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TECHNICAL NOTE

Criminalistics

Clarifying the complex chemistry of cobalt(II) thiocyanate-based tests for cocaine using single-crystal X-ray diffraction and spectroscopic techniques

Raychelle Burks PhD[1,2] | Lars Öhrström PhD[2] | Francoise M. Amombo Noa PhD[2,3]

[1]Department of Chemistry, American University, Washington, District of Columbia, USA

[2]Department of Chemistry and Chemical Engineering, Chalmers University of Technology, Gothenburg, Sweden

[3]AstraZeneca, Mölndal, Sweden

Correspondence
Raychelle Burks, Department of Chemistry, American University, 4400 Massachusetts Ave NW, Washington, DC 20016, USA.
Email: burks@american.edu

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Abstract

Cobalt(II) thiocyanate-based tests are routinely used to screen cocaine products, with the formation of a blue species interpreted as a positive response. An array of other organic bases has been identified as false positives – including well-documented cocaine product adulterant lidocaine and its salt. False positives prompt continued test development, though improvements are hindered by unresolved product structures and reaction pathways. Toward greater clarity, cobalt(II) thiocyanate reactions with cocaine hydrochloride, along with lidocaine and its salt, were investigated using multiple analytical techniques. Reactions involving cocaine hydrochloride yielded glassy, amorphous blue material while reactions of lidocaine hydrochloride monohydrate produced larger, needle-like crystals whose structure was determined via single-crystal X-ray diffraction to be an ion pair (Hlidocaine^{+})$_2$([Co(SCN)$_4$]$^{2-}$)·H$_2$O. While the blue precipitate isolated from reactions involving cocaine hydrochloride was unsuitable for crystallographic structure determination, comparative ultraviolet–visible, attenuated total reflectance infrared, and Raman spectroscopic analysis – along with elemental analysis – supports that this solid is comprised of a comparable ion pair (Hcocaine^{+})$_2$[Co(SCN)$_4$]$^{2-}$. Pink crystals isolated from lidocaine reaction vessels were identified as coordination compounds *cis*-[CoL$_2$(SCN)$_2$] and *trans*-[CoL$_2$(SCN)$_2$] where L = lidocaine, while pink crystals from both cocaine hydrochloride and lidocaine hydrochloride monohydrate reaction vessels were the coordination polymer *trans*-[Co(H$_2$O)$_2$(SCN)$_2$]·H$_2$O. The results presented herein enable reaction optimization to favor a desired product, whether ion pair or coordination species.

KEYWORDS
attenuated total reflection infrared spectroscopy (ATR-IR) spectroscopy, cobalt thiocyanate, cocaine, color tests, lidocaine, presumptive tests, Raman spectroscopy, Scott's test, ultraviolet–visible (UV–vis) spectroscopy, X-ray diffraction

Highlights

- Product structures and reaction pathways of cobalt(II) thiocyanate-based tests are clarified.
- Hallmark blue products of cobalt(II) thiocyanate tests are ion pairs.
- Three pink products were isolated, each a unique coordination compound.

1 | INTRODUCTION

The straightforward operational nature of many color tests may imply that their underlying chemistry is simplistic and exhaustively explored. In reality, color test reaction mechanisms can be quite complex with the elucidation of the chemical identity of their telltale-colored species an area of ongoing research activity [1–3]. The reactions of cobalt(II) thiocyanate typify the complexity of color tests and metal ion coordination chemistry. Cobalt(II) thiocyanate solutions have a long history as a colorimetric reagent for the determination of alkaloids and their salts, along with the wider category of organic nitrogen-containing bases (hereafter 'organic bases') and their salts [4–10]. Arguably, the most widespread forensic use of cobalt(II) thiocyanate reagents is for screening suspected samples of cocaine (base or salt form), with these controlled substances indicated by the formation of a blue species upon exposure of a suspect material with test reagent(s).

Challengingly, numerous organic bases produce blue reaction species when exposed to cobalt(II) thiocyanate solutions such as lidocaine, procaine, diphenhydramine, ephedrine, phencyclidine, fentanyl, α-pyrrolidinopentiophenone, and/or their salts [11–17]. Structures of cocaine and lidocaine are shown in Figure 1. Lidocaine is showcased herein as this local anesthetic is both a long-noted false-positive and oft-encountered adulterant in cocaine products [3, 18, 19]. The litany of false positives for cobalt(II) thiocyanate-based tests has prompted numerous revisions in pursuit of increased selectivity, while retaining ease-of-use and screening speed. Updates to cobalt(II) thiocyanate tests range from the chemical (e.g., Scott's test) to the computational (e.g., incorporating multivariate image analysis) [3, 5]. Stymying continued test improvement efforts are unsettled product structures and cobalt(II) thiocyanate reaction mechanisms [1, 3, 20]. Ahead of a cobalt(II) thiocyanate test solution being introduced to organic base samples, the complexity of the test solution is worthy of note and continued exploration.

