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Synthesis and physico-chemical properties of an acridine analog of the Tröger's base

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Summary — The heterocyclic aromatic amine 3-aminoacridine **1**, a common DNA-intercalator, reacts regioselectively with formaldehyde in trifluoroacetic acid to yield the Tröger's base analog **2**. The two acridine rings in **2** form a dihedral angle of 89.4° as indicated by X-ray analysis. The UV-visible absorption of the acridine chromophore in the Tröger's base **2** exhibits large variations as compared to the parent acridine. An interpretation is presented based on quantum mechanical PM3 calculations. Partial resolution of the racemic Tröger's base analog is described, the (+)-isomer is obtained with 75% ee and exhibits an optical rotation $[\alpha]_D = +1950$ (c 9.3 × 10^{-2}, $CHCl_3$).

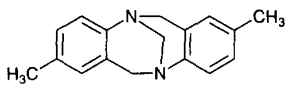
Tröger's base / acridine / 1,5-diazocine

Résumé — Synthèse et propriétés physico-chimiques d'un analogue de la base de Tröger dérivé d'acridine. La 3-aminoacridine **1**, intercalant typique de l'ADN, réagit régiosélectivement avec le formaldéhyde dans l'acide trifluoroacétique pour donner l'analogue **2** de la base de Tröger. Les deux cycles acridiniques de la molécule **2** forment entre eux un angle de 89,4° comme l'indique l'analyse aux rayons X. L'absorption UV-visible des noyaux acridines dans la base de Tröger **2** est notablement différente de celle de l'acridine elle-même. Une interprétation basée sur des calculs de mécanique quantique PM3 est présentée. Un dédoublement partiel du mélange racémique de la base de Tröger **2** est décrit, l'isomère (+) est obtenu avec un excès énantiomérique de 75 %, le pouvoir rotatoire mesuré est : $[\alpha]_D = +1950$ (c 9,3 × 10^{-2}, $CHCl_3$).

base de Tröger / acridine / 1,5-diazocine

Introduction

The Tröger's base or 2,8-dimethyl-6*H*,12*H*-5,11-methanodibenzo[*b*,*f*][1,5]diazocine (scheme 1) was first prepared in 1887 from *p*-toluidine and formaldehyde. The structure was proposed by Spielman in 1935 [1]. Having a C2 axis of symmetry, the Tröger's base is chiral. Prelog and Wieland successfully achieved the first resolution of this chiral molecule in 1944 [2]. The mechanism of formation was later studied by Wagner in 1954 [3].



Tröger's Base

Scheme 1

Recently Tröger's base derivatives have been described as 'fascinating' molecules [4] and they have been extensively studied in the past few years. With an angle close to 90° between the sides of the 1,5-diazocine bridge [5], these rigid molecules are suitable for molecular recognition. They have been incorporated in cyclophanes [6] and other non-macrocyclic receptors [7]. But so far, little has been done to use this property for chiral recognition [8, 9]. The tendency to racemize in an acidic medium represents indeed an intrinsic limitation for general use. In addition, it is important to note that until very recently [10], all Tröger's bases prepared are derived from 4-substituted anilines and not from π-electron deficient heterocyclic aromatic amines.

In a program devoted to the synthesis of new heterocyclic intercalating drugs, we have studied the electrophilic substitution on acridine and acridine derivatives. We have previously observed a total regioselectivity for electrophilic substitution at positions 4 and 5 of 3,6-diaminoacridine (proflavine) [11]. This result prompted us to apply this observation to the synthesis of Tröger's base analogs in the acridine series [12]. Acridine derivatives are known for their affinity for DNA and their intercalating properties. It seems thus reasonable to postulate that Tröger's base analogs, such as **2**, that include two acridine rings in their structure, could interact with DNA, and due to the chirality of the

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Tröger's base, the two enantiomers could show different complexation geometries and then possibly achieve discrimination between left and right handed DNA (fig 1). This hypothesis is further reinforced by the results of molecular modelling and dynamic studies of the interaction between the two acridine-derived Tröger's base enantiomers and a short oligonucleotide [13]. The results of this theoretical study showed that the two enantiomers could interact differently with the B-double helix and thus might be useful as chirality probes.

