3$ Hz), 0.96−1.01 (t, 6H, $J = 7.3$ Hz). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 163.24, 145.24, 136.20, 127.07, 125.44, 122.37, 39.21, 31.95, 22.93, 14.08. HRMS (EI^{+}) *m*/*e*: 292.427 (M^{+}, $C_{20}H_{24}N_2$ requires 292.423).

3,6-Dibutylbenzodipyrido[3,2-*a*:2′3′-*c*]phenazine (5). The synthesis of **5** took place via the oxidation of **4** to the corresponding dione.[33] The resulting 2,9-dibutyl-1,10-phenanthroline-5,6-dione was dissolved

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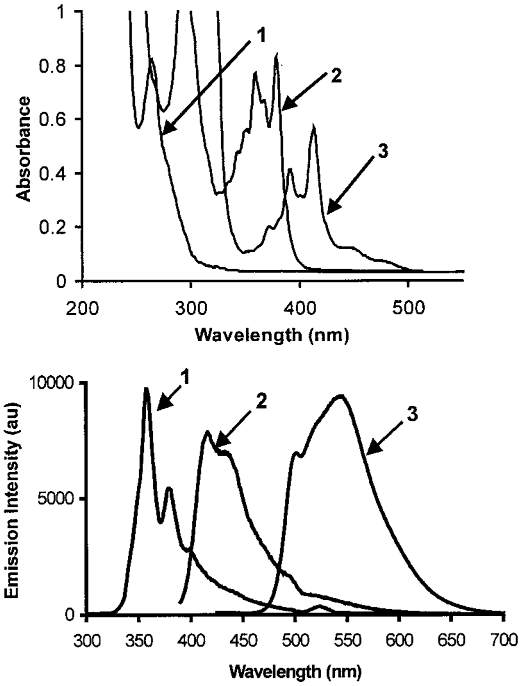


Figure 1. (Top) UV−vis absorption spectra and (Bottom) emission spectra of 1,10-phenanthroline (**1**), DPPZ (**2**), and BDPPZ (**3**).

in ethanol, and 1 equiv of 2,3-diaminonaphthalene was added. The resulting solution was refluxed for 4 h after which the product precipitated. The precipitate was collected by filtration, washed several times with ethanol to remove any unreacted 2,3-diaminonaphthalene, and then recrystallized from methanol. The product was collected in an 82% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.43−9.40 (d, 2H, J = 10.4 Hz), 9.36−9.33 (t, 2H, J = 6 Hz), 8.76−8.73 (d, 2H, J = 11.6 Hz), 8.11−8.09 (d, 2H, J = 10.0 Hz), 7.62−7.55 (m, 2H, J = 9.0 Hz), 3.17−3.03 (t, 4H, J = 8.10 Hz), 1.90−1.78 (m, 4H, J = 7.42 Hz), 1.53−1.50 (m, 4H, J = 7.34 Hz), 1.06−1.02 (t, 6H, J = 7.30 Hz). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 153.81, 152.49, 148.58, 141.86, 138.51, 134.17, 133.65, 128.33, 127.52, 126.87, 124.013, 38.97, 31.82, 22.87, 14.06. HRMS (DEP) *m*/*e*: 444.2314; found, 444.2305. Anal. Calcd (Robertson Microlit Laboratories, Inc., Madison, NJ) for **5**: C, 81.05; H, 6.35; N, 12.60. Found: C, 80.92; H, 6.07; N, 12.38.

Results and Discussion

In tetrahydrofuran (THF), the ligand **5** emits in the green (λ_{max} = 538 nm) region of the spectrum, but when dissolved in ethanol, it fluoresces in the yellow (λ_{max} = 553 nm) region of the spectrum; both emissions are readily observed with the naked eye under UV light. The absorption spectra of **5** in solvents of varying polarity are similar; however, the emission spectra display solvatochromism. An increase in solvent polarity results in a red shift of the emission spectrum, the range being from λ_{max} = 531 nm in benzene to λ_{max} = 562 nm in methanol.

