Antibiotics

Towards Photochromic Azobenzene-Based Inhibitors for Tryptophan Synthase


Abstract: Light regulation of drug molecules has gained growing interest in biochemical and pharmacological research in recent years. In addition, a serious need for novel molecular targets of antibiotics has emerged presently. Herein, the development of a photocontrollable, azobenzene-based antibiotic precursor towards tryptophan synthase (TS), an essential metabolic multienzyme complex in bacteria, is presented. The compound exhibited moderately strong inhibition of TS in its E configuration and five times lower inhibition strength in its Z configuration. A combination of biochemical, crystallographic, and computational analyses was used to characterize the inhibition mode of this compound. Remarkably, binding of the inhibitor to a hitherto-unconsidered cavity results in an unproductive conformation of TS leading to noncompetitive inhibition of tryptophan production. In conclusion, we created a promising lead compound for combating bacterial diseases, which targets an essential metabolic enzyme, and whose inhibition strength can be controlled with light.

Introduction

Antibiotics are crucial for modern medicine.[1] They are used to cure bacterial illnesses and infections, and to facilitate major surgical operations. Most of us have used them at least once in our lives. To further our understanding of their mode of action, antibiotic precursors are often designed for biochemical and pharmaceutical studies. This ultimately paves the way for drugs that are highly efficient, specific, and less prone to build-up of resistance. In particular, focusing on novel types of macromolecular targets and innovative strategies to circumvent resistance are paramount to this cause.[2]

Most antibiotics engage in bacterial cell-division processes or weaken the bacterial membrane.[3] Recently, the search for alternative targets was expanded to metabolic enzymes,[4] such as the well-investigated multienzyme complex tryptophan synthase (TS). TS catalyzes the last two steps of tryptophan biosynthesis in bacteria, plants, and fungi.[5] The complex consists of TrpA (α) and TrpB (β), which are arranged as a heterotetramer in a linear αββα configuration.[6] The functional unit of TS is thereby formed by one αβ heterodimer (Figure 1A).[7] Tryptophan production starts with the TrpA reaction, in which indole-3-glycerol phosphate (IGP) is cleaved in a retro-aldol reaction to glyceraldehyde 3-phosphate (GAP) and indole.[8] In the next step, indole travels through an intermolecular channel to the active site of TrpB,[9] where it is used to synthesize tryptophan from serine by using pyridoxal phosphate (PLP) as a cofactor.[10] Both reactions, indole synthesis in TrpA and tryptophan synthesis in TrpB, require tight allosteric regulation of both subunits (Figure 1B).[10] On binding of IGP in the TrpA active site, the affinity for serine in the TrpB active site is enhanced, as shown by a reduced $K_M$ value, so that the initial reaction of serine with PLP to an aminoacylate intermediate is facilitated.[10] The formation of the aminoacylate in turn enhances the turnover of IGP to indole, as manifested in an increased $k_{cat}$ value of TrpA.[11] Structural analysis of TS from Salmonella typhimurium revealed that a conformational change of the communication (COMM) domain, which includes around 90 residues in TrpB, is in particular responsible for the propagation of the allosteric signals between the two active sites.[12] In the absence of IGP and serine, the COMM domain exhibits an open conformation, while binding of IGP in TrpA and the subse-
quent formation of aminoacrylate in TrpB induce a stepwise transition to a closed conformation\textsuperscript{[12b, 13]} As mammals lack the genes for the biosynthetic pathway of tryptophan, TS represents an excellent target for the development of new antibiotics. Previous studies already reported inhibitors towards TS that compete with IGP for the active site of TrpA,\textsuperscript{[14]} bind at the TrpA:TrpB interface,\textsuperscript{[15]} or interact with the hydrophobic intermolecular indole channel in TrpB.\textsuperscript{[16]} These examples provide good starting points for the development of antibiotic agents.

Direct control of the efficacy of drugs is an innovative approach in biochemical and pharmacological studies, which is increasingly used to gain in depth knowledge of the mode of action. Temporally resolved activation allows one to unambiguously associate the observed effect to the drug. Most recently, the spatiotemporal control of drugs has been addressed by developing light-responsive, bioactive molecules in the growing field of photopharmacology.\textsuperscript{[17]} Besides many other applications, such as photosensitive proteins,\textsuperscript{[18]} DNA modulators,\textsuperscript{[19]} kinase inhibitors,\textsuperscript{[20]} and PROTAGs,\textsuperscript{[21]} the first photocontrollable antibiotics have been developed.\textsuperscript{[22]} The principle of photopharmacology is based on a seemingly simple strategy; the designed drug consists of moieties that convey a biological response, such as an inhibitory effect toward the target structure, and a photosensitive part that facilitates a light-induced structural change. Thus, the drug is rendered effective in one configuration and ineffective in the other. Moreover, the different photosomers can exhibit different pharmacokinetic and pharmacodynamic properties. A frequently used photoactuator is azobenzene, a molecule consisting of two aryl units connected by a diazo bond (N=N). On irradiation with light of a specific wavelength, the thermodynamically more stable $E$ isomer can be converted to its corresponding $Z$ form. This configurational change affects several properties of the molecule including its UV/Vis absorption spectrum, its steric demand, its polarity, and, if embedded in a suitable bioactive structure, its affinity towards, for example, enzymes. The metastable $Z$ isomer can be converted back to the $E$ form by irradiation with light of lower energy or thermally.\textsuperscript{[23]}

In recent years, we have pioneered the control of metabolic multienzyme complexes with diverse photoresponsive tools.\textsuperscript{[24]} In the present work, we explored photocontrollable inhibitors for the essential multienzyme complex TS of the enteric human pathogen \textit{S. typhimurium} as potential antibiotic structures. We designed and synthesized a small library of azobenzene-based compounds, investigated their photochemical behavior, and thoroughly studied their mode of inhibition towards TS. Finally, we substantiated these findings with crystallographic and computational methods and outline a mode of action for this potential drug precursor.
Results and Discussion

Design and molecular realization

Previous studies have described various target sites for inhibitors in the TS complex. We reasoned that targeting the TrpA active site is a good starting point for the design of a photocontrollable inhibitor. Hence, we analyzed the crystal structures of TS with IGP or the inhibitor indole-3-propanol phosphate bound to TrpA to identify the most important ligand–enzyme interactions and steric requirements for binding to the active site (Figure S1.1 in the Supporting Information). Since both ligands form strong hydrogen bonds to residues in the active site with their phosphate motif and their NH moiety (Figure 2 A), we integrated these two groups into our inhibitor design.

Consequently, our synthetic ligands consist of a phosphate motif to which an NH-containing amide moiety is attached through an alkyl linker (Figure 2 B). To allow for reversible photoswitching, we extended the binding part of the molecule with an azobenzene photoswitch attached to the carbonyl group. Finally, we varied the length of the alkyl or aryl linker to find an inhibitor that exhibits the optimal geometry to bind to the TrpA active site in one but not in the other photosomer. Furthermore, we hypothesized that the \( E \) isomers would show stronger binding, whereas the increased steric demand in the \( Z \) isomers should lead to weaker binding. Following this assumption, the inhibitors in \( E \) should competitively displace IGP and inhibit the TrpA reaction, while the \( Z \) isomer should allow for IGP binding and turnover. As a result, due to the strong dependence of the TrpB reaction on binding of IGP to the TrpA active site, we would be able to simultaneously control IGP turnover in TrpA, and tryptophan production in TrpB with light (Figure 2 C).