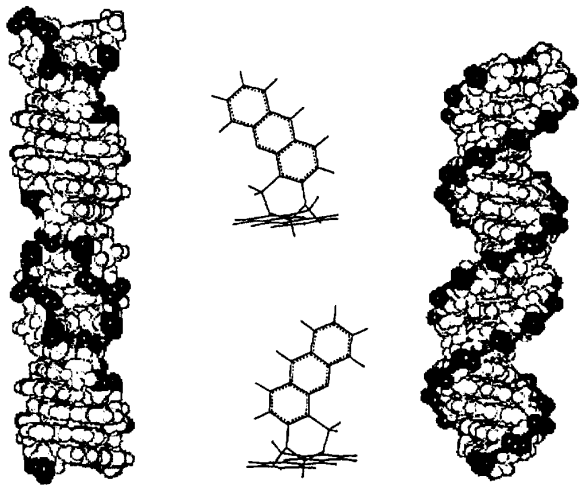


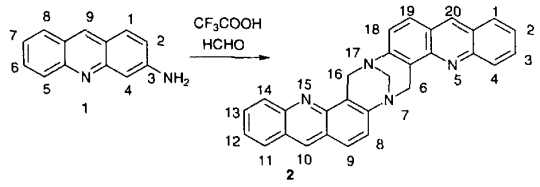
Fig 1. Representation of B- and Z-DNA conformations and of the two enantiomers of Tröger's base **2** shown with one acridine nucleus receding.

The existence and the biological significance of such unusual left-handed Z conformations in DNA are problems of current interest and so far chiral metal complexes such as $[Ru(Phen)_3]^{2+}$ are the only compounds described that exhibit enantioselective recognition for B-DNA [14]. Despite the great importance of Tröger's base derivatives in molecular recognition, little has been published concerning their physical [15] and chemical [16] properties. Before studying the interaction of acridine-derived Tröger's bases with DNA it appeared important to study in detail the properties of the first member of the series, ie, compound **2** that incorporates two unsubstituted acridine nuclei. Whereas we published in preliminary form the synthesis of this molecule **2**, we describe here the full study of this compound.

Results and discussion

Synthesis

Tröger's bases result from the reaction of aromatic amines with formaldehyde in an acidic medium. 3-Aminoacridine **1** reacts with formaldehyde in an acidic medium to give Tröger's base analog **2** (scheme 2) with yields that are extremely sensitive to the acidity of the medium and to the formaldehyde content [12, 17]. The best yield (approaching 90% as indicated by HPLC analysis but leading to 68% in isolated compound due to the inevitable loss of material during chromatography) was obtained when the reaction was performed at room temperature in trifluoroacetic acid using stoichiometric amounts of formaldehyde (1.5 equiv).



Scheme 2

Compound **2** was identified by ^1H NMR spectroscopy. The absence of a signal corresponding to the H-4 of compound **1** was a first indication that a reaction had occurred on position 4. This was confirmed by identification of two doublets for H-8/H-18 and H-9/H-19. The methylene bridge appeared as a singlet at 4.57 ppm and the two benzylic-type methylenes as two doublets at 5.07 and 5.17 ppm. The assignment of the *endo* and *exo* protons was carried out by irradiation of the methylene bridge. The signal at higher fields was enhanced and therefore attributed to the *exo* protons. To confirm this attribution, the H-8/H-18 protons were equally irradiated, leading to enhancement of the signal at lower fields that was attributed to the *endo* protons. It is interesting to point out that the relative chemical shifts of the *endo* and *exo* protons of the Tröger's base **2**, in the acridine series, differ considerably from those in benzene [18], phenanthroline and other heteroaromatic series [10] where the *exo* protons appear at lower fields than the *endo* protons. This difference probably reflects the influence of the ring current of the acridine heterocycle and/or the effect of the acridine heterocyclic nitrogens that are very close to the *endo* protons.

X-ray analysis

The X-ray analysis of compound **2** (as a racemic mixture) was performed. Very thin crystals (thickness 0.01 mm) were obtained by the vapour diffusion method from a dimethylformamide solution equilibrated by ethyl acetate. These crystals were examined on an ENRAF-NONIUS CAD4 rotating-anode X-ray diffractometer. Because of the glide planes in the space group, the crystal is racemate with an equal number of both enantiomers within its crystal structure. The structure found reveals a folding between the two acridine moieties. The intramolecular dihedral angle between the least-squares planes through the acridine rings is 89.5°. This nearly 90° bend in the molecule is illustrated in perspective view (fig 2). A packing diagram shows that the crystal is composed of continuous stacks along *b* (which corresponds to a low crystal thickness) between the acridine parts (fig 3).

