Spectroscopic Investigation of Fluorescence Quenching Agents. Part IV: Selectivity of Nitromethane for Discriminating Between Alternant Versus Nonalternant Polycyclic Aromatic Hydrocarbons in Solvents of Differing Polarities

SHERYL A. TUCKER, HEATHER C. BATES, WILLIAM E. ACREE, JR.,* and JOHN C. FETZER

Department of Chemistry, University of North Texas, Denton, Texas 76203-5068 (S.A.T., H.C.B., W.E.A.); and Chevron Research and Technology Center, Richmond, California 94802-0627 (J.C.F.)

To further assess the applicability of nitromethane as a selective quenching agent for alternant vs. nonalternant polycyclic aromatic hydrocarbons in HPLC analysis, we measured the effect that it has on the fluorescence emission behavior of 96 different polycyclic aromatic hydrocarbons dissolved in a binary ethyl acetate/acetonitrile solvent mixture. Nitromethane quenching results are compared with previously reported acetonitrile, aqueous/acetonitrile, and toluene/acetonitrile solvent mixtures. Results of these measurements revealed that the "selective quenching" rule is obeyed for the vast majority of PAHs in all solvents considered thus far, with the coronene derivatives being the only major exceptions.

Index Headings: Fluorescence; Molecular structure; Spectroscopic techniques.

INTRODUCTION

Polycyclic aromatic compounds (PACs) have received considerable attention in the recent chemical literature, in part because of the widely varying carcinogenic and mutagenic properties of closely related isomers. Carcinogenic properties of select isomers, combined with an increasing awareness of environmental pollution and toxic material disposal, have prompted researchers to develop analytical methods specific for the different aromatic compounds. Current analytical methods generally employ high-resolution chromatographic techniques combined with pre-concentration via supercritical fluid¹⁻⁵ or Soxhlet extraction,⁵⁻⁷ relatively sophisticated or lengthy isolation, or group separation schemes to obtain fractions from environmental or biological samples suitable for chromatographic analysis. Conventional chemically bonded monomeric C₁₈ stationary phases⁸⁻¹² (i.e., phases prepared with monofunctional silanes) can generally separate the various PAH molecules present according to overall size and number of aromatic rings. Monomeric C₁₈ phases possess only limited inherent ability to separate PAH isomers on the basis of molecular shape. Enhanced shape recognition is achieved on either a "charge transfer"¹³ or a polymeric C₁₈ stationary phase^{8-12,14,15} (i.e., phase prepared with either difunctional or trifunctional silanes in the presence of water),

the latter of which is believed to be molecularly ordered to some extent. Relative retention values for similar PAH structures of increasing size (i.e., naphthalene, pyrene, benzo[ghi]perylene, benzo[pqr]naphtho[8,1,2bcd]perylene, benzo[rst]dinaphtho[2,1,8,7defg; 2',1',8',7'ijkl]-pentaphene, and tetrabenzo[def,lm,qrs,yz]pyranthene) with the use of different polymeric C₁₈ stationary and mobile phase combinations, along with the elution strengths of the eleven common HPLC solvents, are reviewed in detail elsewhere.¹⁵

Problems associated with co-eluting components in HPLC can be overcome in part by making the detector selective for each given PAC subclass. Of the four most common HPLC detectors on the market, fluorescence affords the most selectivity in that the excitation and emission wavelengths can be varied independently. While several polycyclic aromatic compounds may absorb at the same excitation wavelength, not all will emit at the wavelength(s) monitored by the detector. Utilization of selective fluorescence quenching agents further simplifies observed emission spectra by eliminating signals from undesired chemical interferences having only slightly different molecular structures. On the basis of limited fluorescence measurements for perylene, dibenzo[b,k]chrysene, dibenzo[h,rst]pentaphene, naphtho[1,2b]-fluoranthene, indeno[1,2,3cd]pyrene, and 12,11-(perinaphthylene)fluoranthene dissolved in a binary aqueous/acetonitrile mixture (20:80 percent by volume), Blümer and Zander¹⁶ noted that nitrobenzene and nitromethane selectively quenched fluorescence emission of the so-called "alternant" polycyclic aromatic hydrocarbons (PAHs). Emission intensities of the three nonalternant PAHs (e.g., naphtho[1,2b]fluoranthene, indeno[1,2,3cd]pyrene, and 12,11-(perinaphthylene)fluoranthene) were unaffected. Published studies¹⁷⁻²² involving over 63 PAHs have identified dibenzo[hi,wx]heptacene, benzo[k]fluoranthene, and naphtho[2,3b]fluoranthene as among the few exceptions to the so-called nitromethane selective quenching rule in the PAH6 benzenoid, fluorenoid, fluoranthene and "methylene-bridged" cyclopenta-PAH subclasses. More recent measurements²³ revealed that nitromethane quenched fluorescence emission of all nine acenaphthylene derivatives studied thus far, which is completely contrary to what would be expected

Received 18 May 1993.