Solid $[Co(SCN)_2]$ is brown–yellow in color and a coordination polymer with a bridging Co-SCN motif [21, 22]. The dissolution of brown–yellow $[Co(SCN)_2]$ in both the classic test (2% w/v cobalt (II) thiocyanate in distilled water) and in Scott's test reagent #1 (1% w/v cobalt (II) thiocyanate in a 1:1 v/v solution of glycerine and 10% v/v acetic acid) results in a pink solution [11, 23]. This pink color indicates that the predominant species formed are octahedral (six-coordinated) cobalt complexes of the type $[Co(H_2O)_n(SCN)_m]^{2-m}$ with $n+m=6$, and a critical evaluation of the corresponding stability constants has been published [24, 25]. Charged complexes such as $[Co(H_2O)_2(SCN)_4]^{2-}$ can be balanced by species such as $[Co(H_2O)_6]^{2+}$ and compounds with multiple cobalt centers (i.e., polynuclear species) [26]. More violet-hued species and solutions indicate the presence of low concentrations of blue tetrahedral species such as $[Co(SCN)_4]^{2-}$, or similar tetrahedral species, along with the aforementioned pink octahedral complexes [2, 20, 27–29]. Like other transition metals, the color of cobalt(II) complexes may indicate the number and geometry of surrounding ligands, and for Co(II), the difference between tetrahedral and octahedral species is especially striking (Figure 1) [2, 30]. Upon exposure of pink cobalt(II) test solutions to select organic bases, blue species form that either precipitate and/or color the bulk solution depending on solvent conditions. The structure of these blue species remains unresolved or unconfirmed for a variety of analytes, including cocaine and its salt, though key work has provided structural insights.

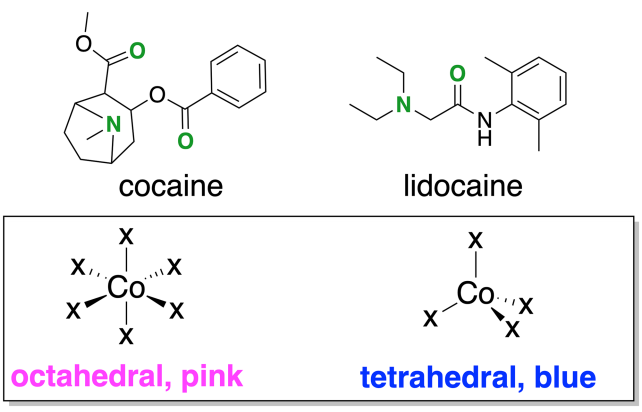

FIGURE 1 Top: Structures of cocaine and lidocaine. Bottom: cobalt(II) tetrahedral and octahedral ligand geometries with corresponding color of appearance.

A variety of researchers have posited the structure of the telltale blue species as an ion pair with the general formula $(HB^+)_2[Co(SCN)_4]^{2-}$, where protonated organic base (HB^+) is paired with an anionic, tetrahedral Co(II) complex [2, 4, 5, 7, 9, 20, 27]. While the International Union of Pure and Applied Chemistry's *Nomenclature of Inorganic Chemistry* [31] directs that ion charges not be denoted in overall neutral species, we have included charges to emphasize ion pairs. Ion pairs such as $(HB^+)_2[Co(SCN)_4^{2-}]^{2-}$ are stabilized by supramolecular interactions, with such interactions finding use in organic synthesis [32]. While a host of such ion pair complexes are insoluble in aqueous media, many are soluble in a variety of organic solvents [10, 33, 34]. Such differential solubility has made ion-pair complex formation a popular extraction strategy [35–37], such as in Scott's test. Toward clarifying the blue species resulting from Scott's and other cobalt(II) thiocyanate-based tests, Oliver et al. recently worked with the citrate salt of the organic base diethylcarbamazine, publishing the crystal structure of an ion pair $(Hdiethylcarbamazine^+)_2[Co(SCN)_4]^{2-}$ resulting from a 1:2 mixture of the citrate salt and $K_2[Co(SCN)_4]$ [38]. Beyond tetrahedral coordination complexes and an ion pair, previous researchers propounded the hallmark blue species resulting from Co(II) reactions with organic base – specifically cocaine – are octahedral, six-coordinate complexes with one or two bis-chelating cocaine ligands [1, 17, 39].

Greater structural clarity of reaction species and reaction mechanisms is 'essential' for the continued use and improvement of color tests [40]. These tests are a vital part of the presumptive-to-confirmatory workflow for identifying seized drug material, even in our era of portable instruments [15]. Toward the continued advancement of cobalt(II) thiocyanate-based tests, we evaluated the reaction products resulting from classic and Scott's tests screening of cocaine

hydrochloride, lidocaine hydrochloride monohydrate, and lidocaine using single-crystal X-ray diffraction along with ultraviolet–visible (UV–vis), attenuated total reflectance infrared (ATR-IR), and Raman spectroscopy with select material subjected to elemental analysis. Lidocaine and its salt were included due to this drug's aforementioned role as cobalt(II) thiocyanate-based tests false positive and cocaine product adulterant. Probing the reaction species further expands our knowledge of these widely employed tests, enabling their continued refinement and general color test innovation.

2 | MATERIALS AND METHODS

2.1 | Materials

Cobalt(II) thiocyanate, cocaine hydrochloride, lidocaine hydrochloride monohydrate, lidocaine, acetic acid, glycerine, concentrated hydrochloric acid, chloroform, and ethyl acetate were purchased from various chemical supply companies such as Sigma-Aldrich (St. Louis, MO) at technical grade or better and were used as received without further purification. Distilled water was used for all aqueous solutions. The use of standard laboratory equipment and glassware is described in the subsequent subsections.