Table I. Molecular calculations: quantities that characterize the degree of mixing of the exocyclic nitrogen AO with the MO's of the acridine fragment.

	AM1		*PM3*	
	1	***2***	***1***	***2***
$\Delta_f H$ (kcal mol^{-1})	76.3	195.0	70.9	152.7
$\Delta\lambda$ (nm)[a]	27.5	8.6	32.6	7.0
[b]	0.91	0.97	0.90	0.97
[c]	$s_\sigma^{0.82}\ p_\sigma^{1.97}\ p_\pi^{0.33}$	$s_\sigma^{0.47}\ p_\sigma^{2.39}\ p_\pi^{0.20}$	$s_\sigma^{0.94}\ p_\sigma^{1.97}\ p_\pi^{0.36}$	$s_\sigma^{0.59}\ p_\sigma^{2.33}\ p_\pi^{0.16}$
[d]	0.195	0.067	0.202	0.058

[a] Although the AM1 and PM3 methods have not been developed for excited-state quantum mechanical calculations, we have tentatively estimated the vertical transition energies between the ground and the first singlet excited states: the calculated bathochromic shifts ($\Delta\lambda = \lambda_i - \lambda_{acridine}$, λ: wavelength corresponding to the $^1\pi\pi^*$ transition, i: 3-aminoacridine or Tröger's base). The observed λ are 380 nm (shoulder) for acridine, 428 nm for **1** and 380 nm (shoulder) for **2**. [b] Composition of the delocalized MO which describes essentially the lone pair of the exocyclic nitrogen: a value of **1** indicates that only the nitrogen center is involved in this MO. [c] Hybridization state of the exocyclic nitrogen: $s_\sigma^{1.0}\ p_\sigma^{2.0}\ p_\pi^{1.0}$ corresponds to an sp^2 hybridization. [d] π-character of the bond between the exocyclic nitrogen atom and the carbon atom of the acridine ring.

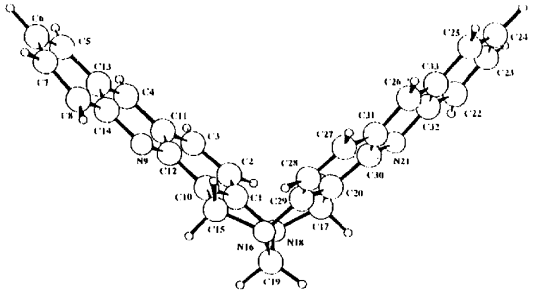


Fig 2. ORTEP drawing of the X-ray structure of Tröger's base **2**.

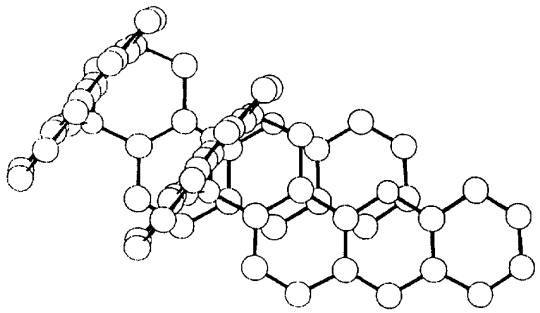


Fig 3. Overlapping of the acridine moieties.

UV-visible spectroscopy – semi-empirical calculation

As shown in figure 4, the UV-visible spectrum of the Tröger's base 2, recorded in ethanol, appears to be different from that of the starting 3-aminoacridine **1**. In fact, the absorbance of compound **2** in the 300–400 nm region is very similar to the absorbance of the unsubstituted acridine nucleus. This difference can be explained by a weaker delocalisation of the free doublet of the exocyclic nitrogens on the heterocycles in the case of the Tröger's base **2**.

In order to assess the reliability of this hypothesis, quantum mechanical PM3 calculations were performed for the following three molecules: acridine, 3-amino-acridine **1** and Tröger's base **2**. The results are summarized in table I.