* Author to whom correspondence should be sent.

on the basis of the fact that the nine solutes are nonalternant PAH molecules. Despite the aforementioned exceptions, nitromethane remains a very useful, selective quenching reagent in fluorescence analysis of unknown mixtures of polycyclic aromatic compounds.

For the most part previous nitromethane quenching investigations have been confined to more polar solvents such as neat acetonitrile or binary aqueous/acetonitrile mixtures. Both systems are used routinely as mobile phases in HPLC analysis of small PAHs having six rings or less. However, larger 6–10 ring PAH molecules may require an aromatic hydrocarbon or a dichloromethane mobile phase cosolvent in order for the solutes to elute from the chromatographic column in timely fashion.¹⁵ To further assess the applicability of nitromethane as a selective quenching agent for HPLC analysis we report the effect that nitromethane has on the fluorescence emission behavior of 96 different alternant and nonalternant PAHs dissolved in a binary ethyl acetate/acetonitrile solvent mixture.

MATERIALS AND METHODS

Synthetic references and/or commercial suppliers for the PAH solutes contained in Table I are listed in our earlier papers. Stock solutions were prepared by dissolving the solutes in dichloromethane. Small aliquots of the stock solutions were transferred into test tubes, allowed to evaporate, and diluted with the solvent of interest. Final solute concentrations were sufficiently dilute to minimize inner-filtering artifacts. Solvents were of HPLC, spectroquality, or AR grade, purchased commercially from either Aldrich or Fisher Scientific, and the resulting solutions were optically dilute (absorbances $\text{cm}^{-1} < 0.01$) at all wavelengths, except for the nitromethane quenching studies.

Absorption spectra were recorded on a Milton Roy Spectronic 1001 Plus and a Hewlett-Packard 8450A photodiode array spectrophotometer in the usual manner. The fluorescence spectra were run on a Shimadzu RF-5000U spectrofluorometer with the detector set at high sensitivity. Solutions were excited at the wavelengths listed in Table I. Fluorescence data were accumulated in a 1-cm² quartz cuvette at 19°C, ambient room temperature, with excitation and emission slit width settings of 15 nm and 3 nm, respectively. For solvent polarity determinations involving pyrene, the emission slit width was closed to 1.5 nm so that the calculated intensity ratios could be compared directly with literature values.²⁴ Street and Acree²⁵ had previously shown that emission intensity ratios vary with emission slit setting.

Emission intensities associated with the quenching study were corrected for primary inner-filtering artifacts arising from the absorption of excitation radiation. Many of the PAHs have excitation wavelengths in the 300–320 nm spectral region, and a few drops of nitromethane gave solutions having appreciable absorbances. Mathematical expressions, computational procedures, and interrogation zone dimensions are given elsewhere.^{17–19,26,27} Every effort was made to work at solution absorbances below $A \text{ cm}^{-1} \leq 0.95$ ($f_{\text{prim}} \leq 3.00$) where the inner-filtering correction equation is valid. Secondary inner-filtering corrections were not necessary in the present study since

nitromethane is “optically transparent” in most of these PAHs’ emission ranges.

RESULTS AND DISCUSSION

Previous studies involving nitromethane as a selective quenching agent for discriminating between alternant vs. nonalternant PAHs utilized either neat acetonitrile or a binary aqueous/acetonitrile mixture (20:80 % by volume). Such solvents work well as mobile phases in HPLC separations for those PAHs that contain six rings or less, but different solvent strengths must be employed for larger PAHs having 6–10 rings. Toluene/acetonitrile or ethyl acetate/acetonitrile mixtures have served well in the past as HPLC mobile-phase solvents for the separation of the larger PAHs.^{15,28} Table I compares the experimental results regarding the ability of nitromethane to act as a selective quenching agent for alternant vs. nonalternant PAHs in the aqueous/acetonitrile mixture and toluene/acetonitrile mixture (40:60 percent by volume) utilized earlier,³⁰ and an ethyl acetate/acetonitrile mixture (40:60 percent by volume). While a published paper¹⁶ has alluded to the fact that solvent polarity affects nitromethane’s ability to act as a selective quenching agent, there was no in-depth study ever reported until we recently compared the aqueous/acetonitrile and toluene/acetonitrile mixtures.³⁰