Synthesis

For the synthesis of a small library of azobenzene-based inhibitors as defined in our design (Figure 2 B), we started from commercially available 4-carboxyazobenzene (1, Scheme 1). We converted the carboxylic acid, by treatment with \( \text{SOCl}_2 \), to the corresponding acyl chloride 2, which was directly treated with differently functionalized amines to give 3a–f (3–31 % yield). As main side reaction, we found chlorination of the arene moiety of the azobenzene, as shown by XRD in a related work. In the last step, the compounds were treated with \( \text{POCl}_3 \) in the presence of 1,8-bis(dimethylamino)naphthalene (proton sponge) as base to functionalize the alcohol group. On aqueous workup, hydrolysis of the phosphorus chloride resulted in the corresponding phosphate derivatives 4a–f.

Figure 2. Design of azobenzene inhibitors of TS by the azo-extension approach. A) Binding of IGP to the active site of TrpA is mainly facilitated by two moieties. The phosphate group (cyan) interacts with the NH groups of the peptide backbone of Gly184, Gly213, Gly234, and Ser235, as well as with the side chain of Ser235. The NH group (orange) forms hydrogen bonds to the sidechain of Asp60. Gray lines indicate the dimensions of the binding pocket. B) The two main binding motifs of IGP, the phosphate and NH groups, were integrated in the design of azo-extended TS inhibitors. The phosphate group was installed at varying distances to an amide through an aryl or alkyl linker. This biologically active module was then extended with an azo moiety that switches configurations (\( E \) = \( Z \); indicated by differently shaped green boxes) on irradiation with UV (365 nm) or visible (420 nm) light. While the \( E \) isomers are expected to bind similar to the native substrate, steric hindrance between inhibitor and binding pocket (gray) is expected to prevent binding of the \( Z \) isomers. C) By displacing IGP (red ellipse) from TrpA with the light-switchable azobenzene inhibitor (green box), TrpA is competitively inhibited and TrpB activity is restored. This step is reversed by irradiation with visible light.

After preparative HPLC purification, the compounds were isolated as orange solids. Unconverted starting material and losses during HPLC purification resulted in only low (0.2%) to moderate (37%) yields. Nevertheless, we obtained enough material for photophysical and photochemical studies as well as for screening of the compounds in a biochemical assay.

Photophysical and photochemical characterization

We next assessed the solubility and switching properties of our inhibitors in aqueous solution to ensure compatibility with the buffer system of our target enzyme TS. Compounds 4a, b, d–f proved to be soluble, and were hence further characterized with UV/Vis spectroscopy in water (Figures S5.1–5.6 in the Supporting Information); the spectra of 4e are shown representatively in Figure 3. Spectra were recorded at thermal equilibrium (black line), after irradiation with UV light of 365 nm (orange line), and after additional irradiation with visible light of 420 nm (green line).

At thermal equilibrium, each compound exhibited a main absorbance maximum between 324 and 331 nm (Table 1), which was assigned to the \( \text{pp}^* \) transition of the \( \text{E} \) isomer.\(^{[23]} \) On irradiation with 365 nm light, the photostationary state \( \text{PSS}^{365\text{nm}} \) formed; the signal of the \( \text{E} \) isomer decreased and simultaneously an absorbance maximum between 423 and 428 nm emerged, which was attributed to the \( \text{np}^* \) transition of the \( \text{Z} \) isomer. The photostationary state distributions (PSD\(^{365\text{nm}} \)) were calculated by peak deconvolution with Gaussian functions and showed that all compounds accumulated 64–88% of the \( \text{Z} \) isomer. Moreover, the metastable \( \text{Z} \) isomer was found to be sufficiently stable for our measurements (vide infra), as we determined a thermal lifetime of 3.76 d for compound 4e (Figure S5.7 in the Supporting Information). Subsequent irradiation with visible light of 420 nm wavelength induced photochemical \( \text{Z} \rightarrow \text{E} \) isomerization to \( \text{PSS}^{420\text{nm}} \). However, the composition of the thermal equilibrium could not be fully regenerated—all compounds only accumulated 71–92% of the \( \text{E} \) isomer (PSD\(^{420\text{nm}} \))—probably due to overlap of the \( \text{np}^* \) band of the \( \text{E} \) and the \( \text{np}^* \) band of the \( \text{Z} \) isomer.\(^{[23]} \)

Evaluation of the inhibition mode

To analyze the inhibitory potential of our compounds, we first determined the concentration range in which the azobenzenes inhibited the overall TS reaction (IGP + Ser → Trp + GAP). We...
measured TS activity by monitoring tryptophan production in a recently established coupled enzymatic assay \([24c]\) in the presence of compounds \(4a,b,d–f\) in their \(E\) or \(Z\) (referring to PSS\(^{25/26}\)) configuration. Inhibitor concentrations were gradually increased, whereas the IGP and serine concentrations were kept constant at 30 \(\mu\)M (\(\approx K_{i}^{\text{app}}\)) and 5 \(\text{mM}\) (saturated\(^{27}\)), respectively. Compounds \(4d–f\) showed 30–70% inhibition in the low millimolar range (0.1–0.25 \(\text{mM}\), Figure S6.1 in the Supporting Information). Compounds \(4a\) and \(4b\), on the other hand, were not able to inhibit TS at soluble concentrations and were therefore excluded from further analyses.

We then quantified the inhibitory effect of compounds \(4d–f\) in their \(E\) and \(Z\) configurations. Since we designed our inhibitors as IGP analogues, we expected a competitive mode of inhibition towards the TrpA substrate (Figure 2C). Hence, we monitored IGP saturation curves for the overall TS reaction in the presence of different inhibitor concentrations. Inhibitor concentrations were chosen from the previous measurements and corresponded to 0% (0 \(\text{mM}\)), \(\approx 30\%\) (0.1 \(\text{mM}\)), \(\approx 50\%\) (0.175 \(\text{mM}\)), and \(\approx 70\%\) (0.25 \(\text{mM}\)) inhibition. For each IGP saturation curve, an apparent Michaelis constant \(K_{i}^{\text{app}}\) and an apparent rate constant \(k_{\text{cat}}^{\text{app}}\) were determined (Figure S6.2, Table S6.1 in the Supporting Information). Competitive inhibition is characterized by a decreased \(k_{\text{cat}}^{\text{app}}\) value and an unchanged \(K_{i}^{\text{app}}\) value; however, we observed unchanged \(k_{\text{cat}}^{\text{app}}\) values and decreased \(K_{i}^{\text{app}}\) values for all our compounds, and this indicates that the inhibitors did not compete with IGP for the TrpA active site.

To identify the actual mode of inhibition, we performed global fits using Equation (2) (vide infra) of the four IGP saturation curves for each inhibitor. Thus, we obtained the factor for inhibitor modality \(\alpha\), which indicates the mode of inhibition, and the inhibition constant \(K_i\) which describes the strength of inhibition, for the inhibitors \(4d–f\) in their \(E\) and \(Z\) configurations. All compounds exhibited finite \(\alpha\) factors indicative of a noncompetitive mode of inhibition\(^{28}\) (Figure S6.2 in the Supporting Information, Table 2), which confirmed our conclusion that the azobenzene inhibitors did not compete with IGP for the TrpA active site. Although the compounds did not exhibit the intended inhibition mode, they nonetheless had \(K_i\) values in the low millimolar range (Table 2). In particular, compound \(4e\) stood out with \(K_i\) values of only \(\approx 0.18\) \(\text{mM}\) for its \(E\) isomer and \(\approx 0.93\) \(\text{mM}\) for its \(Z\) isomer, which correspond to a light regulation factor (LRF) of approximately five. In comparison to \(4e\), the inhibitory strength of \(4d\) was four times weaker, represented by a higher \(K_i\) value, and the LRF of \(4f\) was 2.5 times lower. Compound \(4e\) was consequently chosen as the best candidate for the reversible light-sensitive inhibition of TS, as it combines good inhibitory strength with a high potential for light regulation.

