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Solvent-dependent reactivity of azo-BF<sub>2</sub> switchesQingkai Qi,<sup>†ab</sup> Heyifei Fu,<sup>†a</sup> Lingya Peng,<sup>†c</sup> Shefali Patra,<sup>id a</sup> Xiaogang Liu<sup>id c</sup> and Ivan Arahamian<sup>id \*a</sup>

Azo-BF<sub>2</sub> complexes are visible and near-infrared (NIR) light-activated photoswitches showcasing versatility in applications ranging from energy storage to three-dimensional displays. While highly appealing as molecular switches, factors that affect their photophysical properties and solution-state reactivity still need to be teased out. In this paper, we present the synthesis and characterization of two azo-BF<sub>2</sub> analogues (1 and 2), each modified with structurally distinct dimethylamine-substituted naphthalene moieties. In addition to investigating the effect of the  $\pi$ -system expansion on the photophysical and photoswitching properties of the system, we also elaborate on the stability (*i.e.*, whether they undergo solvolysis or 1,2-BF<sub>2</sub> shift) of the switches in different solvents. Specifically, switch 1 absorbs in the NIR region, enabling its activation with 700 nm light, while switch 2 exhibits enhanced separation between the *trans* and *cis* isomer absorption bands, resulting in an improved photostationary state. As for the solvent effect, we discovered that polar aprotic solvents induce an intramolecular 1,2-BF<sub>2</sub> shift in both switches, transforming the azo-BF<sub>2</sub> photoswitches into boron difluoride hydrazone fluorophores, whereas polar protic solvents facilitate the solvolysis of the azo-BF<sub>2</sub> into the starting hydrazone derivative. In the former, the donor number of the solvent is a major factor in determining the obtained outcome, while in the latter, it is the solvent's hydrogen-bond donation capability. These insights into the design strategy and solvent-mediated reactivity of azo-BF<sub>2</sub>s will contribute to their further development into efficient NIR-responsive photoswitches, paving the way for innovative applications in smart materials and molecular devices.

## Introduction

Visible and near-infrared (NIR) light-activated photoswitches have gained popularity in the fields of photopharmacology and adaptive materials in recent years,<sup>1–8</sup> because they enable deep substrate penetration while maintaining low phototoxicity. This interest resulted in the development of an array of red-light and NIR-activated photoswitches, such as azobenzenes,<sup>9–17</sup> diarylethenes,<sup>18–21</sup> indigoids,<sup>22–25</sup> dihydropyrenes,<sup>26,27</sup> donor-acceptor Stenhouse adducts,<sup>28–32</sup> and heteroaryl azoswitches.<sup>33,34</sup> Our contribution to this research area was the introduction of azo-BF<sub>2</sub> photoswitches,<sup>35</sup> which were the first azobenzene derivatives to be activated with NIR light.<sup>36</sup> These switches also exhibit other sought-after characteristics, such as high photostationary states (PSS), enhanced isomerization quantum yields ( $\Phi$ ), and negative photochromism. We recently took advantage

of these unique features to develop a rewritable, solid-state, hand-held volumetric 3D photochromic display capable of showcasing both static 3D images and dynamic 2D animations.<sup>37</sup> We also demonstrated how such photoswitches can be used in molecular solar thermal energy storage applications.<sup>38</sup> Beyond these applications, structural modifications of azo-BF<sub>2</sub> switches have revealed several key insights: (1) extending the  $\pi$ -system from quinolinyl to phenanthridinyl results in self-aggregates that enhance the half-life ( $\tau_{1/2}$ ) of its thermal relaxation;<sup>39</sup> (2) an oxygen atom adjacent to the BF<sub>2</sub> bridge can induce a thermal 1,2-BF<sub>2</sub> shift, converting the azo-BF<sub>2</sub> photoswitch into a borondifluorohydrazone (BODIHY) in both solution and the solid state;<sup>40</sup> and (3) increasing the electron density through *para*-substitution causes a bathochromic shift in the activation wavelength, enabling control over the *trans/cis* isomerization process using NIR light.<sup>36</sup> Nonetheless, and despite the many promising features of azo-BF<sub>2</sub> switches, practical applications in the solution state are hindered by their reactivity, especially in polar media, particularly water. Hence, understanding the solvent interactions with these switches is an essential step towards extending their utility, especially *in vivo* settings.

Here, we report on two azo-BF<sub>2</sub> analogues (1 and 2) that incorporate an *N,N*-dimethylnaphthalen-1-amine or *N,N*-dimethylnaphthalen-2-amine moiety attached at the 5 or 6-

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position, respectively (Fig. 1a). Our initial goal was to investigate how modifications to the  $\pi$ -system will influence the activation wavelength and overall photoswitching efficiency compared to the parent azo-BF<sub>2</sub>. Structural analysis revealed that these two switches exhibit distinct photophysical properties and photoswitching performances. Specifically, the absorption spectrum of **1** extends into the NIR region, thus allowing NIR activation. In contrast, switch **2** has a more pronounced separation between the *trans* and *cis* absorption bands, resulting in an improved PSS ratio.