Examination of Table I reveals that the toluene/acetonitrile mixture ($P_y = 1.49$) and ethyl acetate/acetonitrile ($P_y = 1.68$), although less polar than the aqueous/acetonitrile mixture (observed $P_y = 1.60^{29}$; $P_y = 1.80$ after correction for slit width effects²⁵) or pure acetonitrile ($P_y = 1.79$),²⁴ can effectively be used as an HPLC solvent when nitromethane is used to selectively quench the fluorescence emission signals of alternant vs. nonalternant PAHs. Of the 96 compounds examined, only eleven behave differently in the ethyl acetate/acetonitrile solvent mixtures as compared to either the aqueous/acetonitrile solvent mixture or neat acetonitrile. As in the toluene/acetonitrile solvent study, seven of the exceptions noted were coronene derivatives. Our initial studies utilized the aqueous/acetonitrile mixtures, but after a more exhaustive investigation involving 96 compounds we found that, except for the aforementioned coronene derivatives, the selective quenching rule is obeyed in neat acetonitrile as well. Since then, we have employed acetonitrile, rather than the aqueous/acetonitrile mixture, to enhance the solubility of the larger PAHs.

Two nonalternant compounds, naphtho[2,3b]fluoranthene and benzo[k]fluoranthene, that were exceptions to the nitromethane selective quenching rule in both aqueous/acetonitrile and toluene/acetonitrile mixtures are no longer exceptions when dissolved in the ethyl acetate/acetonitrile solvent. Interestingly, the two benzo[k]fluoranthene derivatives, 3-methoxybenzo[k]fluoranthene and 3-hydroxybenzo[k]fluoranthene, are quenched in ethyl acetate/acetonitrile even though the parent compound was not quenched. In both toluene/acetonitrile and ethyl acetate/acetonitrile solvents, benzo[rs]t]dinaphtho[2,1,8,7defg; 2',1',8',7'ijkl]pentaphene (BNP) was not quenched by nitromethane. BNP should have been quenched on the basis of the fact that it is an alternant compound. Other than the coro-

TABLE I. Summary of excitation wavelength, probe character, and fluorescence quenching (by nitromethane) data for alternant and nonalternant PAHs.