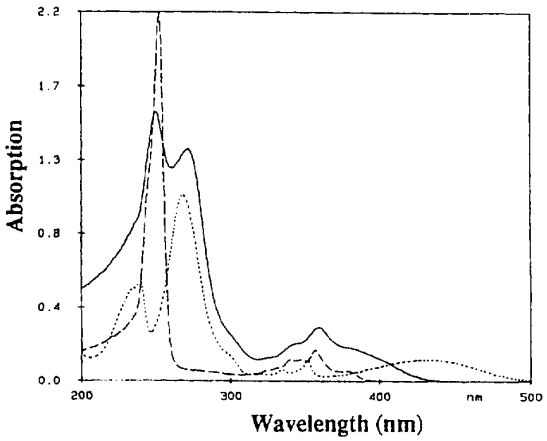


Fig 4. UV spectra recorded in ethanol (2.3×10^{-5} M). Dotted line: 3-aminoacridine **1**; continuous line: Tröger's base **2**; dashed line: unsubstituted acridine.

A representation of the individual HOMO's of **1** and **2** is given in figure 5. From these data, it appears that the exocyclic nitrogen is involved significantly in the π-system only in compound **1**. For Tröger's base **2**, the main feature of this orbital can be essentially explained by the interaction of the HOMO's of the two acridine fragments, the Tröger's base HOMO resulting from the out-of-phase combination of fragment orbitals. The energy gap between the Tröger's base HOMO and the next occupied molecular orbital (not represented) which corresponds to the in-phase combination of fragment orbitals is very small (0.027 eV). This result indicates that fragments of MO's do not overlap significantly.

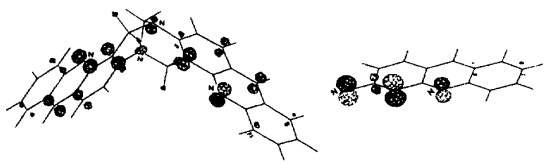
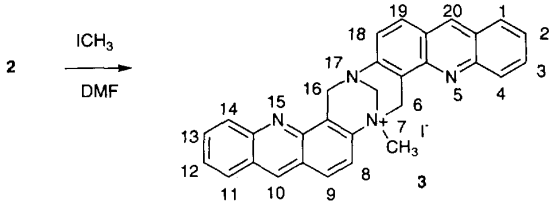


Fig 5. HOMO representations for compounds **1** and **2**.

Chemical reactivity

From the results obtained by semi-empirical calculations, we can anticipate that the tertiary amines of the methano-1,5-diazocine bridge behave as aliphatic amines rather than as aromatic amines. Reaction of compound **2** with methyl iodide in DMF yielded only one product that was isolated with 80% yield (scheme 3).



Scheme 3

The mass spectrum indicated that only one methyl group has been introduced. In the ^{1}H-NMR spectrum the two acridine nuclei appeared as two sets of signals, thus the H-10 and H-20 appeared as two well-separated singlets at 9.14 and 9.05 ppm. The characteristic methylene protons of the methano-1,5-diazocine bridge were also modified and appeared as two multiplets, each integrating for three protons. The modifications observed in the ^{1}H-NMR spectrum of the methano-1,5-diazocine unit are in favor of the alkylation of one nitrogen of the bridge with no methylation occurring at the acridine heterocyclic nitrogens. This lack of reactivity of the endocyclic nitrogens can be due to the weak delocalisation of the exocyclic amines and to the steric hindrance of the methylene group in the *peri* position.

Enantiomeric enrichment–racemization

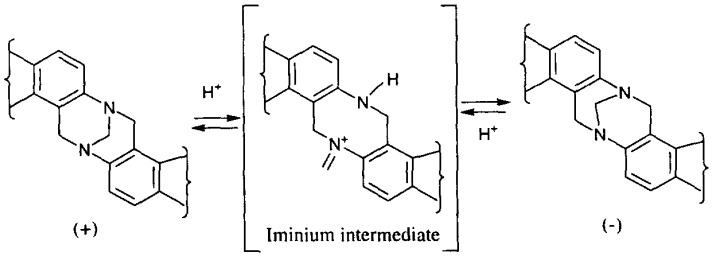
For the original Tröger's base, Prelog achieved the resolution by column chromatography using a chiral phase, ie, lactose, followed by a series of crystallizations [2]. The (+) isomer gave $[\alpha]_D = +285$ (±7) (*c* 0.279, hexane) and the (−) isomer $[\alpha]_D = -272$ (±8) (*c* 0.275, hexane). HPLC separation of the same Tröger's base has been published using cellulose derivatives [19] and other HPLC chiral phases [20], but only for analytical purposes. In 1991, Wilen and Qi [9] described the resolution and asymmetric transformation of the Tröger's base by crystallization using chiral binaphthyl phosphoric acid. The yield in pure enantiomers was close to 90% with ee > 99%. The authors also determined the configuration of the (+)-Tröger's base as the (5*S*, 11*S*) from an X-ray study of the diastereoisomeric salt [21]. Very recently, the resolution on a chiral HPLC column of a bis(porphyrine) Tröger's base analog was also published [7b]. Column chromatography of compound **2** on lactose gave only very poor enantiomeric excess (5–10% ee). Using the (*R*)-(−)-binaphthyl phosphoric acid, we obtained crystals that after treatment with a base yielded the (+)-Tröger's base analog **2** with 75% ee as determined by ^{1}H-NMR (using 1-(9-anthryl)-2,2,2,-trifluoroethanol as chiral solvating agent). With this sample we observed an optical rotation $[\alpha]_D = +1950$ (*c* 9.3 × 10^{-2}, $CHCl_3$). The concentration of the sample has been determined by UV spectroscopy. From this measurement, we can estimate the error on $[\alpha]_D$ to be ± 50. Using the same method, the (−)-isomer was also isolated, $[\alpha]_D = -2100$ (*c* 9.3 × 10^{-2}, $CHCl_3$).