To gain a deeper understanding of how polar solvent environments affect the molecular properties of the switches, we systematically examined the behavior of both derivatives under various solvent environments. Our focus was on understanding the correlation between their stability and key solvent parameters, including donor number (DN), dipolarity/polarizability ( $\pi^*$ ), basicity, and hydrogen bond donation ability ( $\alpha$ ).<sup>41</sup> We discovered that polar aprotic solvents such as dimethyl sulfoxide (DMSO), dimethylformamide (DMF), and dimethylacetamide (DMAc) induce the intramolecular 1,2-BF<sub>2</sub> shift in both derivatives, leading to the formation of the BODIHY product (Fig. 1b and c). In solvents such as acetone, tetrahydrofuran (THF), ethyl acetate (EA) and polar protic alcohols both switches undergo solvolysis yielding their starting hydrazones, though at different time-scales. A comprehensive analysis of solvent parameters revealed a strong correlation between the DN of the solvents and the rate of BODIHY formation, suggesting that solvents with a greater lone pair donation ability result in a more efficient 1,2-BF<sub>2</sub> shift. In solvents with lower DN (e.g., acetone, THF, and EA), both switches undergo solvolysis,

regenerating their original hydrazones on a timescale comparable to that of the BF<sub>2</sub> shift. We hypothesize that the trace amounts of water (<50 ppm) present in these solvents facilitate solvolysis; in contrast, in non-nucleophilic solvents such as toluene and dichloromethane (DCM), no reaction is observed. On the other hand, the relatively fast solvolysis of the azo-BF<sub>2</sub> switches to their hydrazone precursors in polar protic alcohols is primarily driven by the solvents' hydrogen bond donation ability ( $\alpha$ ).

## Results and discussion

Azo-BF<sub>2</sub>s **1** and **2** were synthesized by reacting their respective hydrazone precursors with boron trifluoride diethyl etherate, in the presence of *N,N*-diisopropylethylamine (Schemes S1 and S2). The azo-BF<sub>2</sub> switches and their precursors were fully characterized using NMR spectroscopy and mass spectrometry (Fig. S1–S13).

The photoisomerization performance of the switches in DCM was evaluated using UV-Vis and NMR spectroscopies (Fig. S14–S20), and the data are summarized in Table 1. Switch **1** predominantly exists in its thermodynamically stable *trans* form in the dark (95%), with a maximum UV-Vis absorbance ( $\lambda_{\max}$ ) at 675 nm ( $\epsilon = 34\,300\text{ M}^{-1}\text{ cm}^{-1}$ , Fig. 2c) and an absorption tail extending to approximately 800 nm. While the  $\lambda_{\max}$  is slightly blue-shifted relative to the parent system ( $\lambda_{\max} = 680\text{ nm}$ ), the absorption tail extends further by 50 nm into the near-infrared region, making it the most red-shifted azo-BF<sub>2</sub> system reported to date. These results indicate that attaching a naphthyl group to the azo-BF<sub>2</sub> core through the  $\beta$ -position effectively elongates the  $\pi$ -conjugation. Upon irradiation with 700 nm light, the *cis* isomer ( $\lambda_{\max} = 620\text{ nm}$ ;  $\epsilon = 17\,500\text{ M}^{-1}\text{ cm}^{-1}$ , Fig. 2c) becomes predominant, accompanied by a slight color change of the solution from greenish cyan to cyan blue (Fig. 2a). The thermal half-life ( $\tau_{1/2}$ ) of the metastable *cis*-**1** isomer in aerated DCM was measured to be  $2.2 \pm 0.01\text{ min}$  at 294 K (Fig. S25). Because of the rapid back isomerization, accurate PSS<sub>700</sub> could not be determined. The lowest estimated amount of the *cis* isomer at PSS<sub>700</sub> is 47% (Fig. S16), with a quantum yield ( $\Phi_{\text{trans} \rightarrow \text{cis}}$ ) of  $13.6 \pm 1.7\%$  (Fig. S21). This value is underestimated because of the fast back isomerization process. A deduced absorption curve for *cis*-**1**, based on previously reported methods,<sup>42,43</sup> gives a  $\lambda_{\max}$  of 595 nm with an  $\epsilon$  of  $15\,800\text{ M}^{-1}\text{ cm}^{-1}$  (Fig. 2c), yielding a  $\Delta\lambda_{\max}$  value of 80 nm. Further irradiation at 480 nm results in a PSS<sub>480</sub> of 63% *trans* (Fig. S16) and a  $\Phi_{\text{cis} \rightarrow \text{trans}}$  of  $35.1 \pm 2.7\%$  (Fig. S22). This value is overestimated because of the fast back isomerization process. The relatively low PSS values for both the forward and backward photoisomerization processes are attributed to the significant overlap of the absorption bands of the two isomers and the short  $\tau_{1/2}$ . The photoswitching can be cycled multiple times with no signs of photodegradation (Fig. S14c).