2.2 | Cobalt (II) thiocyanate testing

Classic cobalt (II) thiocyanate test reagent and Scott's test reagents were prepared and administered as detailed in [11, 23], respectively. The former reagent is a 2% w/v cobalt (II) thiocyanate in distilled water and is hereafter referred to as 'classic test'. Scott's test is a trio of reagents (#1–#3) prepared as follows: (#1) 1% w/v cobalt (II) thiocyanate in a 1:1 v/v solution of glycerine and 10% v/v acetic acid, (#2) concentrated HCl, and (#3) chloroform. All presumptive testing and reagent storage was in a temperature-controlled indoor laboratory (~72°F or 22°C), being mindful of observed temperature effects on the sensitivity of cobalt (II) thiocyanate tests [20, 41]. Care was taken with regard to the w/v ratio of analyte to reagents, given the known complications excessive analyte amounts relative to test reagents can elicit [13]. Similarly, the ratio of Scott's test reagent #1 to #2 was carefully monitored as excessive addition of HCl can result in the formation of a blue species that is likely tetrachlorocobaltate (II), $CoCl_4^{2-}$, which is soluble in polar solvents [33, 42–46]. Analyte and reagent amounts were scaled in tandem for larger experimental yields as done in reference [3]. Samples of cocaine hydrochloride, lidocaine hydrochloride monohydrate, and lidocaine were subjected to both classic and Scott's test. For the salts, precipitates were not anticipated for Scott's test due to the enhanced solubility of reaction species in test reagents. The water insolubility of lidocaine [47] was expected to impact its reactivity in all reagent solutions. A total of thirty-six tests were run, and all resulting solutions were evaluated visually, including with the assistance of Zeiss Stemi SV6 microscope, for precipitate that could be evaluated using either single-crystal or powder x-ray diffraction.

2.3 | Single-crystal X-ray diffraction

All crystallography work was done at the Chalmers Materials Analysis Laboratory (CMAL). Crystals obtained from test solutions – or grown in organic solvents like chloroform as specified – were selected and mounted on a nylon loop on an XtaLAB Synergy R, HyPix diffractometer. The crystal was kept at a steady T = 100.0(7)K during data collection. Data reduction, scaling, and absorption corrections were performed using CrysAlisPro (Rigaku, V1.171.41.119a, 2021). The structures were solved with the ShelXT [48] structure solution program using the Intrinsic Phasing solution method and by using Olex2 [49] as the graphical interface. The model was refined with version 2016/6 of ShelXL 2016/6 using Least Squares minimization. Further details can be found in the supplementary material, and the CCDC entries 2235446-2235447 and 2235449-2235450 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +441,223 336,033. Structure searches discussed within were conducted among the more than 1 million structures in the Cambridge Structural Database (CSD) version 5.44, April 2023 [50].

2.4 | UV–vis, IR, and Raman spectroscopy

For spectra collection, cocaine hydrochloride and lidocaine hydrochloride monohydrate samples that provided positive results upon addition of the classic test reagent were used. For UV–vis analysis, ethyl acetate was added directly to selected positive test vials as in [51], with the resulting blue solution transferred to a new vial where additional ethyl acetate was added to generate suitably dilute solutions. Solutions were passed through 0.45 μm polytetrafluoroethylene (PTFE) membrane filters prior to UV–vis analysis using a Varian Cary® 50 UV–Vis spectrophotometer.

All ATR-IR and Raman spectroscopic work was done at CMAL. For ATR-IR and Raman analysis, blue solid material from representative classic test reaction vessels of cocaine hydrochloride and lidocaine hydrochloride was transferred to glass slides for solvent evaporation in a hood with no additional sample preparation prior to spectra collection. ATR-IR spectra were collected using a Bruker VERTEX 70v with ATR accessory, while Raman spectra were collected using an Oxford Instruments' alpha300 Raman Imaging Microscope with 10×, 50×, and 100× objective magnifications. Samples were measured using a 532 nm laser with accompanying 600 grooves/millimeter grating was employed. To maximize Raman peak clarity and intensity while maintaining precipitate integrity, the

laser power, accumulations, and measurement time were varied for each sample analyzed.

2.5 | Elemental analysis

Elemental analysis (C, N, and S) was conducted at CMAL using an Elementar vario MICRO cube instrument. Blue solid material from a representative classic test reaction vessel of cocaine hydrochloride was transferred to a separate container and dissolved in chloroform. This solvent was allowed to evaporate and the resulting blue solid was wrapped in a small square of tin foil prior to placement in the instrument. All estimated element percentages were determined using instrument software and subsequently compared to theoretical elemental compositions using the analysis function in the ChemDraw software (version 20.1.0.112, PerkinElmer Informatics, 2021).

3 | RESULTS AND DISCUSSION

Upon screening of cocaine hydrochloride and lidocaine hydrochloride monohydrate samples via the classic test, blue precipitate was readily observed. As anticipated for samples subjected to Scott's test, no collectable blue precipitate was observed, though expected solution color changes were noted. Pink precipitates were isolated from reaction vessels containing cocaine hydrochloride, lidocaine hydrochloride, and lidocaine samples screened by the classic test. In the sections directly following, evaluation of said blue and pink precipitates are discussed.