We further tested whether the azobenzene inhibitors might associate with the hydrophobic binding site of indole in TrpB instead of the active site of TrpA. Hence, we measured the TrpB reaction (indole + Ser→Trp) with varying concentrations of indole and saturating concentrations of serine in the presence of our best inhibitor \(4e\). The \(K_{i}^{\text{app}}, k_{\text{cat}}^{\text{app}}, K_i\) and \(\alpha\) values were determined accordingly (Figure S6.3, Table S6.2 in the Supporting Information). Similar to the inhibition studies with IGP, the \(K_{i}^{\text{app}}\) values remained unchanged, whereas the \(k_{\text{cat}}^{\text{app}}\) values decreased with increasing inhibitor concentrations. Consistently, the \(\alpha\) factors for both isomers were finite (\(\approx 0.7\)), indicating that compound \(4e\) does not compete with indole for binding at the TrpB active site. Furthermore, \(4e\) showed \(K_i\) values of approximately 0.18 \(\text{mM}\) for its \(E\) isomer and approximately 0.50 \(\text{mM}\) for its \(Z\) isomer, corresponding to an LRF of approximately three, comparable to the measurements with IGP. These results demonstrate that the inhibitory mode of our light-switchable azobenzene inhibitors is also noncompetitive towards the TrpB active site.

In conclusion, other than originally intended, our synthesized azobenzene-based compounds led to noncompetitive inhibition of TS activity. Nevertheless, inhibition strength could still be light-regulated for all our inhibitors by a factor of 2–6. The \(E\) configuration conferred a stronger inhibitory effect suggesting that this isomer associates more easily with the TS complex than the sterically more demanding \(Z\) isomer. Moreover, increasing length of the alkyl linker in \(4d–f\) resulted in increasingly stronger inhibition; however, it also reduced the potential for light-responsive inhibition. Our best inhibitor \(4e\) showed both a relatively large inhibition constant for the \(E\) isomer of 0.18 \(\text{mM}\) and a relatively high LRF. Previously reported TS inhibitors that bind at the TrpA active site or close to the protein interface showed high or even ultrahigh inhibition strengths with \(K_i\) values of 4.8 \(\mu\)M\(^{26}\) and 40 \(\text{nm}\)\(^{16}\), respectively. In comparison, \(4e\) only shows medium-strength inhibition, which is expected to have at best a slightly harmful effect on bacteria. However, taking into account that this inhibitor was not designed for a noncompetitive inhibition mode, inhibition in the low millimolar range is still noteworthy. We reasoned that, by identifying the exact binding site of \(4e\), we might be able to optimize the structure of this lead compound, and hence its inhibition strength, in future studies.

### Table 2. Inhibition values (\(\alpha, K_i\)) and light-regulation factors for the IGP- and serine-dependent reaction of TS with compounds \(4d–f\) in their \(E\) and \(Z\) configurations.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Isomer</th>
<th>(\alpha)</th>
<th>(K_i) (\text{(mM)})</th>
<th>LRF(^{[a]})</th>
</tr>
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<tbody>
<tr>
<td>(4d)</td>
<td>(E^i)</td>
<td>4.9</td>
<td>0.64 ± 0.08</td>
<td>&gt;6</td>
</tr>
<tr>
<td></td>
<td>(Z^i)</td>
<td>5.9 × 10(^{-11})</td>
<td>&gt;4.0</td>
<td></td>
</tr>
<tr>
<td>(4e)</td>
<td>(E^i)</td>
<td>0.9</td>
<td>0.18 ± 0.04</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(Z^i)</td>
<td>0.3</td>
<td>0.93 ± 0.42</td>
<td></td>
</tr>
<tr>
<td>(4f)</td>
<td>(E^i)</td>
<td>5.0</td>
<td>0.05 ± 0.00</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(Z^i)</td>
<td>5.4</td>
<td>0.10 ± 0.01</td>
<td></td>
</tr>
</tbody>
</table>

\(^{[a]}\text{E}\) refers to the compound at the thermal equilibrium containing approximately 100\% \(E\) isomer. \(\text{Z}\) refers to the compound with the \(Z\)-enriched PSD after irradiation with UV light. \(\text{C}\) LRF = light-regulation factor. Values for \(K_i\) ± standard error were determined by fitting the substrate saturation curves for four different inhibitor concentrations (Figure S6.2 in the Supporting Information) with Equation (2) (vide infra).

### Cocrystallization of TS with azobenzene inhibitor \(4e\)

For identification of the binding site of \(4e\) in the TS complex, we performed cocrystallization experiments. To ensure that TS
was uniformly loaded with 4e in the crystallization setup, we first determined the binding constant $K_d$ of the inhibitor to the TS complex. Isothermal titration calorimetry (ITC) provided a $K_d$ value of approximately 67 μM indicating strong binding of 4e to the TS complex (Figure S7.1 in the Supporting Information). Additionally, we measured the $K_d$ values of 4e to the isolated subunits, obtaining $K_d$ values of approximately 130 μM for TrpA and approximately 10 μM for TrpB (Figures S7.2 and S6.3 in the Supporting Information). Thus, 4e binds to TrpB with significantly higher affinity. We therefore expected that the binding site of 4e was located in the TrpB subunit. Following this analysis, we crystallized the TS complex in the presence of 4e at saturated concentration (≈750 μM) and in excess (ca. twofold) over the enzyme and solved its structure (TS$_{4e}$) with approximately 2.5 Å resolution (PDB-ID: 7A20; Table S7.1 in the Supporting Information). The TS$_{4e}$ structure contained two chain pairs of the functional unit of TS per unit cell. Since crystallization took several weeks, we expected to find the E isomer instead of the thermally unstable Z isomer of 4e (vide supra). However, no electron density could be assigned to the inhibitor. The high binding affinity of 4e to the TS complex and the high concentrations used for the crystallization experiments led to the conclusion that 4e was bound to the TS complex but could not be resolved, which suggested highly dynamic behavior of 4e in the binding site.

We compared TS$_{4e}$ with an active conformation and an inactive conformation of TS to identify potential structural changes induced by 4e (Figure 4). In the structure of the active TS (TS$_{AA}$; blue) an IGP analogue is bound to TrpA, the aminocrylate intermediate is bound to TrpB, and the COMM domain adopts a “closed” conformation. In the structure of the inactive TS (TS$_{IA}$; gray), internal aldime is bound to TrpB, and the COMM domain adopts an “open” conformation. In TS$_{4e}$ (red), no significant structural differences were found in the TrpA subunit and the core structure of the TrpB subunit (Figure 4A). However, the COMM domain is even further shifted towards an “extended-open” conformation (Figure 4B). Notably, the PLP cofactor was missing in the TrpB active site, and instead a single buffer molecule was detected, that is, the TrpB active site is exposed to solvent.