Switch **2** exists predominantly in the *trans* form (62–64%, Fig. S53 and S54) when equilibrated under dark ( $\lambda_{\max} = 578\text{ nm}$ ,  $\epsilon = 21\,300\text{ M}^{-1}\text{ cm}^{-1}$ , Fig. 2d). The  $\lambda_{\max}$  of *trans*-**2** is blue shifted by around 100 nm from that of the parent compound ( $\lambda_{\max} = 680\text{ nm}$ ) and *trans*-**1** ( $\lambda_{\max} = 675\text{ nm}$ ), as the NMe<sub>2</sub> group is not

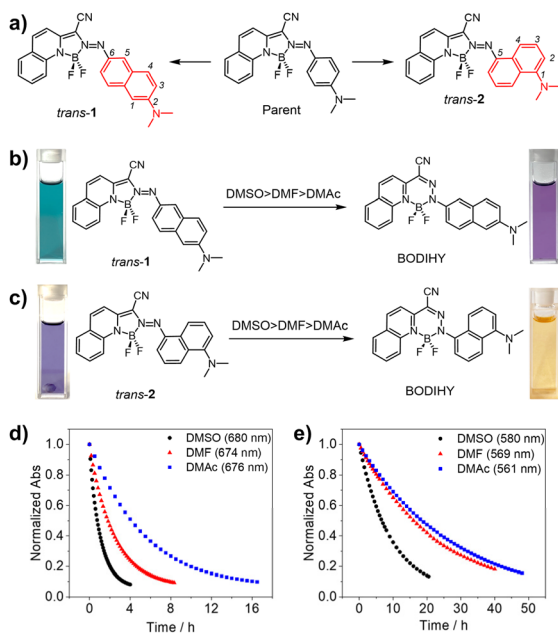


Fig. 1 (a) The structures of the two azo-BF<sub>2</sub> derivatives **1** and **2**. (b) Photographs of the solution of *trans*-**1** and (c) *trans*-**2** before and after the 1,2-BF<sub>2</sub> shift in various solvents, along with their corresponding molecular structures. (d) Kinetic profiles of the 1,2-BF<sub>2</sub> shift of *trans*-**1** and (e) *trans*-**2** in DMSO, DMF, and DMAc ( $4 \times 10^{-5}\text{ M}$ ).



Table 1 Summary of photophysical data for azo-BF<sub>2</sub>s 1 and 2 in DCM

Azo-BF <sub>2</sub>	$\lambda_{\text{abs}}^a$ (nm)/ $\epsilon^b$ (M <sup>-1</sup> cm <sup>-1</sup> )		PSS (%) @ $\lambda_{\text{irr}}^c$ (nm)		$\Phi_{\text{isom}}^d$		$\tau_{1/2}^e$ (min)
	<i>trans</i>	<i>cis</i>	<i>trans</i> : <i>cis</i>	<i>trans</i> : <i>cis</i>	<i>trans</i> → <i>cis</i>	<i>cis</i> → <i>trans</i>	
1	675/34 300	595/15 800 <sup>f</sup>	25 : 75 @ 700 <sup>f</sup>	63 : 37 @ 480	13.6 ± 1.7	35.1 ± 2.7	2.2 ± 0.1
2	578/21 300	473/19 800 <sup>f</sup>	21 : 79 @ 650 <sup>f</sup>	67 : 33 @ 442	6.3 ± 0.1	24.7 ± 2.3	384 ± 4

<sup>a</sup> Absorption maximum. <sup>b</sup> Extinction coefficient. <sup>c</sup> Photostationary state measured at the optimal irradiation wavelength. <sup>d</sup> Photoisomerization quantum yield. <sup>e</sup> Thermal half-life of the *cis* → *trans* transformation at 298 K. <sup>f</sup> Deduced using previously reported methods.<sup>41,42</sup>

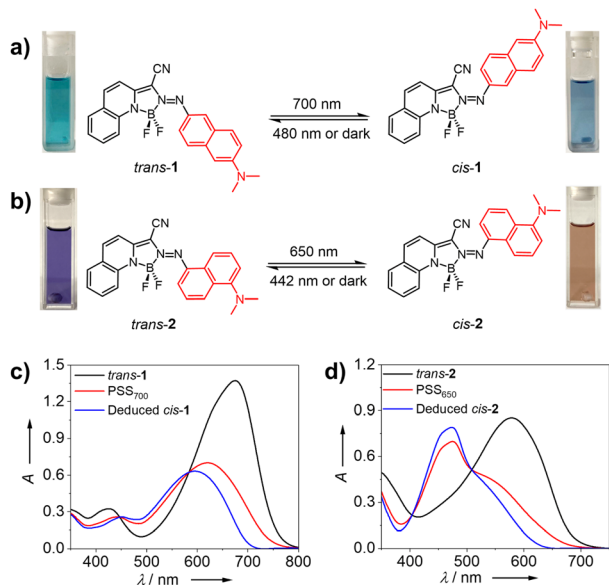


Fig. 2 Light-induced *trans/cis* isomerization of (a) 1 and (b) 2, along with the corresponding UV/vis absorption changes (c) and (d), respectively, in DCM ( $4 \times 10^{-5}$  M).