The effect of Li^+ on the emission properties of **5** was investigated with excitation at 410 nm. Solutions of **5** in ethanol ($\sim 10^{-5}$ M) were titrated with up to 0.1 M $LiClO_4$ solution. The increase in Li^+ concentration resulted in a quenching of the fluorescence intensity that was accompanied by a red shift (Figure 2a). The emission lifetime of **5** in ethanol was measured to be 26.3 ns. Upon Li^+ addition, the lifetime of **5** slightly decreased to 23.0 ns. Similar experiments were performed in THF. In this solvent, the emission spectrum of **5** was affected when as little as 0.05 mM $LiClO_4$ dissolved in THF was added. The increase in Li^+ concentration had the opposite effect of the ethanol result: the fluorescence increased in intensity and was further accompanied by spectral broadening and a slight red shift (Figure 2b). The emission lifetime of **5** was measured to be 5.5 ns in THF. Upon addition of Li^+, the lifetime of **5** increased to 26 ns. Both decays were clean single exponentials, supporting the notion that **5** is pure and its Li^+ complex is a single compound. At the end of titration, the ethanol solution containing **5** and Li^+ that initially fluoresced yellow was orange and its fluorescence was quenched; on the other hand, the THF solution containing **5** and Li^+, which initially fluoresced green, fluoresced yellow and was brighter (Supporting Information, Figure S1). There was no notable change in the UV−vis absorbance spectrum of **5** in either solvent environment upon addition of Li^+.

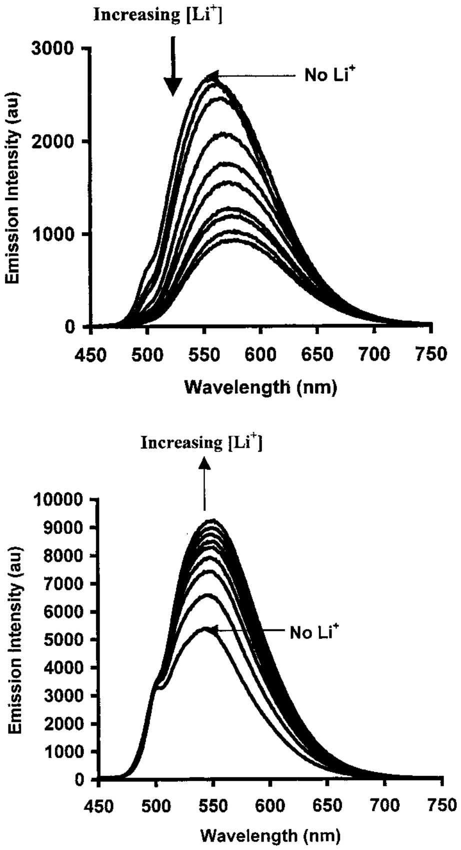


Figure 2. (Top) Titration of **5** (6.07×10^{-5} M) with Li^+ in ethanol; the fluorescence is quenched and red shifted. From top to bottom, [Li^+] = 0.00, 0.11, 0.21, 0.38, 0.53, 0.65, 0.81, 0.90, 0.98, and 1.05 M. (Bottom) Titration of **5** (3.60×10^{-5} M) with Li^+ in THF; the fluorescence is enhanced and red shifted. From bottom to top, [Li^+] = 0.0, 3.3, 6.6, 9.9, 13.0, 16.0, 19.0, 23.0, and 26.0 mM.

The relative selectivity of compounds **3** and **5** to Li^+ was investigated by titrating them with equal amounts of Li^+, Na^+, and K^+. On the basis of fluorescence spectra, compound **3** was unable to distinguish between the alkali metals. In contrast, **5** showed no changes in emission wavelength for any of the alkali metal ions except with Li^+. The selectivity of **5** may be attributed to the bulky butyl substituents adjacent to the ligating nitrogens that create a cavity small enough for Li^+.[24] Compound **4** (λ_{max} = 320 nm) that was reported by Hiratani et al.[27] to be Li^+ selective was compared to **5**. The increase in Li^+ concentration in a solution of **4** in either THF or ethanol resulted in an increase in the fluorescence intensity, but there was no change in color. Unlike **5**, the fluorescence changes of **4** with Li^+ occur in the near-UV region (λ_{max} = 388 nm).