3.1 | Blue precipitates

Markedly different blue precipitates were observed upon exposure of cocaine hydrochloride and lidocaine hydrochloride monohydrate to the classic test reagent. Images of representative precipitates are inserted in Figures 2 and 3. Cocaine hydrochloride reactions yielded glassy, amorphous blue material unsuitable for single-crystal X-ray diffraction. Crystallization efforts with either chloroform or ethyl acetate resulted in the same glassy, amorphous solid as dissolved in said solvents. Lidocaine hydrochloride monohydrate reactions yielded larger needle-like blue crystals whose structure was straightforwardly elucidated by single-crystal X-ray diffraction to be the ion pair $(HL^+)_2([Co(SCN)_4]^{2-})(H_2O)$ where HL^+ is the cationic form of lidocaine referred to as lidocainium (Figure 4). Our low-temperature structure determination of $(HL^+)_2([Co(SCN)_4]^{2-})(H_2O)$ has considerably higher precision than an earlier room temperature structure of the ion pair, CSD code YEPHIK [52]. A space-filling drawing and a plot of the asymmetric unit are available in the Supplemental Information (SI), Figures S1 and S2. As illustrated in Figure 4, adjacent ion pairs interact through neighboring lidocainium ions via double hydrogen bonds between their C=O...$^+$H–N_{amine}, forming a well-known supramolecular heterosynthon motif denoted R2,2(10) as ten atoms are linked in a supramolecular ring [53]. This notable interaction is not a feature of lidocaine monohydrate hydrochloride structures with codes LIDOCN and LIDOCN0 in the CSD. While the formation of the R2,2(10) motif is available to lidocainium, the cationic form of cocaine (cocainium) is unable to engage in such hydrogen bonding which may contribute to the more disordered nature of precipitate formed upon classic test screening of cocaine hydrochloride.

Of the more than one million structures in the CSD [50], seven are cocaine or cocainium featuring compounds being either the free base or ion pairs. Three ion pairs are of particular interest here as each is associated with forensic applications. The long-used standard microcrystal test for cocaine featuring a 5% gold chloride ($HAuCl_4$) that results in the asymmetric ion pair $(Hcocaine^+)[AuCl_4]^-$, CSD code SETLOT, with the chloride ions arranged about Au(III) in a distorted square planar geometry [54, 55]. Laussmann et al. prepared the green appearing $(Hcocaine^+)_2[Cu(NCS)_4]$, CSD code HAGSEQ, with thiocyanate groups arranged in a distorted square

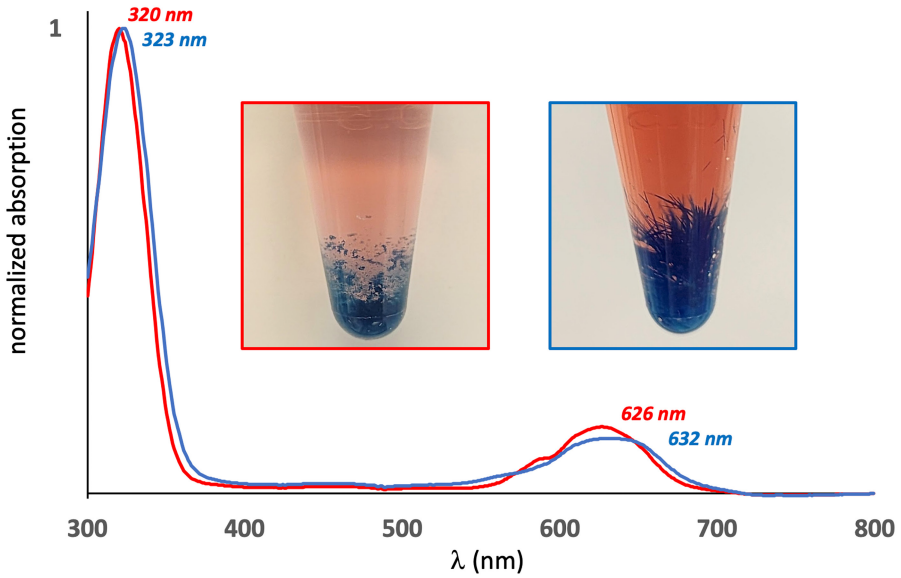

FIGURE 2 UV–vis spectra of blue precipitate retrieved from representative cocaine hydrochloride (—) and lidocaine monohydrate hydrochloride (—) reaction vessels dissolved in ethyl acetate. Image inserts of sampled reaction vessels show the markedly different appearance of each product.