in direct conjugation with the azo core. Upon irradiation with 650 nm light, *trans-2* switches to its *cis* form ( $\lambda_{\text{max}} = 475$  nm,  $\epsilon = 17\,500$  M<sup>-1</sup> cm<sup>-1</sup>; deduced  $\lambda_{\text{max}} = 473$  nm,  $\epsilon = 19\,800$  M<sup>-1</sup> cm<sup>-1</sup>;

Fig. 2d), accompanied by a drastic color change of the solution from purple to brown (Fig. 2b). The PSS<sub>650</sub> for *trans-2* was measured to be 74% *cis* (Fig. S17), with a  $\Phi_{\text{trans} \rightarrow \text{cis}}$  of  $6.3 \pm 0.1\%$  (Fig. S23). Switch 2 exhibits a better band separation between the *trans* and *cis* isomers than switch 1 ( $\Delta\lambda_{\text{max}}$ : 105 vs. 80 nm, respectively). The reverse process (*cis* → *trans*) can be triggered using a 442 nm light source, resulting in a PSS<sub>442</sub> of 67% *trans* (Fig. S17) and a  $\Phi_{\text{cis} \rightarrow \text{trans}}$  of  $24.7 \pm 2.3\%$  (Fig. S24). The  $\tau_{1/2}$  for the *cis* → *trans* process of switch 2 was calculated to be  $384 \pm 4$  min (Fig. S26), approximately 175 times longer than that of switch 1. Again, and as previously discussed, this difference is attributed to the fact that the NMe<sub>2</sub> group is not in direct conjugation with the azo core. The longer  $\tau_{1/2}$  allows for a better assessment of the system's photoswitching efficacy. The photoswitching can be cycled numerous times with no signs of photodegradation (Fig. S15c).

The major challenge with using azo-BF<sub>2</sub> switches in the solution state lies in the stability of the N → B coordination bond, which can undergo 1,2-BF<sub>2</sub> shift and/or hydrolysis. It should be noted here that this reactivity is mainly observed for the *trans* form, while the *cis* isomer is far more stable.<sup>36,40</sup> To probe the effect of solvent polarity and proticity on the stability of this bond, we conducted a comprehensive investigation across a range of solvents (Fig. 1d and e). Both switches exhibit good stability, *i.e.*, undergo no reaction, in non-polar solvents such as DCM (Fig. S41 and S42) and toluene (Fig. S53 and S54). On the other hand, polar aprotic solvents such as DMSO, DMF,

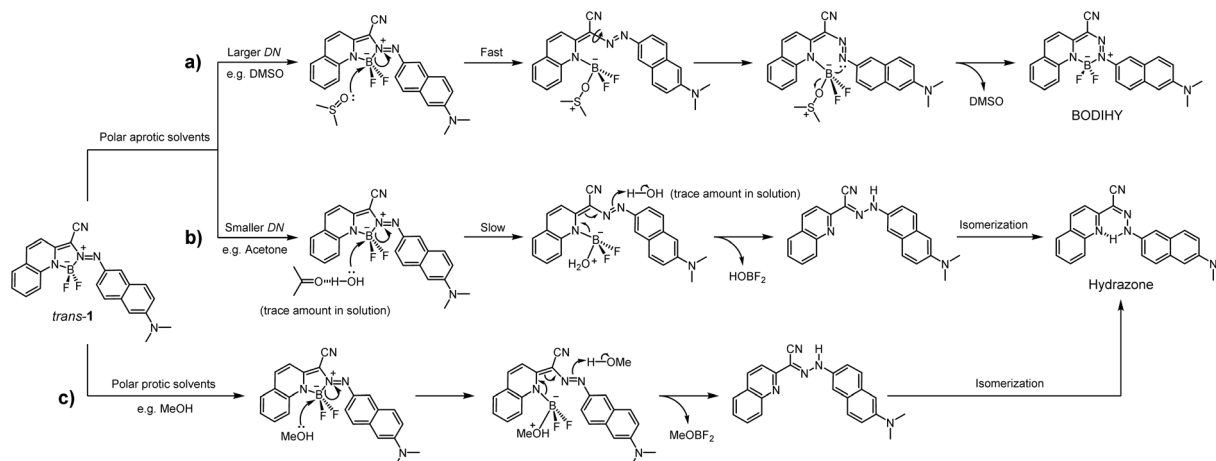


Fig. 3 Proposed reaction mechanisms for azo-BF<sub>2</sub> compounds. (a) 1,2-BF<sub>2</sub> shift in polar aprotic solvents having high DN (e.g., DMSO); (b) solvent-assisted slow solvolysis in polar aprotic solvents with low DN (e.g., acetone); and (c) rapid solvolysis in polar protic solvents (e.g., MeOH).