These findings suggest that 4e holds the TS complex in an unproductive conformation defined by an extended-open COMM domain. Similar observations were made by Arnold and co-workers in their studies on TS from *Pyrococcus furiosus*. They found that a single molecule of β-methyl tryptophan bound to a solvent-accessible binding cleft close to the TrpB active site led to an extended-open state that is, the COMM domain was shifted away from the protein core, similar to our extended-open conformation induced by 4e. This conformation of the COMM domain in TS$_{4e}$ most likely prohibits the allosteric communication between the two active sites and renders both enzymes inactive. In addition, access to the TrpB active site is opened by the inhibitor, so that it is unprotected against entry of solvent. These effects of 4e on the TS structure explain the noncompetitive mode of inhibition. However, it is still unclear where the binding site of the inhibitor is located and how the inhibitor causes these changes. Since 4e showed the highest affinity toward the TrpB subunit in binding studies, and since it strongly affected the COMM domain and the TrpB active site in crystallization studies, we continued to search for the binding site in the TrpB subunit by a computational approach.

**Figure 4.** Structural comparison of TS in the presence of 4e (red; PDB-ID: 7A20, chain pair AB) with the fully active aminocrylate bound TS$_{AA}$ (blue; PDB-ID: 2J9X, chain pair AB), and the inactive internal aldime bound TS$_{IA}$ (gray; PDB-ID: 1BKS, chain pair AB). A) Superposition of the three structures. No structural differences were observed in the TrpA subunit (top, transparent) and the core of the TrpB subunit (bottom). B) 4e induced significant conformational changes in the COMM domain. While the COMM domain adopts a closed conformation in TS$_{AA}$ (blue) and an open conformation in TS$_{IA}$ (gray), it is extended-open in the presence of 4e (red).
noncompetitive mode of inhibition with respect to both the TrpA and TrpB active sites. To the best of our knowledge, this binding site has so far been unexplored in inhibition studies. Two other groups described similarly allosteric inhibitors, but their binding site is located within the indole channel and closer to the TrpA:TrpB interface.\(^{[15, 16]}\)

In the presence of the inhibitor, the allosteric communication between the TrpA and TrpB active sites can take place, activating the turnover of IGP in TrpA and serine in TrpB (Figure 6 A, left panel). The \(E\) isomer of \(4e\) binds with high affinity to the TrpB subunit and disturbs the allosteric communication by shifting the COMM domain to the extended-open conformation, rendering TrpB, and most likely TrpA, inactive (Figure 6 A, right panel). Thus, the active, closed conformation of the COMM domain is reconstituted, the allosteric communication is restored, and TrpA and TrpB are both reactivated (Figure 6 A, right panel).

We further evaluated this sequence of events in an in situ irradiation setup (Figure 6 B) by monitoring the activity of the overall TS reaction in three samples. One reaction assay was performed in the presence of inhibitor \(4e\) in its \(E\) configuration in the dark (“dark”). The second assay was started in the presence of inhibitor \(4e\) in its \(E\) configuration and then irradiated during the initial linear activity phase of the enzyme (“direct photocontrol”). Moreover, we applied the same treatment as control to a reaction assay in the absence of \(4e\) (“uninhibited”). TS activity was inhibited approximately twofold by \(4e\) in the dark and direct-photocontrol (prior to irradiation) samples relative to the activity in the uninhibited sample. This confirmed the medium-strength inhibition effect observed in inhibitory studies and depicted in the middle panel of Figure 6 A.

Figure 5. Identification of the \(4e\) binding site in TS. A) Mole2.5\(^{[32]}\) analysis of TS\(_{4e}\) (PDB-ID: 7A20) identified a pocket (gray mesh) between the TrpB active site (marked with the bound buffer molecule in spheres) and the COMM domain (blue) that matches the dimensions of the inhibitor. Note: the cavity is only shown for the chain pair CD; however, it also forms in the chain pair AB. B, C) Docking analysis with YASARA\(^{[33]}\) demonstrated that \(4e\) (green) can bind in various orientations in the binding pocket identified in A) (black); two variations, which represent the binding orientations of cluster 1 (B) and cluster 3 (C), are shown with their predicted \(K_D\) values.

Continuing our computational examination, we tested whether \(4e\) could sterically fit into this cavity and interact with the lining residues. To this end, we performed a docking analysis using YASARA.\(^{[33]}\) In this experiment, the protein conformation was kept fixed, while the inhibitor was docked with full conformational freedom. As a result, 17 binding geometries could be identified for the inhibitor, out of which ten had predicted \(K_D\) values below 5 \(\mu\)M (Table S8.1, Figure S8.2, Figure S8.3 in the Supporting Information). Remarkably, the orientation of \(4e\) in most of the binding geometries differed significantly, as illustrated by two exemplary orientations in Figure S8 B and C, which exhibited predicted \(K_D\) values of 0.5 and 2.0 \(\mu\)M. In these examples, the phosphate group is buried at the deep end of the cavity (Figure S5 B) or points towards the surface of the protein (Figure 5 C). This variety of putative inhibitor geometries in the binding pocket confirms a highly dynamic binding behavior of \(4e\), and is therefore consistent with the lack of electron density in the crystal structure.

Photocontrolling the noncompetitive inhibition of TS

Our findings showed that inhibitor \(4e\), which was originally designed to associate at the TrpA active site, most likely binds to a cavity between the TrpB active site and the COMM domain, and shifts the latter into an unproductive extended-open conformation. In this way, \(4e\) might also block the hydrophobic channel, which is located close to its binding site, and thus impede indole transport from the TrpA active site to the TrpB active site. As a result, the light-sensitive inhibition of TS by \(4e\) is noncompetitive. Hence, a revision of our proposed strategy of light-dependent inhibition of TS (Figure 2 C) was required.

In the absence of the inhibitor, the allosteric communication between the TrpA and TrpB active sites can take place, activating the turnover of IGP in TrpA and serine in TrpB (Figure 6 A, left panel). The \(E\) isomer of \(4e\) binds with high affinity to the TrpB subunit and disturbs the allosteric communication by shifting the COMM domain to the extended-open conformation, rendering TrpB, and most likely TrpA, inactive (Figure 6 A, middle panel). As confirmed by inhibition studies, the \(Z\) isomer, obtained by irradiation with UV light, has lower apparent binding affinity and dissociates from the TrpB subunit. Thus, the active, closed conformation of the COMM domain is reconstituted, the allosteric communication is restored, and TrpA and TrpB are both reactivated (Figure 6 A, right panel).

We further evaluated this sequence of events in an in situ irradiation setup (Figure 6 B) by monitoring the activity of the overall TS reaction in three samples. One reaction assay was performed in the presence of inhibitor \(4e\) in its \(E\) configuration in the dark (“dark”). The second assay was started in the presence of inhibitor \(4e\) in its \(E\) configuration and then irradiated during the initial linear activity phase of the enzyme (“direct photocontrol”). Moreover, we applied the same treatment as control to a reaction assay in the absence of \(4e\) (“uninhibited”). TS activity was inhibited approximately twofold by \(4e\) in the dark and direct-photocontrol (prior to irradiation) samples relative to the activity in the uninhibited sample. This confirmed the medium-strength inhibition effect observed in inhibitory studies and depicted in the middle panel of Figure 6 A. On irradiation of the direct-photocontrol sample, the reaction velocity increased 1.2-fold. This LRF is unexpectedly small and disagrees with the LRF determined in \(K_i\) studies. However, TS
activity in the absence of 4e in our uninhibited sample was decreased by a factor of 2.2 on irradiation with UV light. We previously observed this effect during our studies on light control of TS with photosensitive unnatural amino acids, \[24c\], and associated it with degradation of the light-sensitive PLP cofactor. When we now consider this additional phototoxic effect, light-induced isomerization of 4e actually translates into a 2.6-fold regulation of TS activity, approximating the LRF of about 5 in the \(K_i\) studies. This recovery of enzyme activity constitutes the situation depicted in the right panel of Figure 6 A.