Racemization of Tröger's base is known to occur in an acidic medium [2, 22]. The mechanism shown in scheme 4 implies the protonation of one nitrogen of the methano-1,5-diazocine bridge, opening of the bridge, formation of an iminium intermediate and reclosure.

We have compared the racemization of compound **2** with that of the original Tröger's base. Both compounds were solubilized in 0.1 N hydrochloric acid in dimethylformamide and their optical rotations were registered at different time intervals. The original Tröger's base racemized at room temperature (20 °C) with a half-life-time of 8 days, for compound **2** we only observed a 10% decrease of the optical rotation after 6 weeks. An HPLC analysis showed that compound **2** had slowly decomposed and that the rate of decomposition accounted for the decrease of optical rotation. The racemization was also checked under neutral conditions. In a mixture of dimethyl sulfoxide and pH 7 buffer (80:20, v:v), the Tröger's base **2** showed a very small decrease (less than 5%) of the optical rotation after a month, that was again attributed to a slow decomposition. The presence of the two basic heterocyclic nitrogens of the acridine nuclei in compound **2** modifies the protonation of the Tröger's base and thus inhibits the racemization in an acidic medium.

Conclusion

We describe here the synthesis of a new Tröger's base analog using regioselective substitution at position 4



Scheme 4

of the 3-aminoacridine. It was possible to control the formation of by-products by using a stoichiometric amount of formaldehyde (1.5 equiv) in trifluoroacetic acid. Tröger's base analog **2** was thus obtained with a 68% yield after purification. X-ray analysis and molecular calculations have been performed on this molecule. The results indicate that the two heterocycles are almost in perpendicular planes to each other. The exocyclic nitrogens of the methano-1,5-diazocine bridge are only partly delocalized on the acridine nucleus due to the very restricted conformation of the methano-1,5-diazocine bridge. These two tertiary amines are thus more nucleophilic than normal aromatic amines and react with methyl iodide to give a monoalkylation. This reactivity could be used to functionalyze the Tröger's bases and prepare a series of new polar quaternary derivatives. We have also obtained a 75% enantiomeric excess by crystallization with the chiral binaphthyl phosphoric acid and we have shown that the acridine-derived Tröger's base analog **2** does not racemize under conditions where the original Tröger's base fully racemizes. We also showed that it is stable under neutral conditions. This observation is important as the stability of the enantiomers is a prerequisite for any study of the interaction with DNA. The UV spectrum of the Tröger's base analog **2** was also studied and it showed characteristic absorptions above 300 nm. Such absorption will be useful in the study of the interaction with nucleic acids or oligonucleotides as the macromolecules do not absorb at these wavelenghts.

To increase the solubility in water of the acridine-derived Tröger's base, we are now preparing a series of analogs derived from substituted aminoacridines to study their interaction with DNA.