Table 2 Summary of decomposition data for both azo-BF<sub>2</sub>s in aprotic solvents

Azo-BF <sub>2</sub> s	Donor number	1		2	
		$\tau_{1/2}^a$ (h)	$k^b$ (s <sup>-1</sup> )	$\tau_{1/2}^a$ (h)	$k^b$ (s <sup>-1</sup> )
DMSO <sup>c</sup>	29.8	0.68 ± 0.03	2.8 ± 0.1 × 10 <sup>-4</sup>	6.2 ± 0.6	3.1 ± 0.3 × 10 <sup>-5</sup>
DMF <sup>c</sup>	26.6	1.8 ± 0.2	1.1 ± 0.1 × 10 <sup>-4</sup>	16 ± 1	1.2 ± 0.1 × 10 <sup>-5</sup>
DMAc <sup>c</sup>	27.8	3.3 ± 0.4	5.8 ± 0.6 × 10 <sup>-5</sup>	17 ± 2	1.1 ± 0.1 × 10 <sup>-5</sup>
THF <sup>d</sup>	20.0	44 ± 3	4.4 ± 0.3 × 10 <sup>-6</sup>	36 ± 5	5.5 ± 0.8 × 10 <sup>-6</sup>
Acetone <sup>d</sup>	17.0	53 ± 7	3.7 ± 0.4 × 10 <sup>-6</sup>	109 ± 9	1.8 ± 0.2 × 10 <sup>-6</sup>
EA <sup>d</sup>	17.1	82 ± 15	2.4 ± 0.4 × 10 <sup>-6</sup>	184 ± 26	1.1 ± 0.1 × 10 <sup>-6</sup>

<sup>a</sup> *Trans*-1 decomposition half-life. <sup>b</sup> The reaction rate of decomposition. <sup>c</sup> 1,2-BF<sub>2</sub> Shift. <sup>d</sup> Solvolysis.

and DMAc initiate an intramolecular 1,2-BF<sub>2</sub> shift in both switches, leading to the formation of BODIHY products (Fig. S35–S37 and S44–S46). We hypothesize that these polar aprotic solvents coordinate with the boron core of the azo-BF<sub>2</sub> switches, leading to the cleavage of the intramolecular N → B coordination bond (Fig. 3a). The resulting bond dissociation increases the rotational freedom of the C–N single bond, allowing it to adopt a conformation that favors the formation of a new and more stable intramolecular N → B bond. This transformation is reminiscent of our earlier finding, where an oxygen atom located near the BF<sub>2</sub> group catalyzed the 1,2-BF<sub>2</sub> shift, resulting in the formation of a BODIHY product.<sup>40</sup> The rate of the shift in *trans*-1 based on UV/Vis spectroscopy studies follows the order DMSO > DMF > DMAc, with a  $\tau_{1/2}$  of 0.68 ± 0.03, 1.8 ± 0.2, and 3.3 ± 0.4 h, respectively (Table 2). The formation of BODIHY was confirmed using <sup>1</sup>H and <sup>19</sup>F NMR spectroscopies in DMSO-*d*<sub>6</sub> (Fig. S27). Specifically, the <sup>19</sup>F spectra showed the disappearance of the initial azo-BF<sub>2</sub> resonance signal at –145.0 ppm and the simultaneous appearance of a new signal at –123.5 ppm, which corresponds to the corresponding BODIHY dye.<sup>40</sup> The formation rate of BODIHY was determined to be 0.53 h, which aligns well with the result obtained from the UV/Vis measurements. In aprotic solvents with lower donor numbers, such as THF, acetone, and EA (Fig. S38–S40 and S48–S50), no 1,2-BF<sub>2</sub> is observed. Nonetheless, even though ultra-dry (H<sub>2</sub>O < 50 ppm) solvents are used, the switches undergo slow solvent-assisted solvolysis (Fig. 3b). The reaction follows the order: THF > acetone > EA, with  $\tau_{1/2}$  of, 44 ± 3, 53 ± 7, and 82 ± 15 h, respectively for *trans*-1. Similar trends are observed for *trans*-2 (Table 2).

Finally, in alcohols methanol (MeOH), ethanol (EtOH), 1-propanol (*n*-PrOH), 2-propanol (*i*-PrOH), 2-methyl-1-propanol (*i*-BuOH), 2-butanol (*sec*-BuOH), and benzyl alcohol (BnOH, Fig. S28–S34 and S47) the switches quickly revert to their hydrazone precursors (Table 3 and Fig. 3c).<sup>40</sup>