An LRF of 3–5 sets high expectations for the inhibitor’s effect on bacterial growth. In general, photochromic inhibitors of enzymes are often more convincing in vivo than in vitro.\[17b\] This holds true particularly for enzymes in signaling cascades, but also for antibacterial lead compounds, for which it could be shown that an LRF of approximately 2 is sufficient to control bacterial death with light.\[34\] The photocontrolled effect of 4e on the essential multi-enzyme complex TS of S. typhimurium is therefore promising, but various improvements are necessary before its efficacy against bacteria can be proved and ultimately its antibiotic potential can be tested in vivo. First, binding and inhibition strengths need to be increased to improve the effectiveness of the inhibitor in biological systems. For this, the structure of the azobenzene-based compound can be customized for binding to the cavity between the TrpB active site and the COMM domain. Motifs for the specific interaction with residues lining the cavity can be introduced into the linker region or might replace it. Moreover, the irradiation wavelength needs to be shifted towards higher regions of the electromagnetic spectrum, for example, in the red region of visible light, to increase the penetration depth of light and minimize phototoxic effects on the tissue. The hazardous effect of UV light was emphasized by the strong decrease of TS activity after irradiation. The irradiation wavelength, PSD, and thermal lifetime of the Z isomer can be optimized by introducing suitable substituents\[35\] or by applying heteroaryl design.\[36\] Ultimately, the photocontrollable inhibitor can be deployed to tackle common drawbacks of customary antibiotics. These are especially the collateral damage that they cause, for example, by attacking pathogenic and nonpathogenic bacteria, and their permanent biological activity. As a consequence, accumulation of these drugs in the environment promotes the creation and rapid spreading of multiresistance in bacterial strains.\[37\] Hence, a spatiotemporally restricted mode of the antibacterial efficacy of antibiotics is desirable. Our inhibitor 4e is not yet suited for this purpose, as the less inhibitory Z isomer is also the thermally unstable one. Consequently, the amount of the more-inhibitory E isomer would be increased over time. However, by, for example, applying the sign-inversion strategy the thermodynamic stability of the two

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**Figure 6.** Activity modulation of TS by the photoswitchable noncompetitive inhibitor 4e. A) Binding of 4e in its E configuration (green rectangle) to TrpB shifts the COMM domain to an extended-open conformation, which likely disrupts the allosteric activation between TrpA and TrpB and thus diminishes tryptophan production from IGP (red ellipse) and Ser. On irradiation with UV light, the inhibitor is isomerized to its Z configuration (green elbow), which restores TrpA and TrpB activity. This step is reversed by irradiation with visible light. B) Direct photocolor of TS activity with 4e (red) compared to a dark control (kept in the dark; gray) and an uninhibited control (in the absence of 4e, black). Reaction conditions: 50 mM potassium phosphate pH 7.5, 100 mM KCl, 5 mM L-serine, 3.0 mM phenol, 3.0 mM 4-aminoantipyrine, 20 \(\mu\)M PLP, 0.075 g L\(^{-1}\) HRP, 1.0 g L\(^{-1}\) VioA, and, in the case of direct photocolor and dark, 250 \(\mu\)M 4e. All three reactions were started with the TS complex (0.1 mM), monitored for approximately 30 min, irradiated for 15 s at 365 nm while enzyme velocity was still in the initial linear range, and monitored further up to 50 min.
photoisomers could be inverted to make the strongly inhibitory E isomer the metastable form.[30]

Conclusion
Despite an urgent need, the search for new antibiotics was only recently expanded to inhibitors that target metabolic enzymes or that can be controlled externally. Following this research direction, we set out to explore the TS of S. typhimurium as a potential antibiotic target enzyme by designing an inhibitor that can be controlled in a spatiotemporal manner by light. Hence, we synthesized a small library of azobenzene-based inhibitors towards the TrpA subunit. The compounds can be reversibly switched in water up to approximately 90% of the photochemically generated isomer by using UV or blue light. Inhibition studies quickly identified 4e as the most promising TS inhibitor, as it provides exceptionally good solubility, distinct photochromism, reasonable inhibition, and a pronounced difference in inhibition strength between the photoisomers. This analysis also revealed a noncompetitive mode of inhibition towards both the TrpA and TrpB active sites, a finding contrary to our design. We consequently used a combination of ITC-based binding studies, crystallization experiments, and computational analyses to unravel the potential binding site of 4e, which is a cavity at the TrpB subunit. Moreover, structural analysis showed pronounced conformational changes of the COMM domain, which adopted an allosterically unproductive extended-open conformation. In further studies, we aim to improve the design of this new lead compound, taking the characteristics of its actual binding site into account, and to optimize the photophysical and photochemical properties of the parent azobenzene. These findings are the starting point to develop fully light-controllable TS inhibitors, which can be further optimized into smart antibiotic agents.

Experimental Section
General information
Analytical samples of the alcohols and final compounds were purified by preparative HPLC [MeCN in H2O/0.05% trifluoroacetic acid (TFA) 5–100% over 20 min] to give all compounds as orange solids. NMR spectra were recorded with a Bruker Avance 400 MHz NMR or a Bruker Avance 600 Kryo. Some of the alcohols partly decomposed during the measurement. Thus, carbon signals were assigned by means of HSQC measurements (quaternary carbon atoms could not be assigned in these cases). Due to the low reaction yields, 13C NMR spectroscopy was not feasible for 4a-d.f. A description of the general working methods can be found in Section 1 of the Supporting Information.

Synthesis
General procedure for amide formation: In a crimp-top vial, (E)-4-(phenyl diazenyl)benzoic acid (1 equiv) was dissolved in SOCl2 (1 mL per 200 mg). The suspension was heated to 80 °C for 2 h to give a clear, red solution. The reaction mixture was cooled to ambient temperature and the solvent was removed in vacuo. The vial was flushed with vacuum/nitrogen three times and dry CHCl3 (5 mL) was added under nitrogen atmosphere. Then, a solution of the respective aniline (1 equiv) or amino alcohol (1 equiv), in dry pyridine (1 mL) was added dropwise through a syringe. The solution was stirred for 16 h and the solvent was removed in vacuo. The crude product was purified by MPLC (20→100% EtOAc in petroleum ether).

(E)-N-(4-(2-hydroxyethyl)phenyl)-4-(phenyl diazenyl)benzamide (3a): (E)-4-(Phenyl diazenyl)benzoic acid (4.42 mmol) was employed. Compound 3a was obtained in 8% yield (0.37 mmol), Rf (10% MeOH in CH2Cl2): 0.6. 1H NMR (500 MHz, CD3OD in CDCl3): δ = 8.03 (d, J = 8.5 Hz, 2 H), 7.98–7.93 (m, 2 H), 7.92–7.89 (m, 2 H), 7.57 (d, J = 8.3 Hz, 2 H), 7.53–7.45 (m, 3 H), 7.19 (d, J = 8.4 Hz, 2 H), 3.76 (t, J = 6.9 Hz, 2 H), 2.80 (t, J = 6.9 Hz, 2 H). 13C NMR (151 MHz, D2acetate): δ = 132.0 (+), 130.3 (+), 130.1 (+), 129.6 (+), 123.8 (+), 123.4 (+), 121.1 (+), 64.0 (–), 30.4 (–). Assignment was based on HSQC measurements due to low concentrations and lability of the compound. Thus, quaternary carbon atoms could not be assigned. IR: ν = 3351(m), 2926 (w), 2863 (w), 1648 (s), 1502 (m), 1454 (m), 1407 (s), 1339 (m), 1272 (m), 1199 (w), 1092 (w), 1051 (s), 996 (w), 943 (m), 861 (m), 820 (m), 771 (m), 686 cm−1 (m). ESI-MS: calcld. 345.1477, found: 371.3 (2MNa+, 5%), 368.1 (MNa+, 10%), 346.2 (M−, 100%). HRMS (ESI): found: 368.1373 (MNa+, 15%), 346.1559 (M−, 100%).