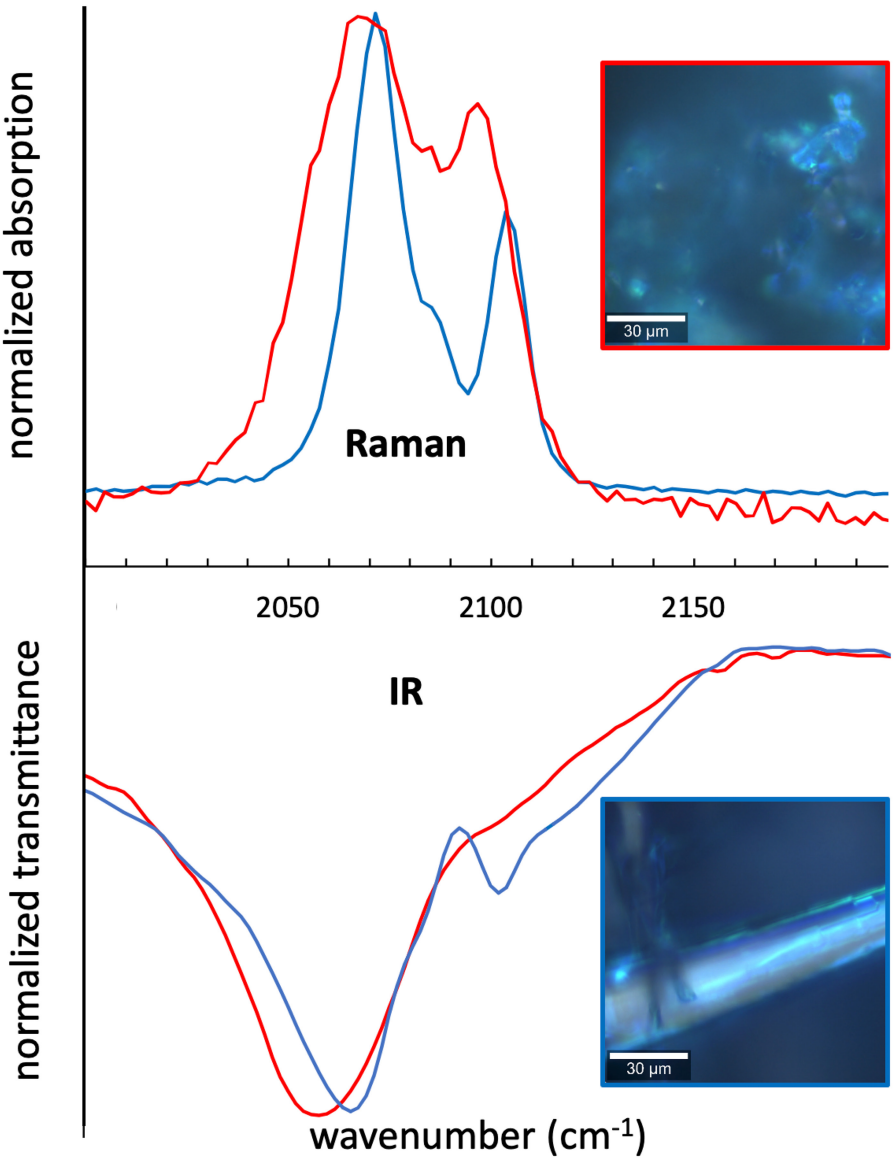

FIGURE 3 Distinctive ATR IR and Raman C≡N stretching band region around 2100 cm^{-1} of blue precipitate retrieved from representative cocaine hydrochloride (—) and lidocaine monohydrate hydrochloride (—) reaction vessels. Inserted images collected during Raman analysis provide magnified views of the precipitate resulting from reactions involving cocaine hydrochloride (—) versus lidocaine monohydrate hydrochloride (—).

planar geometry around Cu(II) [37]. The third complex of note is the yellow cocaine salt with Erdmann's anion, *trans*–$[Co(NH_3)_2(NO_2)_4]^-$, CSD code OSEFIE, which features two cocainium ions and two cobalt(III) containing Erdmann's anions in the asymmetric unit [56]. The paucity of cocainium containing ion pairs in the CSD may, in some part, reflect the commonality of non-crystalline precipitates such as we observed for samples of cocaine hydrochloride exposed to the classic test. While our crystallization efforts employing either chloroform or ethyl acetate did not yield crystalline material, we recognize that other crystallization methods may do so.

UV–vis, ATR-IR, and Raman spectroscopic analysis of blue precipitates was performed to ascertain if a comparable ion pair comprised the glassy, amorphous blue solid produced by reactions involving cocaine hydrochloride. Representative UV–vis spectra of solubilized blue species resulting from classic test screening of lidocaine hydrochloride monohydrate and cocaine hydrochloride samples are shown in Figure 2. These spectra agree with those presented in [51], with the peaks around 320 nm most likely π-π^* transitions of the C≡N group and broader peaks around 630 nm more complicated, consisting of overlapping bands corresponding to d-d transitions [57]. Similar results were noted with chloroform (data not shown), though the enhanced solubility of all precipitates in ethyl acetate [51] resulted in spectra with higher signal to noise. Given the color of the precipitates and their resulting solutions, peaks within the red zone of the UV–vis regions are expected. As seen in Figure 2, similarities abound between the UV–vis spectra of the studied blue reaction species, suggesting similar structures. IR and Raman analysis of blue precipitates provided further structural insights.

An overview of the vibrational spectroscopy of thiocyanate complexes can be found in [58]. Critical for the examination of such complexes are the distinctive C≡N stretching bands around 2100 cm^{-1} [37, 51, 58]. Figure 3 highlights this distinctive wavenumber area for ATR-IR and Raman spectra of representative blue precipitates resulting from classic test screening of lidocaine hydrochloride monohydrate and cocaine hydrochloride. Though Figure 3 image insets show the dissimilarity in blue precipitate