Fluorescence data were treated with the method of continuous variation, which indicated a 2:1 stoichiometry of the ligand to the metal ion. The equilibrium binding constant for **5** to Li^+ was evaluated using the expression derived from the reaction $M^+ + 2L \rightarrow ML_2^+$, thus

$$K = [ML_2^+]/[M^+][L]^2 \qquad (1)$$

where K is the equilibrium binding constant (units of M^{-2}), $[ML_2^+]$ is the equilibrium concentration of the metal–ligand complex in which two ligands are bound to one metal ion, $[M^+]$ is the equilibrium concentration of free metal ion, and [L] is the concentration of free ligand at equilibrium. If we assume that the total ligand concentration $[L]_t = [L]_{bound} + [L]_{free}$ and likewise that the metal ion concentration $[M^+]_t = [M^+]_{bound} + [M^+]_{free}$, the following substitutions can be made for complexes of the form ML_2^+:

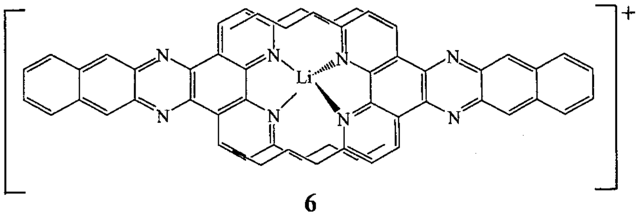
$$[ML_2^+] = [M^+]_{bound} = 2[L]_{bound} \qquad (2)$$

The measured quantities are $[ML_2^+]$ (assumed to be proportional to the fluorescence signal changes, see below), the total metal ion added to the ligand solution $[M^+]_t$, and $[L]_t$. In our titrations, $[L]_t$ is held constant as metal ion is added. Thus, the following equation is obtained from eq 1 upon substitution:

$$K = [ML_2^+]/([M^+]_t - [ML_2^+])([L]_t - 0.5[ML_2^+])^2 \quad (3)$$

We assume that $[ML_2^+] = \{(I - I_o)/(I_f - I_o)\}[M^+]_t$, where I is the integrated intensity of the fluorescence signal for a given $[M^+]_t$, I_o is the initial fluorescence intensity in the absence of metal ion, and I_f is the final maximum or minimum (in THF or ethanol titrations, respectively) fluorescence intensity of the solution (at maximal metal ion concentration). Least-squares fits to eq 3 to solve for K were performed by a home-written Maple (version 5; Waterloo, Canada) program.

Accordingly, K was calculated to be $(2.2 \pm 0.2) \times 10^4$ M^{-2} in ethanol and $(3.7 \pm 2.8) \times 10^5$ M^{-2} in THF. In the less polar THF solvent, **5** competes better for Li^+. We have been unable to grow crystals of the ligand–Li^+ complex in either solvent. However, as Li^+ prefers tetrahedral coordination, the most plausible structure is compound **6**.



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The solvent dependence of the emission may be examined by considering the "back-end" phenazine nitrogens, which are solvent accessible. The lowest excited state for DPPZ-like compounds involves an increase in electron density at the phenazine nitrogens.[34] Thus, in polar solvents, the fluorescence is red shifted compared to that in less polar solvents. The presence of Li^+ in both solvent environments results in a further red shift of the emission, giving rise to color changes readily observed with the naked eye. The quantum yields were measured in ethanol and in THF, using coumarin 153 as a standard, and were found to be 0.147 in ethanol and 0.057 in THF. Quantum yields of **5** with excess amounts of Li^+ were also measured and found to be 0.037 in ethanol and 0.114 in THF. From these data and lifetime data, we were able to calculate the radiative and nonradiative rate constants k_r and k_{nr}, respectively. To calculate k_r and k_{nr}, the relations $\phi_r = k_r\tau$ and $\tau = 1/(k_r + k_{nr})$ were used, where ϕ_r is the quantum yield of emission, k_r is the radiative rate constant in s^{-1}, τ is the observed luminescent lifetime in s, and k_{nr} is the sum of all the rate constants for nonradiative processes.[35] In THF, k_r decreases by a factor of 2 for maximum Li^+ addition, while k_{nr} decreases by a factor of 5; hence, the observed increase in emission intensity upon Li^+ addition to **5** is due to a suppression of nonradiative decay pathways in THF. However, in ethanol, k_r decreases by a factor of 3.7 and k_{nr} increases by a factor of 1.5 upon Li^+ addition to **5**. Thus, in ethanol, the observed decrease in fluorescence intensity of **5** upon addition of Li^+ is due to both k_r and k_{nr}.

Conclusion

We have synthesized a Li^+-selective ligand that changes emission color upon Li^+ binding. The influence of the local environment on the binding event may prove useful in the design of sensors that can monitor the analyte in complex environments in real time.

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Supporting Information Available: A photograph taken under UV light showing the fluorescence color changes of **5** in a polar solvent (free) and upon addition of Li^+, and in a nonpolar solvent (free) and upon addition of Li^+. This material is available free of charge via the Internet at http://pubs.acs.org.

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