(E)-N-(2-hydroxyethyl)4-(phenyl diazenyl)benzamide (3b): (E)-4-(Phenyl diazenyl)benzoic acid (4.42 mmol) was employed. Compound 3b was obtained in 31% yield (1.39 mmol). Rf (10% MeOH in CH2Cl2): 0.5. 1H NMR (500 MHz, D2acetate): δ = 8.10–8.05 (m, 2 H), 7.98–7.90 (m, 4 H), 7.60–7.51 (m, 3 H), 3.68 (t, J = 5.7 Hz, 2 H), 3.50 (q, J = 5.6 Hz, 2 H). 13C NMR (151 MHz, D2acetate): δ = 129.5 (+), 129.2 (+), 128.2 (+), 122.3 (+), 60.8 (–), 42.5 (–). Assignment was based on HSQC measurements due to low concentrations and decomposition of the compound during the extended measuring time. Thus, quaternary carbon atoms could not be assigned. IR: ν = 3258 (w), 3064 (w), 3926 (w), 1722 (m), 1626 (m), 1268 (s), 1092 (m), 857 (m), 686 cm−1 (s). ESI-MS: calculated: 269.1164, found: 361.2 (2MNa+, 20%), 329.1 (MNa+, 20%), 270.1 (M−, 100%), HRMS (ESI): found: 292.1062 (M2Na+, 20%), 270.1242 (M−, 100%).

(E)-N-(3-hydroxypropyl)-4-(phenyl diazenyl)benzamide (3c): (E)-4-(Phenyl diazenyl)benzoic acid (2.21 mmol) was employed. Compound 3c was obtained in 3% yield (0.06 mmol), Rf (10% MeOH in CH2Cl2): 0.5. 1H NMR (500 MHz, D2acetate): δ = 8.16–8.06 (m, 2 H), 8.03–7.87 (m, 4 H), 7.75–7.57 (m, 3 H), 3.64 (t, J = 6.0 Hz, 2 H), 3.55 (q, J = 6.5 Hz, 2 H), 1.80 (p, J = 6.5 Hz, 2 H). 13C NMR (101 MHz, D2acetate): δ = 166.1 (q), 153.9 (q), 152.5 (q), 137.1 (q), 131.7 (+), 129.3 (+), 128.3 (+), 122.8 (+), 122.5 (+), 59.1 (–), 36.9 (–), 32.5 (–). IR: ν = 3368 (w), 3291 (m), 3060 (w), 2937 (w), 2881 (w), 1627 (s), 1536 (s), 1073 (m), 775 (m), 686 (s). ESI-MS: calculated: 383.1234, found: 360.1 (M−, 20%), 284.1 (M−, 100%), HRMS (ESI): found: 306.1215 (M−, 20%), 284.1401 (M−, 100%).

(E)-N-(4-hydroxybutyl)-4-(phenyl diazenyl)benzamide (3d): (E)-4-(Phenyl diazenyl)benzoic acid (2.1 mol) was employed. Compound 3d was obtained in 10% yield (0.22 mmol), Rf (10% MeOH in CH2Cl2): 0.5. 1H NMR (500 MHz, D2acetate): δ = 8.11–8.06 (m, 2 H), 7.99–7.93 (m, 4 H), 6.73–6.55 (m, 3 H), 3.59 (t, J = 6.2 Hz, 2 H), 3.51–3.39 (m, 2 H), 1.78–1.66 (m, 2 H), 1.66–1.55 (m, 2 H). 13C NMR (101 MHz, D2acetate): δ = 165.5 (q), 153.8 (q), 152.5 (q), 137.4 (q), 131.7 (+), 130.8 (+), 129.3 (+), 128.2 (+), 122.4 (+), 61.3 (+), 39.6 (+), 30.2 (+), 26.2 (–). IR: ν = 3321 (w), 3045 (w), 2926 (w), 2862 (w), 1647 (s), 1521 (s), 861 (m), 820 (s), 771 (s), 865 cm−1 (s). ESI-MS: calculated: 397.1477, found: 417.3 (2MNa+, 40%), 320.1 (M−, 20%), 298.2 (M−, 100%), HRMS: 320.1376 (MNa+, 40%), 298.1559 (M−, 100%).
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**Phosphorylation**

**General procedure I for phosphorylation:** An oven-dried crimp-top vial was loaded with compound 3a,b,d,f (1 equiv), proton sponge (3 equiv), and a stirring bar, and sealed. The vial was purged with vacuum/nitrogen (3× each) before dry CHCl₃ (1 mL per 0.15 mmol) was added. The reaction mixture was cooled to 0 °C and POCl₃ in dry THF (1:2, 0.5 mL per 0.15 mmol) was added dropwise via syringe. Then, the mixture was allowed to warm to ambient temperature and was stirred for 2 h. After quenching with acetic anhydride (1:1), the solvent was removed in vacuo and the crude product was purified through preparative HPLC (MeCN in H₂O/0.05% TFA, 95→99%). The products were obtained as orange powders after lyophilization.

**Phosphorylation**

**General procedure II for phosphorylation:** An oven-dried crimp-top vial was equipped with compound 3c,e (1 equiv), proton sponge (3 equiv), and a stirring bar, and sealed. The vial was purged with vacuum/nitrogen (3× each) before PO(O)Me (1 mL per 0.15 mmol) was added. The reaction mixture was cooled to 0 °C and POCl₃ (0.5 mL per 0.15 mmol) was added dropwise by syringe. Then, the mixture was allowed to warm to ambient temperature and was stirred for 2 h. After quenching with acetic anhydride (1:1), the solvent was removed in vacuo and the crude product was purified by preparative HPLC (MeCN in H₂O/0.05% TFA, 5→95%). The products were obtained as orange powders after lyophilization.

(E)-N-(5-hydroxypent-4-yl)phenyl diazenyl)benzamide (3e): 6-(4-(Phenyldiazenyl)benzamido)hexyl dihydrogen phosphate (4e): Compound 3e (125 mg, 0.36 mmol) was employed. Compound 4a was obtained in 0.5% yield (0.8 mg, 0.002 mmol). HPLC: Rₜ = 15.7 min, >99% purity (220 nm), 96% purity (254 nm trace).

**General procedure I for phosphorylation:** An oven-dried crimp-top vial was loaded with compound 3a,b,d,f (1 equiv), proton sponge (3 equiv), and a stirring bar, and sealed. The vial was purged with vacuum/nitrogen (3× each) before PO(O)Me (1 mL per 0.15 mmol) was added. The reaction mixture was cooled to 0 °C and POCl₃ (0.5 mL per 0.15 mmol) was added dropwise by syringe. Then, the mixture was allowed to warm to ambient temperature and was stirred for 2 h. After quenching with acetic anhydride (1:1), the solvent was removed in vacuo and the crude product was purified through preparative HPLC (MeCN in H₂O/0.05% TFA, 5→95%). The products were obtained as orange powders after lyophilization.

(E)-4-(phenyl diazenyl)benzamidephenethyl diphosphoryl phosphate (4a): Compound 3a (125 mg, 0.36 mmol) was employed. Compound 4a was obtained in 0.5% yield (0.8 mg, 0.002 mmol). HPLC: Rₜ = 15.7 min, >99% purity (220 nm), 96% purity (254 nm trace).