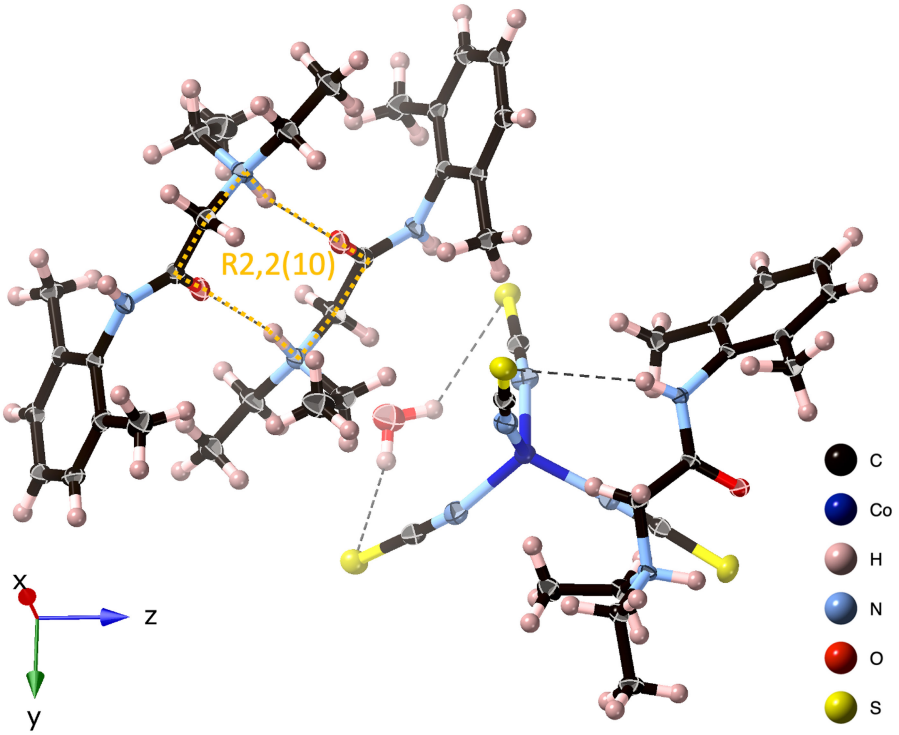

FIGURE 4 Crystal structure of $(HL^+)_2([Co(SCN)_4]^{2-})(H_2O)$ where HL^+ = lidocainium. The supramolecular heterosynthon motif R2,2(10) between neighboring lidocainium ions incorporated in adjacent ion pairs is highlighted in yellow. Also illustrated are the hydrogen bonds between (i) water and $[Co(SCN)_4]^{2-}$ and (ii) amide hydrogen and $[Co(SCN)_4]^{2-}$. Displacement ellipsoids shown at 50%. See also Figures S1 and S2.

appearance, similarities in nitrile stretching bands indicate similar ion pair complexes. Peak shifting around the 2100 cm^{-1} reflects the sensitivity of nitrile groups to their local electrostatic and hydrogen-bonding environment [59]. Full ATR-IR and Raman spectra of collected blue precipitates, along with lidocaine hydrochloride monohydrate and cocaine hydrochloride are provided in SI Figures S3 and S4, respectively. Considering SI Figure S3, we note the bands associated with protonated amines around 2500 cm^{-1} [60] are much weaker for both cobalt-containing compounds compared to either analyzed drugs' salt. Considering the elucidated structure for the lidocainium containing ion pair (Figure 4), the diminished protonated amine peaks are likely due to substantial changes in hydrogen bonding in $(HL^+)_2([Co(SCN)_4]^{2-})\cdot H_2O$ compared to lidocaine monohydrate hydrochloride. For the blue precipitate produced by classic test screening of cocaine hydrochloride, the near vanishing of protonated amine peaks in the spectrum of the precipitate versus the salt also likely indicates changing hydrogen bond interactions.

A representative sample of blue precipitate produced by classic test screening of cocaine hydrochloride was further investigated via C, N, S elemental analysis as detailed in Section 2. It is important to note the potential inclusion of chloroform, $CHCl_3$, into solubilized material even after subsequent solvent evaporation. The inclusion of $CHCl_3$ can make the element percentages deviate 1%–2% from the expected values. We found more than 17,000 $CHCl_3$-incorporating compounds reported in the CSD. Elemental analysis of the specified sample revealed 49.37% C, 8.61% N, and 13.66% S with a sulfur-to-nitrogen ratio of 1.59. These percentages are consistent with an ion pair $(Hcocaine^+)_2[Co(SCN)_4]^{2-}$ having 0.3 $CHCl_3$ molecules per Co, a species with calculated percentages of 49.16% C, 8.98% N, 13.70% S and a sulfur-to-nitrogen ratio of 1.53. In contrast, our experimentally determined C, N, and S percentages are incompatible with $[Co(cocaine)_2(SCN)_2]$ – where cocaine is non-chelating – which has calculated percentages of 55.31% C, 7.17% N, 8.20% S and a sulfur-to-nitrogen ratio of 1.14.

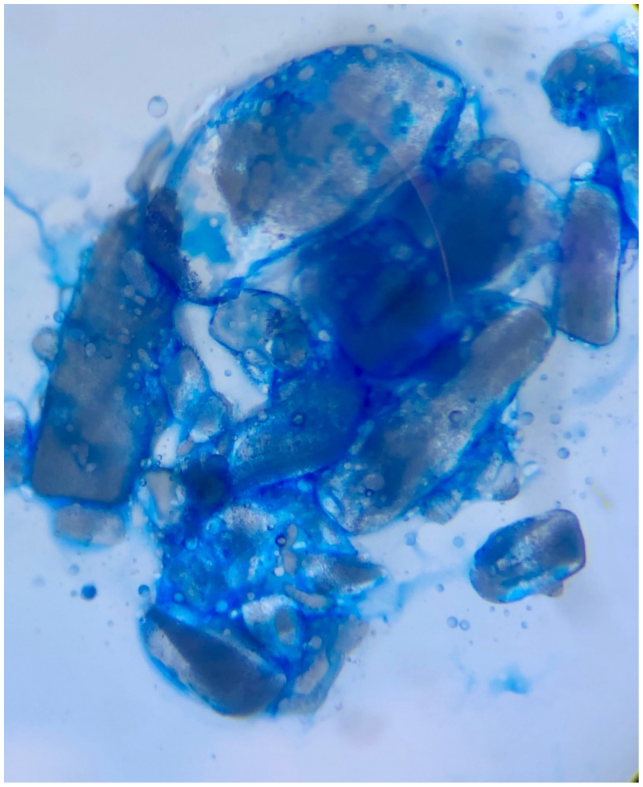

FIGURE 5 Image of a representative sample of lidocaine after classic test screening. The blue liquid-like layer is likely the lidocainium (HL^+) containing ion pair $(HL^+)_2([Co(SCN)_4]^{2-})(H_2O)$ localized at the drug–reagent interface.