Experimental section

General

Melting points were determined on a Totolli melting point apparatus and are uncorrected. IR spectra were taken with Perkin-Elmer 298 and 1320 spectrometers. ^{1}H-NMR spectra were recorded on Bruker AC200 (200 MHz) and AM300 (300 MHz) spectrometers. Chemical shifts are expressed in parts per million, solvents are used as internal standards ($CDCl_3$: 7.24 ppm; DMSO-d_6: 2.49 ppm). The mass spectra (MS) were taken on a Delsi NERMAG R10-10. UV spectra were taken with a Perkin-Elmer Lambda UV-visible spectrophotometer. Optical rotation was measured with a Perkin-Elmer 241 polarimeter, the specific rotation was measured at the wavelength of the sodium D-line (589 nm). Elemental analyses were performed at the Laboratoire central d'analyse – CNRS (Lyon). Thin-layer chromatography (TLC) was achieved on 0.2 mm precoated aluminium sheets of silica gel 60 F-254 (Merck). Visualization was made with ultraviolet light (254 and 365 nm). For preparative column chromatography, silica gel 60 Merck (230–240 mesh ASTM) was used. High-performance liquid chromatography (HPLC) was performed on a Waters equipment (two M-510 pumps, solvent gradient M-680) with UV detection (diode array detector 990). Reversed-phase μ-bondapak C-18 (Waters) was used with methanol–water pH 2.5 (phosphoric acid) gradient, flow 2 mL/min. All reagents were purchased from Aldrich Chimie and used without further purification.

Synthesis

- *6H,16H-7,17-Methanodiacridino [3,4-b,3',4'-f][1,5]diazocine* **2**

A mixture of 3-aminoacridine hydrochloride (1.08 g, 4.68 mmol) and paraformaldehyde (0.25 g, 8.3 mmol) in trifluoroacetic acid (15 mL) was stirred at room temperature for 2 h. The reaction mixture was then basified with aqueous ammonium hydroxide and extracted with methylene chloride. The organic layers were collected, washed with water and evaporated to dryness. The solid residue was triturated in the minimum amount of methanol and filtered. Tröger's base **2** was obtained with 68% yield (0.684 g, 1.6 mmol).

Mp = 350 °C.

IR (KBr): 3 020, 2 900, 1 600 (s), 1 430, 1 400, 1 280, 1 200, 1 065, 930, 910, 740 cm^{-1}.

UV (EtOH): $\lambda_{max}(\varepsilon)$ 358.4 (15200), 265.4 (72600), 247 (81700).

^{1}H NMR (200 MHz, $CDCl_3$): δ 8.48 (2H, s), 8.10 (2H, d, J = 5.8 Hz), 7.82 (2H, d, J = 5.5 Hz), 7.66 (4H, m), 7.40 (4H, m), 5.17 (d, 1H, J = 10 Hz), 5.07 (d, 1H, J = 10 Hz), 4.57 (2H, s).

MS (FAB (+), NBA, NaCl): m/z 460 $(M + 1 + Cl)^+$, 425 $(M + 1)^+$.

Anal calc for $C_{29}H_{20}N_4$: C, 82.05; H, 4.75; N, 13.2. Found: C, 81.51; H, 4.75; N, 13.09.

- *7-Methyl-6H,16H-7,17-methanodiacridino [3,4-b,3',4'-f][1,5]diazocin-7-ium iodide* **3**

To compound **2** (0.05 g, 0.118 mmol) dissolved in dimethylformamide (5 mL) was added methyl iodide (0.075 mL). The solution was stirred at room temperature for 20 days until the reaction was complete. The solvent was evaporated and the resulting solid washed with diethyl ether. Compound **3** was obtained with 80% yield (0.052 g, 0.092 mmol).

Mp > 310 °C.

IR (KBr): 3 400, 3 040, 2 970, 1 625, 1 610, 1 560, 1 520, 1 460, 1 435, 1 390, 1 295, 1 260, 1 150, 1 125, 1 080, 995, 930, 910, 850, 830, 790, 755, 743 cm^{-1}.

UV (EtOH): $\lambda_{max}(\varepsilon)$ 358.1 (10800), 260.6 (60900), 256 (60600).

^{1}H NMR (300 MHz, DMSO-d_6): δ 9.14 (1H, s), 9.05 (1H, s), 8.3–8.5 (2H, m), 8.14 (6H, m), 7.8–8.0 (2H, m), 7.5–7.7 (2H, m), 5.7–5.9 (3H, m), 5.3–5.5 (3H, m), 4.05 (3H, s, N–CH_3).

MS (FAB (+), NBA): m/z 439 $(M + 1)^+$.

Anal calc for $C_{30}H_{23}N_4I$, $1H_2O$: C, 61.65; H, 4.31; N, 9.59. Found: C, 61.85; H, 4.19; N, 9.39.