To understand the different solvent-dependent outcomes, we correlated the reaction rates to various solvent parameters, including  $\alpha$ ,  $\pi^*$ , DN, acceptor number (AN), and the acidity, basicity, and polarity index (*Z*). In the case of *trans*-1, the best correlations for the 1,2-BF<sub>2</sub>-shift rates were with the DN ( $R^2 = 0.95$ , Fig. 4a) and  $\pi^*$  ( $R^2 = 0.92$ , Fig. S51a).<sup>44</sup> Similarly, *trans*-2 exhibited the best correlation with DN ( $R^2 = 0.91$ , Fig. 4b) followed by  $\pi^*$  ( $R^2 = 0.74$ , Fig. S51b). Other solvent parameters show much weaker correlations. These findings strongly suggest that the solvent donor number has the most substantial influence on the molecular reaction pathway in 1 and 2. That is, solvents that donate lone pair electrons to the boron in the azo-BF<sub>2</sub> switches more readily result in faster 1,2-BF<sub>2</sub> shifts. As for the hydrolysis in alcohols, surprisingly, the process is not governed by the p*K*<sub>a</sub> of the solvents, but rather by their hydrogen bond donating ability ( $\alpha$ , Fig. 4c,  $R^2 = 0.97$ ). Hydrogen bond donation ability is determined not solely by the intrinsic acidity (p*K*<sub>a</sub>) of the solvent, but by a combination of factors, including the electronegativity of the hydrogen-bearing atom, the polarity of the hydrogen-donating bond, steric hindrance, and the overall solvent structure (including resonance effects). Under our experimental conditions, it appears that steric effects in protic solvents play a decisive role in modulating the reaction rate by influencing the accessibility and strength of hydrogen bonding at the coordination site. These findings highlight that the multifaceted nature of solvent interactions must be carefully considered when evaluating the stability of the N → B coordination bond in azo-BF<sub>2</sub> switches.

To elucidate the mechanism of the BF<sub>2</sub>-shift and solvolysis reactions in *trans*-1 and *trans*-2, we conducted DFT-based quantum chemical calculations in three representative solvents: dichloromethane (DCM, a weakly polar solvent), dimethyl sulfoxide (DMSO, a strong polar aprotic Lewis base), and methanol (MeOH, a protic solvent with moderate Lewis base strength). These calculations were performed at M06-2X/

Table 3 Summary of solvolysis data for *trans*-1 in polar protic alcohols

Solvent	MeOH	EtOH	<i>n</i> -PrOH	<i>i</i> -PrOH	<i>i</i> -BuOH	<i>sec</i> -BuOH	BnOH
$\tau_{1/2}^a$ (h)	0.063 ± 0.005	0.13 ± 0.01	0.16 ± 0.01	0.38 ± 0.04	0.20 ± 0.01	0.42 ± 0.04	0.82 ± 0.09
$k^b$ (s <sup>-1</sup> )	3.1 ± 0.3 × 10 <sup>-3</sup>	1.5 ± 0.1 × 10 <sup>-3</sup>	1.2 ± 0.1 × 10 <sup>-3</sup>	5.2 ± 0.6 × 10 <sup>-4</sup>	9.4 ± 0.2 × 10 <sup>-4</sup>	4.6 ± 0.4 × 10 <sup>-4</sup>	2.4 ± 0.3 × 10 <sup>-4</sup>

<sup>a</sup> *Trans*-1 decomposition half-life. <sup>b</sup> The reaction rate of decomposition.



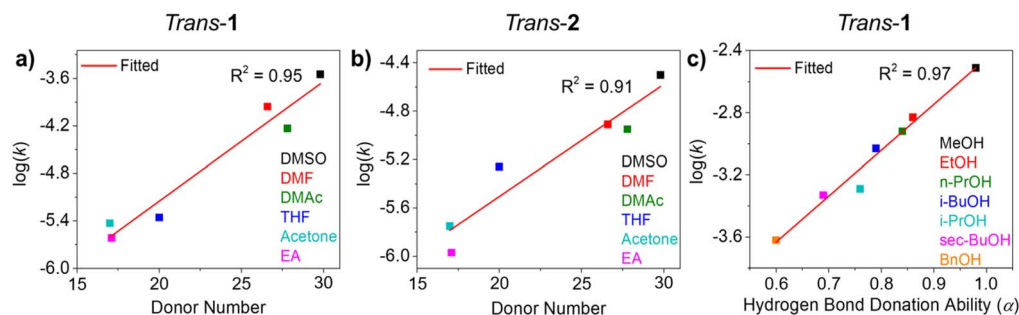


Fig. 4 Correlation of reaction rate with the most relevant parameter: (a) *trans*-1 in aprotic solvents versus DN, (b) *trans*-2 in aprotic solvents versus DN, and (c) *trans*-1 in protic solvents versus  $\alpha$ .

def2-TZVP/SMD level for single-point energies, with initial geometries optimized at the B3LYP-D3/def2-SVP/SMD level (for more computational details, please see the SI).