Lidocaine is noted as water-insoluble [47], which impacts reactivity within aqueous test reagents. For select lidocaine samples exposed to the classic test reagent and all lidocaine samples exposed to Scott's test reagent #1, the formation of a blue-colored layer upon solid lidocaine crystals was observed. Evaluation of these layered samples under magnification revealed a blue layer between the lidocaine solid surface and the bulk reagent solution. A representative image is shown in Figure 5. Based on analysis detailed in this subsection's previous paragraphs, we suggest the blue liquid-like layer is likely the lidocainium containing ion pair localized at the drug–reagent interface.

3.2 | Pink precipitates

Pink precipitates of a crystalline appearance were observed and collected from select classic test reaction vessels containing cocaine hydrochloride, lidocaine hydrochloride, and lidocaine. Three distinct pink-appearing compounds – designated herein as A, B, and C – were identified (Figure 6). The structure of A crystals, which were analyzed by single-crystal X-ray diffraction directly after classic test screening of lidocaine, was revealed to be *cis*-$[CoL_2(SCN)_2]$ where L = lidocaine binding to cobalt in a bidentate fashion via tertiary amine N and the carbonyl O. Interestingly, the structure of crystals B that were retrieved approximately 8 weeks after classic test screening of lidocaine was determined to be *trans*-$[CoL_2(SCN)_2]$. Based on a solid-state general rule [61] saying that intermolecular interactions are maximized when molecular entities come closer together, we posit the *trans* product to be the thermodynamic product as the calculated density from the crystal structure is 1.318 g/cm^3, compared to the kinetic product *cis* with a calculated density of 1.255 g/cm^3.

To the best of our knowledge, we are the first to report the structure of *trans*-$[CoL_2(SCN)_2]$ where L = lidocaine, while room temperature structural elucidation of *cis*-$[CoL_2(SCN)_2]$ was previously reported by Tabrizi et al. (CSD code XUTYUI) in their work probing the bioactivity of cobalt(II) and nickel(II) complexes of lidocaine [62]. There was an absence of comparable *cis* or *trans* compounds in reaction vessels containing cocaine hydrochloride or lidocaine monohydrate hydrochloride. For both salts, this absence may be explained by the tertiary amine site being unavailable for coordination with cobalt(II) due to protonation. Crystals C retrieved from cocaine hydrochloride and lidocaine hydrochloride monohydrate samples screened via the classic test were determined to be the coordination polymer *trans*-$[Co(H_2O)_2(SCN)_2]\cdot H_2O$. An earlier room temperature structure determination of *trans*-$[Co(H_2O)_2(SCN)_2]\cdot H_2O$ was detailed in [22].

3.3 | Structures and reactivity

Though the structures of lidocaine and cocaine are markedly different (Figure 1), they share a common feature of nonbonding electrons pairs available for Lewis acid-base interactions with Co(II) via tertiary amine and carbonyl groups [3, 19]. As discussed by de Jong et al., [19] these shared features may explain similar appearing blue species interpreted as positive cobalt(II) thiocyanate bases test results for an array of organic bases. Beyond reactive species with both tertiary amine and carbonyl groups, de Jong et al. noted that analytes observed to yield false positive results without a carbonyl (e.g., diphenhydramine) all have an electron-donating tertiary amine group. In this context, it is important to distinguish between (i) ion pairs formed by the combination of a protonated Lewis base such as lidocainium or cocainium and Co(II) containing anions like

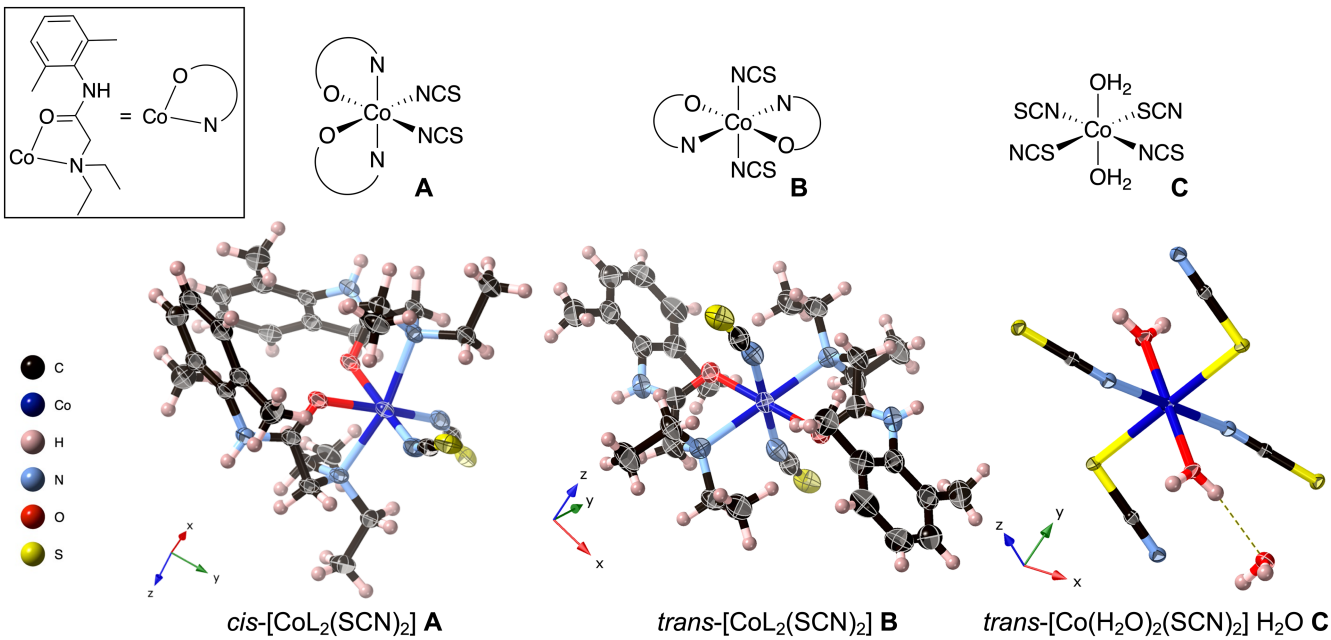

FIGURE 6 Crystal and line structures of *cis*-$[CoL_2(SCN)_2]$ A, *trans*-$[CoL_2(SCN)_2]$ B, and coordination polymer *trans*-$[Co(H_2O)_2(SCN)_2]\cdot H_2O$ C. For A and B, L = lidocaine. Displacement ellipsoids shown at 50%.