Semi-empirical calculations:
MOPAC (version 6.0) molecular orbital package running on an IBM RSC6000-540 computer was used for the semi-empirical calculations. Geometries were optimized in internal coordinates by minimizing the sum of their squared scalar gradients. A value of 99.8° is obtained for the dihedral angle between the rings of the Tröger molecule.

Enantiomeric enrichment–racemization studies:
Racemic Tröger's base analog **2** (0.1 g, 0.24 mmol) was dissolved in chloroform (15 mL) in the presence of (*R*)-(−)-binaphthyl phosphoric acid (0.164 g, 0.48 mmol). The mixture was refluxed for 1 h and then allowed to cool down slowly to room temperature. After 48 h, the resulting crystals were collected and washed with chloroform (40 mL). The crystals were then treated with 1 N sodium hydroxide and the free base of the (+)-Tröger's base was extracted with dichloromethane. The organic layer was washed twice

with diluted sodium hydroxide and twice with water. After evaporation of the solvent, the (+)-isomer was obtained with 15% yield (15.1 mg).

Racemization:
The racemization was studied in two solvents HCl 0.1 N in dimethylformamide and a 80:20 mixture of dimethyl sulfoxide:pH 7 phosphate buffer. In a typical experiment, the Tröger's base was dissolved in the solvent (0.4 mg in 5 mL). The optical rotation of the solution was taken at different time intervals.

X-ray analysis

Very thin crystals (thickness of 0.01 mm) were obtained by the vapor diffusion method from a dimethylformamide solution of Tröger's base **2** equilibrated by ethyl acetate.

– *Crystal data*: $C_{29}H_{20}N_4$, $M = 424$, orthorhombic, $a = 13.726(6)$, $b = 5.132(1)$, $c = 28.986(9)$ Å, $V = 2042(1)$ Å^3 (by least-squares refinement on diffractometer angles for 25 centred reflections), $\lambda = 1.54178$ Å, space group $Pna2_1$, $Z = 4$, $D_x = 1.38$ g/cm^3, crystal dimensions $0.25 \times 0.2 \times 0.01$ mm, $\mu(\mathrm{CuK}\alpha) = 6.1$ cm^{-1}.

– *Data collection and processing*: CAD4 diffractometer, $\omega/2\theta$ mode with ω scan width $= 2 + 0.15$ tg θ, ω scan speed 1.3–6.8 deg min^{-1}, graphite monochromated CuKα radiation, 1302 reflections measured ($1 \leqslant \theta \leqslant 50°$), with a rotating anode Nonius GX21 working at 45 kV 90 mA with 6000 rpm, giving 765 with $I \geqslant 2\sigma(I)$, a linear correction factor (19.4%) was applied on the basis of standard monitoring, empirical absorption correction (absorption transmission range 0.991–0.923).

– *Structure analysis and refinement*: the structure was found by direct methods using SHELXS 86 [23]. Initially, the positions of 22 atoms were assigned, the remaining C and N atoms were found by means of Fourier recycling procedures. Although peaks for many H were found in difference maps, theoretical positions were used. Subsequently, their coordinates were refined by a least-squares full matrix using SHELX 76 [24] (function minimized being $\sum_w |F_o - F_c|^2$) with anisotropic thermal parameters for non-hydrogen atoms and isotropic for hydrogen. The weighting scheme $w = 1/[\sigma^2(F_o) + 0.037342F_o^2]$, with $\sigma(F_o)$ from counting statistics gave satisfactory agreement analyses. Final R and R_w values are 0.057 and 0.059, maximum Δ/σ in the final cycle refinement 0.6; maximum variation in the final difference Fourier maps within $\pm$ 0.2 e Å^3. Atomic scattering factors were those incorporated in SHELX 76. A perspective view, drawn with spherical atoms is given in figure 2. Bond lengths and bond angles are normal with slight differences between C(20)–C(17) (1.56 Å) and C(15)–C(10) (1.51 Å), C(20)–C(29) (1.34 Å) and C(9)–C(10) (1.39 Å); the standard deviations are 0.02 Å.

Supplementary material available

A stereoscopic view of the crystal together with tables of atomic coordinates, equivalent isotropic displacement parameters, anisotropic parameters (non-hydrogen atoms), bond lengths and angles are given (6 pages). Supplementary material data have seen deposited with the British Library, Document Supply Centre at Boston Spa, West Yorkshire, LS 23 7BQ, UK, as supplementary publication N° SUP 90451 and are available on request from the document supply centre.

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