Starting with *trans*-1 in DCM, the direct 1,2-BF<sub>2</sub> shift was found to have a high free energy activation barrier of 34.5 kcal mol<sup>-1</sup> through transition state **TS1a** (Fig. 5a). This substantial barrier suggests that the 1,2-BF<sub>2</sub> shift will unlikely proceed in

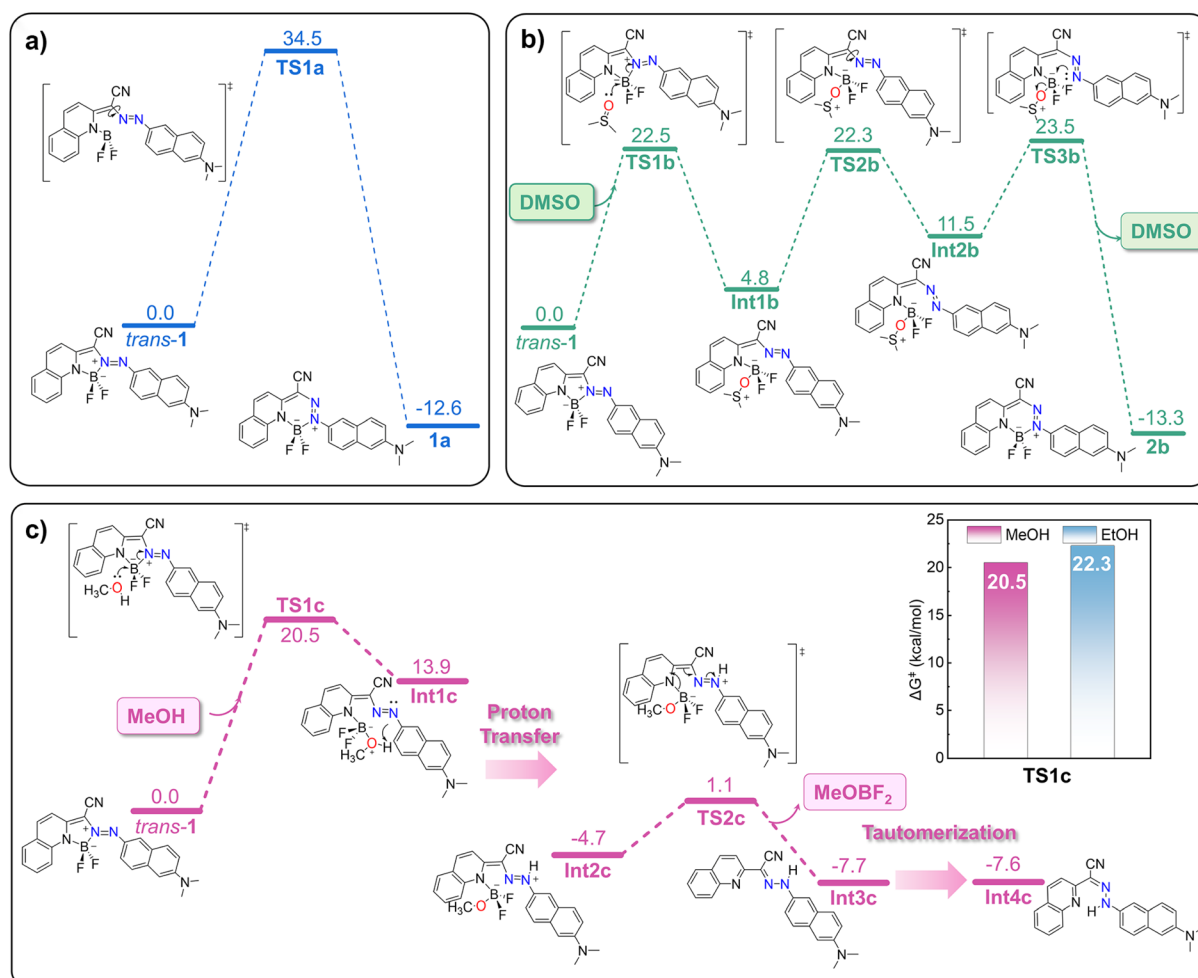


Fig. 5 Computed reaction mechanisms illustrating the 1,2-BF<sub>2</sub> shift in (a) DCM and (b) DMSO, as well as (c) the solvolysis of *trans*-1 with MeOH. All calculations were performed at the M06-2X/def2-TZVP/SMD//B3LYP-D3/def2-SVP/SMD level of theory. The subpanel in (c) shows a comparison of the energy barriers at **TS1c** in methanol and ethanol. The free energy activation barriers ( $\Delta G^\ddagger$ ) and free energy differences ( $\Delta G^0$ ) are relative to the individual starting species *trans*-1, and explicit solvent molecules are used when applicable. Values are free energies in kcal mol<sup>-1</sup>. Panel (c) is not drawn to scale to improve clarity.



DCM, aligning with experimental observations. It is important to note that these calculations were performed using an implicit solvent model, as the 1,2-BF<sub>2</sub> shift in DCM is proposed to be a single-step process with no solvent mediation (Fig. S55).