**General procedure II for phosphorylation:** An oven-dried crimp-top vial was equipped with compound 3c,e (1 equiv), proton sponge (3 equiv), and a stirring bar, and sealed. The vial was purged with vacuum/nitrogen (3× each) before PO(O)Me (1 mL per 0.15 mmol) was added. The reaction mixture was cooled to 0 °C and POCl₃ (0.5 mL per 0.15 mmol) was added dropwise by syringe. Then, the mixture was allowed to warm to ambient temperature and was stirred for 2 h. After quenching with acetic anhydride (1:1), the solvent was removed in vacuo and the crude product was purified by preparative HPLC (MeCN in H₂O/0.05% TFA, 5→95%). The products were obtained as orange powders after lyophilization.

(E)-4-(phenyl diazenyl)benzamidephenethyl diphosphoryl phosphate (4a): Compound 3a (125 mg, 0.36 mmol) was employed. Compound 4a was obtained in 0.5% yield (0.8 mg, 0.002 mmol). HPLC: Rₜ = 15.7 min, >99% purity (220 nm), 96% purity (254 nm trace).

**Phosphorylation**

**General procedure I for phosphorylation:** An oven-dried crimp-top vial was loaded with compound 3a,b,d,f (1 equiv), proton sponge (3 equiv), and a stirring bar, and sealed. The vial was purged with vacuum/nitrogen (3× each) before dry CHCl₃ (1 mL per 0.15 mmol) was added. The reaction mixture was cooled to 0 °C and POCl₃ in dry THF (1:2, 0.5 mL per 0.15 mmol) was added dropwise via syringe. Then, the mixture was allowed to warm to ambient temperature and was stirred for 2 h. After quenching with acetic anhydride (1:1), the solvent was removed in vacuo and the crude product was purified through preparative HPLC (MeCN in H₂O/0.05% TFA, 5→95%). The products were obtained as orange powders after lyophilization.

(E)-4-(phenyl diazenyl)benzamidephenethyl diphosphoryl phosphate (4a): Compound 3a (125 mg, 0.36 mmol) was employed. Compound 4a was obtained in 0.5% yield (0.8 mg, 0.002 mmol). HPLC: Rₜ = 15.7 min, >99% purity (220 nm), 96% purity (254 nm trace).
Photophysical and photochemical characterization

UV/Vis absorption spectra of compounds 4a–f were recorded with a JASCO V-650 spectrophotometer. Compound 4c and the thermal lifetime of compound 4e were analyzed with an Agilent 8453 spectrophotometer. For temperature control, a Varian Cary single-cell Peltier apparatus was used. The used solvent and concentration are stated for each experiment. UV-induced isomerization reactions were performed with a Soul Veasos single-spot LED (365 nm, 0.9 W), an OSRAM Oslo SDL 80 single-spot LED (455 nm, 1.2 W), or a Sylvania UV lamp with two 8 W fluorescent black-light bulbs (settings: 250 mA, 220 V). Sample volume was ≤1 mL. For direct photocontrol experiments, 4e was isomerized by using a high-power LED (LED Engin, Osram; settings: 700 mA and 16 V) for 15 s. The sample volume was 200 μL.

Bacterial strains, plasmids, and chemicals

The proteins used in this work were produced in the E. coli expression strains E. coli BL21 Gold (DE3) (purchased from Agilent Technologies, Santa Clara, CA, USA) and E. coli BL21 (DE3) Rosetta (purchased from Novagen, Merck, Darmstadt, Germany). The following technologies, Santa Clara, CA, USA) and E. coli were expressed in BL21 (DE3) Rosetta and BL21 Gold (DE3), respectively. Expression and purification of TS strains were grown in 4L LB medium supplemented with kanamycin at 37 °C. Cells were harvested by centrifugation and the pellets were suspended in 20 mM Tris-HCl pH 7.5, 300 mM KCl, 80 mM NaCl, and 20 mM imidazole. The target protein was obtained from the supernatant after sonication and repeated centrifugation steps. VioA was captured by nickel-affinity chromatography (HiTrap FF Crude column, 5 mL, GE Healthcare, Chicago, IL, USA) and eluted with a linear gradient of imidazole (0–500 mM). Fractions containing the target protein were identified by SDS-PAGE analysis, pooled, and further purified by size-exclusion chromatography (Superdex 75 HiLoad 26/600, GE Healthcare, Chicago, IL, USA) with 20 mM Tris-HCl pH 8.0 as running buffer. Fractions containing the purified protein were pooled and dripped into liquid nitrogen for storage at −80 °C.

Steady-state activity measurements and inhibition studies

In general, steady-state enzyme kinetic measurements were performed at 25 °C and monitored spectrophotometrically by using a microplate reader (Infinite M200 Pro, TECAN, Männedorf, Switzerland). Turnover of IGP or.indole to Trp was measured with a coupled enzymatic assay[24c] employing VioA, which oxidized Trp to produce the side-product peroxide, and horseradish peroxidase (HRP), which then turned over peroxide with 4-aminooantipyrine and phenol to water and a quinone imine. Formation of the latter was monitored at 505 nm (ΔA505 (quinone imine) = 6,400 m−1 cm−1). All reactions were started by addition of the TS complex in 1:1 stoichiometry. Reaction conditions were: 50 mM KP, pH 7.5, 100 mM KCl, 5 mM Ser, 1.0 mM phenol, 1.0 mM 4-aminooantipyrine, 20 μM pyridoxal phosphate (PLP), 0.15 g L−1 horseradish peroxidase (HRP), 1.0 g L−1 VioA, and varying concentrations of substrate (0–200 μM for indole, 0–150 μM for IGP). In order to determine turnover rates, the initial slopes v_i of the substrate turnover curves were measured and divided by the total enzyme concentration (E_T). These turnover rates v_i/E_T (in s−1) were plotted against the substrate concentration [S]. Michaelis–Menten constants K_m and turnover numbers k_cat were determined by fitting the data with Equation (1) by using Origin 2019 (OriginLab).

\[
v_i = \frac{k_{cat}[S]}{K_m + [S]}
\]

To identify the concentration range in which the azobenzene-based compounds inhibited TS, activity measurements were performed with varying inhibitor concentrations and constant IGP and Ser concentrations. Reaction conditions were: 50 mM KP, pH 7.5, 100 mM KCl, 5 mM Ser, 1.0 mM phenol, 1.0 mM 4-aminooantipyrine, 20 μM PLP, 0.15 g L−1 HRP, 1.0 g L−1 VioA, 30 μM IGP, and 0–300 mM 4d–f. Reactions were performed at 25 °C. After baseline detection, the reactions were started by addition of the 0.1 μM TS complex in 1:1 TrpA:TrpB stoichiometry. All measurements were performed by using a microplate reader (Infinite M200 Pro, TECAN, Männedorf, Switzerland). The initial reaction rates for different inhibitor concentrations were normalized to the reaction rate in the absence of inhibitor, and plotted against the logarithm of the inhibitor concentration.