$[Co(SCN)_4]^{2-}$ from (ii) compounds resulting from such bases forming a coordination bond to Co(II). In ion pairs, charged species are held together by electrostatic forces and intramolecular (supramolecular) interactions such as hydrogen bonds. Coordination compounds (complexes) result from bonds between a Lewis base and a metal ion such as Co(II).

For the blue ion pair $(HL^+)_2[Co(SCN)_4]^{2-}$ where L = select reactive organic bases, it is the anion's tetrahedral geometry that is responsible for these tests' hallmark color (Figure 1). Considering the link between a blue appearance and tetrahedral geometry, two coordination compounds featuring organic bases as ligands are possibilities: $[CoL(SCN)_2]$ and $[CoL_2(SCN)_2]$. The first features a chelating base, while the second features a non-chelating base. We found no structures resembling $[CoL(SCN)_2]$ in the CSD. The only structure resembling $[CoL_2(SCN)_2]$ in the CSD is the green [Co(4-((2,6-Di-isopropylphenyl)amino)-3-methylpent-3-en-2-one)$_2$(SCN)$_2$], code WUWDUO, with a distorted tetrahedral geometry elucidated by Lugo and Richards [63] shown in SI Figure S5. Contrary to the fairly mild conditions of cobalt(II) thiocyanate-based tests, this compound was prepared in boiling toluene.

Moving to an octahedral coordination geometry about Co(II), we observed such species with the formation of the pink-appearing compounds *cis*-$[CoL_2(SCN)_2]$ and *trans*-$[CoL_2(SCN)_2]$ where L = lidocaine (Figure 6). While comparable species were not observed for cocaine hydrochloride and lidocaine hydrochloride monohydrate, reactions of these salts with classic test reagent did yield the pink coordination polymer *trans*-$[Co(H_2O)_2(SCN)_2]\cdot H_2O$ with an octahedral geometry (Figure 6). As stated previously, the seven cocaine or cocainium featuring compounds in the CSD are either the free base or ion pairs. Thus, there are no structures of compounds with cocaine as a coordinating ligand deposited in the CSD.

The coordination compounds and ion pairs we observed for the evaluated cobalt(II) thiocyanate-based tests typify reactivity seen for Lewis acid metal ions. Specifically speaking of Co(II), it has fast ligand exchange kinetics so that in principle thermodynamic products should be obtained, but any type of coordination entity may be formed especially if trapped in a stable solid form [64]. In addition, which species will be thermodynamically most stable, and the corresponding reaction rates, will be critically dependent on the concentrations of all participating components and reaction conditions. There is a very facile conversion and co-existence of the tetrahedral $[Co(SCN)_4]^{2-}$ (blue) and octahedral (pink) coordination geometries (Figure 1), in part explaining the performance of cobalt(II) thiocyanate based rapid color tests.

4 | CONCLUSION

A litany of organic bases (L) can participate in the Lewis acid–Lewis base interactions giving rise to ion pairs and coordination compounds observed in cobalt(II) thiocyanate reactions. Our work with cocaine hydrochloride, lidocaine hydrochloride monohydrate, and lidocaine greatly bolsters the conclusion that an ion pair of general structure $(HL)_2^+[Co(SCN)_4]^{2-}$ is the origin of the hallmark blue color interpreted as a positive result for cobalt(II) thiocyanate-based tests. Single-crystal X-ray diffraction work identified $(HLidocaine^+)_2([Co(SCN)_4]^{2-})\cdot H_2O$ as the blue species produced for reactions involving lidocaine hydrochloride monohydrate, with the reasonable extension that this ion pair composes the blue layer around lidocaine crystals exposed to cobalt(II) thiocyanate-based reagents. While the glassy, amorphous blue precipitate resulting from reactions involving cocaine hydrochloride was unsuitable for crystallographic analysis, our comparative spectroscopic work supports its composition to be $(Hcocaine)^+_2[Co(SCN)_4]^{2-}$. Co-existing with these blue ion pairs were pink coordination compounds, the structure of each determined by single-crystal X-ray diffraction. The coordination polymer *trans*-$[Co(H_2O)_2(SCN)_2]\cdot H_2O$ was isolated from cocaine hydrochloride and lidocaine hydrochloride monohydrate reaction vessels, while *cis*-$[Co(lidocaine)_2(SCN)_2]$ and *trans*-$[Co(lidocaine)_2(SCN)_2]$ were retrieved in lidocaine reaction vessels. This cataloging of products per analyte enables the optimization of appropriate reaction conditions to favor a desired product. In general for Co(II), different chemistry strategies would be required to optimize for an ion pair versus a coordination compound for each specific analyte.

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CONFLICT OF INTEREST STATEMENT

The authors report no conflicts of interest.

ORCID

Raychelle Burks https://orcid.org/0000-0003-4696-609X
Francoise M. Amombo Noa https://orcid.org/0000-0001-8361-3432

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