The energy barrier for the 1,2-BF<sub>2</sub> shift reaction is significantly lower in DMSO than in DCM. Our modelling suggests that DMSO, a strong Lewis base with its high donor number, participates directly in the reaction, playing a critical role in the 1,2-BF<sub>2</sub> shift, *i.e.*, DMSO directly attacks the boron atom, displacing the azo group bound to it. Computations show that this substitution proceeds *via* transition state **TS1b**, requiring a free energy barrier of only 22.5 kcal mol<sup>-1</sup> (Fig. 5b and S56), leading to intermediate **Int1b**, which is endergonic by 4.8 kcal mol<sup>-1</sup>. Analysis of the structure of **Int1b** reveals a key bond distance of 2.91 Å for the broken B–N bond and 1.53 Å for the newly formed B–O bond, creating sufficient space for the rotation of the azo group, which occurs *via* the transition state **TS2b** ( $\Delta G^\ddagger = 22.3$  kcal mol<sup>-1</sup>) resulting in intermediate **Int2b** (11.5 kcal mol<sup>-1</sup>). Finally, dissociation of DMSO *via* **TS3b** ( $\Delta G^\ddagger = 23.5$  kcal mol<sup>-1</sup>) and rebinding of the rotated azo group to the boron leads to the formation of the exergonic product **2b** (–13.3 kcal mol<sup>-1</sup>). These calculated moderate energy barriers in DMSO explain why the 1,2-BF<sub>2</sub> shift occurs readily in this solvent, as observed experimentally.

The DFT calculations also indicate that in methanol, solvolysis is more facile than the 1,2-BF<sub>2</sub> shift (Fig. 5c and S57). Methanol, being a protic solvent, initiates the reaction by attacking the boron atom, leading to the displacement of the azo group *via* the transition state **TS1c** ( $\Delta G^\ddagger = 20.5$  kcal mol<sup>-1</sup> relative to the free starting materials). This process is followed by a rearrangement through proton transfer (facilitated by surrounding solvent molecules) to **Int2c**. Subsequently, the dissociation of BF<sub>2</sub>OMe occurs *via* **TS2c** ( $\Delta G^\ddagger = 1.1$  kcal mol<sup>-1</sup>), resulting in the intermediate **Int3c** that tautomerizes to **Int4c**.<sup>45</sup>

The H-bonds between the two fluorine atoms in the BF<sub>2</sub> bridge and surrounding methanol molecules result in a lower azo group displacement energy barrier (20.5 kcal mol<sup>-1</sup>) compared to DMSO (22.5 kcal mol<sup>-1</sup>, Fig. 5b and c). Electrostatic potential energy surface analysis of *trans*-1 derivatives reveals significant negative charge density at the fluorine atoms (Fig. S58 and Table S1). These H-bond interactions, partially accounted for in the solvent model, stabilize the transition states and lower the energy barriers. More importantly, the protic nature of methanol promotes solvolysis by donating a proton to *trans*-1 and supports the formation of **Int2c** by enabling efficient proton diffusion. Notably, alcohol molecules act as H-bond donors, and their donating ability is a key factor governing the solvolysis rate of the azo-BF<sub>2</sub> compounds. When we modeled a similar solvolysis reaction in ethanol ( $\alpha = 0.86$ ), which has a weaker H-bond donating ability than methanol ( $\alpha = 0.98$ ), the energy barrier of **TS1** increased from 20.5 to 22.3 kcal mol<sup>-1</sup> (Fig. 5c and Table S2), respectively. These findings demonstrate that the H-bond donating ability of the protic solvent significantly influences reaction kinetics, which is consistent with experimental observations. It is also worth mentioning that methanol is more effective than ethanol at facilitating proton transfer, owing to its greater polarity and

smaller steric hindrance. These properties enhance the formation of **Int2c** and promote more efficient solvolysis. The calculated results for *trans*-2 showed similar trends (Fig. S59–S64).

## Conclusions

In summary, the synthesis and characterization of two structurally distinct azo-BF<sub>2</sub> photoswitches presented in this work underscore the significant potential of structural modulation in enhancing their photophysical performance. We demonstrate that expanding the  $\pi$ -conjugation profoundly influences the activation wavelength and photoswitching performance, with switch **1** achieving an extended NIR absorption profile, and switch **2** benefiting from improved separation of the absorption bands. The solvent-dependent behavior, particularly the 1,2-BF<sub>2</sub> shift, highlights the critical role of solvent donor number in dictating reaction pathways and product stability. On the other hand, the observed solvent-mediated solvolysis showcases the importance of the solvent's hydrogen bond donation ability in driving the process. Importantly, the interplay between solvent proticity and steric effects can be leveraged to mitigate the reaction. Moreover, the data indicate that lowering accessibility to the N → B bond through steric hindrance can lower its reactivity. Overall, the gained insights can be harnessed to further the design of these efficient visible and NIR-responsive photoswitches, and expand opportunities in adaptive materials, molecular devices, and energy storage applications.

## Author contributions

Q. Qi conceived the initial project, synthesized the compounds, and conducted their photophysical and structural characterization. Q. Qi also wrote the original draft of the manuscript. H. Fu investigated and analyzed the solvent-dependent behavior of the compounds and co-wrote the original draft. L. Peng performed and summarized the DFT calculations under the guidance of X. Liu. S. P. assisted with UV-Vis absorption measurements. I. A. supervised the overall project and provided critical revisions to the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Data availability

All data are available in the main text and the SI. See DOI: <https://doi.org/10.1039/d5sc05042a>.

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