To determine the mode of inhibition, steady-state kinetics were recorded for four different inhibitor concentrations, which corresponded to degrees of inhibition of 0% (0 μM), 50% (100 μM), 50% (175 μM), and 70% (250 μM), as measured in the previous setup. Reaction conditions were: 50 mM KP pH 7.5, 100 mM KCl, 5 mM l-serine, 1.0 mM phenol, 1.0 mM 4-aminooantipyrine, 20 μM PLP, 0.15 g L−1 HRP, 1.0 g L−1 VioA, and varying concentrations of substrate (0–150 μM for IGP and 0–200 μM for indole). Reactions were started by addition of 0.1 μM TS complex in 1:1 TrpA:TrpB stoichiometry. Fitting the data of a single kinetic experiment to the Michaelis–Menten equation [Eq. (1)] provided an apparent rate constant k_app and the apparent Michaelis constant K_app. The values of the inhibition constant K_i and the α value, which describes the mode of inhibition, were determined by using a gener-
al model for enzyme inhibition.\[^{[20]}\] For this, the steady-state kinetic data in presence of inhibitor was evaluated by plotting the measured reaction rates \(v_i\) divided by the total enzyme concentration \(E_i\) against the substrate concentration \(S\). The values for \(k_{ow}\), \(K_m\), \(K_i\), and \(\alpha\) were determined by a global fit of the four inhibition curves for the four inhibitor concentrations \([I]\) with Equation (2).\[^{[20]}\]

\[
v_i = \frac{k_{ow}[S]}{[S] + K_m(1 + \frac{1}{K_i} + \frac{[I]}{K_i})}
\]  

(2)

Competitive inhibition is characterized by an infinite \(\alpha\) value (\(\alpha \to \infty\)), because there is no binding of the inhibitor to the enzyme:substrate (ES) complex. Uncompetitive inhibition leads to an \(\alpha\) value close to zero (\(\alpha \ll 1\)), because there is no binding to the free enzyme.\[^{[20]}\] In noncompetitive inhibition, there is affinity for both the ES complex and the free enzyme, which is characterized by a finite value of \(\alpha\).

**Determination of binding constants**

Binding constants were determined by means of ITC measurements with a MicroCal PEAQ-ITC system (Malvern). Solutions of protein (50–100 \(\mu\)m) and \(4e\) (1.0 mm) were prepared by using the same buffer stock (\(\approx 300 \text{mm Tris-HCl, pH 8.0}\)). Three control experiments, namely the titration of buffer with buffer, the titration of protein solution with buffer, and the titration of buffer with ligand, were performed. Each titration experiment was baseline corrected and the signal peaks of each injection were integrated by MicroCal PEAQ-ITC analysis (version 1.22, Malvern Panalytical). Then, each protein–ligand titration experiment was corrected for each control experiment and processed by using the built-in functions of MicroCal PEAQ-ITC analysis with the “single set of identical sites” option. Thus, a \(\Delta H\) versus molar ratio (ligand:protein) plot and fit values for the binding constant \(K_D\), the number of binding sites \(n\), and the molar heat of ligand binding \(\Delta H\) were obtained. The fitted number of binding sites in initial analyses was close to one. For better comparability, the number of binding sites was then set to one for all experiments.

**Crystallization**

Tryptophan synthase was cocristallized with ligand \(4e\) by using the hanging-drop vapor-diffusion method. For this, TrPA and TrPB were complexed in equimolar amounts and supplemented with a twofold excess of ligand \(4e\) to final concentrations of 30 g L\(^{-1}\) TS complex and 750 \(\mu\)m ligand \(4e\) in 50 mm Tris-HCl pH 7.5. Then, 1 \(\mu\)L of the mixture was mixed with 1 \(\mu\)L of reservoir solution containing 7\% PEG 8000 and 0.1 mm sodium citrate, pH 5. Crystals grew within several weeks in a rod-like morphology. Crystals were mounted on a nylon loop and shock-frozen in liquid nitrogen with addition of further cryoprotectants.

**Identification of tunnels with MOLE 2.5**

To find cavities in the crystal structure of TS\(_{4e}\), the graphical user interface of MOLE 2.5.17.4.24 was used. The structure of TS\(_{4e}\) was loaded into the program and tunnels were identified by applying the automated built-in protocol with default parameter settings, that is, a bottleneck radius of 1.25 \(\AA\), an origin radius of 5.00 \(\AA\), a surface cover radius of 10.00 \(\AA\), a bottleneck length of 0.00 \(\AA\), a cutoff ratio of 0.90, a minimum tunnel length of 0.00 \(\AA\), and a minimum pore length of 0.00 \(\AA\). The default weight function was the Voronoi scale. Note: we use the term “cavity” for the identified pocket, whereas MOLE 2.5 uses the term “tunnel”.

**Docking with YASARA**

Compound \(4e\) was docked to TrPB by VINA docking\[^{[41]}\] as implemented in YASARA, by utilizing the YASARA2 force field\[^{[29]}\]. For this, TrPB residues 85, 87, 109, 112, 114, 115, 166, 190, 350, 379, and 382 that surround the binding site were set as flexible. Compound \(4e\) was docked 100 times to different TrPB conformations and the results were sorted according to their estimated binding energies. Additionally, these poses were clustered into 17 distinct complex conformations that had a distance of at least 5 \(\AA\) deduced as root mean square deviation of the heavy atoms of \(4e\). Moreover, checking the planarity of the azobenzene moiety after each docking run confirmed that the integrity of the ligand was constantly preserved.

**In situ irradiation**

Reaction conditions for the direct photocontrol of enzymatic turnover included 50 mm K\(_P\) pH 7.5, 100 mm KCl, 5 mm Ser, 1.0 g L\(^{-1}\) VioA, 0.075 g L\(^{-1}\) HRP, 100 \(\mu\)m IGP, 1.0 mm 4-aminooantipyrine, 1.0 mm phenol, 20 \(\mu\)mol PLP, 200 \(\mu\)mol \(4e\), and 0.1 mm TS complex. The reaction was started by the addition of the 0.1 mm TS complex in 1:1 stoichiometry and monitored at \(\lambda = 505\) nm with \(\Delta A_{505}\) (quinine imine) = 6400 M\(^{-1}\) cm\(^{-1}\).\[^{[40]}\] Measurements were performed in a plate reader (Tecan Infinite M200 Pro) and activities were deduced from the slopes of the transition curves. Altogether two samples and two controls were measured simultaneously. The reaction rate of the first sample was monitored in the dark. The second sample was irradiated during the initial linear-activity phase. Control experiments were performed either in the absence of \(4e\) or with buffer instead of TS complex. Irradiation of the second sample and the two controls was carried out by pausing the measurement in the plate reader, taking out the plate, and exposing the three wells to UV light, while keeping the other well (positioned furthest away), containing the first sample, covered. The samples were irradiated after 30 min for 15 s with 365 nm (Mouser, high-power LED, 365 nm, 1.7 V, 700 mA), which corresponded to the irradiation time necessary for \(Z \rightarrow E\) isomerization under these conditions. The turnover curves of the irradiated second sample and control sample in the absence of \(4e\) were baseline-corrected by subtraction of the buffer control. The first sample was baseline corrected by subtraction of a linear fit of the first 20 min of the buffer control.

**Acknowledgements**

We thank Elisabeth Bauer, Sonja Fuchs, Jeannette Ueckert, and Sabine Laber for excellent technical assistance, Stefanie Zwi- sele for preparing crystals of TS, and Karin Rustler for fruitful discussions. We are grateful to Dr. Stefano Crespi (University of Groningen) for his assistance regarding the PSD analysis. NAS thanks the Studienstiftung des Deutschen Volkes for a PhD scholarship. This work was supported by a grant of the Deut- sche Forschungsgemeinschaft to RS (STE 891/12-2). Open access funding enabled and organized by Projekt DEAL.
Conflict of interest

The authors declare no conflict of interest.

Keywords: antibiotics · azo compounds · enzymes · inhibitors · photo pharmacology