Letter ^a	Chemical name	Probe	λ_{ex} (nm)	λ_{em}^b (nm)	Quenched ACN	Quenched ACN-TOLN ^c	Quenched ACN-EA ^d
Group I—Alternant PAHs							
A	Coronene	Yes	334	425	Yes ^f	No	No
B	Benzo[a]coronene	Yes	316	429	Yes ^f	No	No
C	Naphtho[2,3a]coronene	Yes	333	442	Yes ^f	No	No
D	Dibenzo[a,j]coronene	Yes	324	431	Yes ^f	No	No
E	Naphtho[8,1,2abc]coronene	Yes	322	458	Yes ^f	No	No
I	Tetrabenzo[de,hi,mn,qr]naphthacene	No	318	418	Yes	Yes	Yes
K	Dinaphtho[8,1,2abc;2',1',8'jkl]coronene	NA ^e	370	481	Yes	No	No
L	Anthra[2,3a]coronene	Yes	357	488	Yes ^f	No	No
M	Pyrene	Yes	338	371	Yes	Yes	Yes
N	Perylene	No	403	437	Yes	Yes	Yes
O	Benzo[ghi]perylene	Yes	380	405	Yes	Yes	Yes
Q	Naphtho[1,2,3,4ghi]perylene	No	316	416	Yes	Yes	Yes
R	Benzo[pqr]naphtho[8,1,2bcd]perylene	No	325	418	Yes ^f	Yes	Yes
T	Benzo[a]pyrene	No	350	402	Yes	Yes	Yes
U	Benzo[e]pyrene	Yes	335	386	Yes	Yes	Yes
V	Dibenzo[a,e]pyrene	No	360	394	Yes	Yes	Yes
AC	Benzo[b]perylene	No	312	437	Yes ^f	Yes	Yes
AF	Dibenzo[cd,k]naphtho[8,1,2fghi]perylene	No	321	451	Yes ^f	Yes	Yes
AG	Benzo[a]naphtho[8,1,2cde]naphthacene	No	411	446	Yes ^f	Yes	Yes
AH	Dibenzo[def,p]chrysene	Yes	310	419	Yes	Yes	Yes
AI	Anthranthrene	No	306	430	Yes	Yes	Yes
AJ	Benzo[rst]pentaphene	Yes	307	432	Yes	Yes	Yes
AK	Benzo[rst]dinaphtho[2,1,8,7defg;2',1',8',7'ijkl]pentaphene	No	315	438	Yes	No	No
AM	Dibenzo[h,rst]pentaphene	Yes	366	416	Yes ^f	Yes	Yes
AN	Dibenzo[a,rst]naphtho[8,1,2cde]pentaphene	No	300	413	Yes	Yes	Yes
AQ	Dinaphtho[2,1,8,7defg;2',1',8',7'opqr]pentacene	No	410	484	Yes ^f	Yes	No
AR	Pyranthene	NA ^e	300	467	Yes	Yes	Yes
AT	Dibenzo[de,st]pentacene	No	408	470	Yes	Yes	Yes
AU	Dibenzo[fg,qr]pentacene	No	400	435	Yes	Yes	Yes
AV	Naphtho[8,1,2hij]hexaphene	No	360	446	Yes	Yes	Yes
AW	Benzo[vwx]hexaphene	Yes	360	477	Yes	Yes	Yes
AX	Benzo[1,2,3cd;4,5,6c'd']diperylene	No	400	437	Yes	Yes	Yes
AY	Dibenzo[hi,wx]heptacene	No	400	485	No	No	No
AZ	Benzo[b]triphenylene	No	300	375	Yes	Yes	Yes
BA	Anthracene	No	340	377	Yes	Yes	Yes
BB	Triphenylene	No	300	354	Yes	Yes	Yes
BC	Phenanthrene	No	300	363	Yes	Yes	Yes
BD	Chrysene	No	320	380	Yes	Yes	Yes
BE	Benzo[g]chrysene	No	320	392	Yes	Yes	Yes
BF	Naphtho[2,3g]chrysene	No	350	424	Yes	Yes	Yes
Group II—Alternant PAH Derivatives							
A	1-Methylpyrene	No	330	375	Yes ^f	Yes	Yes
B	2-Methylpyrene	No	333	374	Yes ^f	Yes	Yes
C	4-Methylpyrene	No	320	375	Yes ^f	Yes	Yes
D	1,5-Dimethylpyrene	No	320	379	Yes ^f	Yes	Yes
E	1-Butylpyrene	No	320	375	Yes ^f	Yes	Yes
F	1-Decylpyrene	No	320	375	Yes ^f	Yes	Yes
G	4-Methylchrysene	No	320	368	Yes	Yes	Yes
H	5-Methylchrysene	No	320	370	Yes	Yes	Yes
I	5-Methyldibenzo[b,def]chrysene	No	300	460	Yes ^f	Yes	Yes
J	3,4,5-Trihydrobenzo[cd]pyrene	No	340	377	Yes	Yes	Yes
K	3,4-Dihydrobenzo[ghi]perylene	Yes	334	381	Yes	Yes	Yes
L	5,6,7,8,9,10-Hexahydrobenzo[ghi]perylene	No	350	384	Yes	Yes	Yes
Group III—Alternant Cyclopenta-PAH Derivatives							
A	11H-benzo[bc]aceanthrylene	Yes	350	389	Yes	Yes	Yes
B	4H-cyclopenta[def]phenanthrene	No	320	362	Yes	Yes	Yes
C	4H-cyclopenta[def]chrysene	Yes	320	360	Yes	Yes	Yes
D	13H-dibenzo[a,g]fluorene	No	340	381	Yes	Yes	Yes
E	13H-dibenzo[a,i]fluorene	No	320	384	Yes	Yes	Yes
F	4H-benzo[b]cyclopenta[mno]chrysene	Yes	330	398	Yes	Yes	Yes
G	4H-cyclopenta[pqr]picene	Yes	330	395	Yes	Yes	Yes
H	13H-dibenz[bc,l]aceanthrylene	Yes	320	398	Yes	Yes	Yes
I	13H-dibenz[bc,k]aceanthrylene	No	400	460	Yes	Yes	Yes
J	4H-benzo[b]cyclopenta[jkl]triphenylene	No	300	397	Yes	Yes	Yes
K	7H-dibenzo[c,g]fluorene	No	300	386	Yes	Yes	Yes
L	9H-benz[6,7]indeno[1,2l]phenanthrene	No	345	394	Yes	Yes	Yes
M	4H-benzo[def]cyclopenta[mno]chrysene	No	320	400	Yes	Yes	Yes
N	4H-benzo[c]cyclopenta[mno]chrysene	No	300	383	Yes	Yes	Yes

TABLE I. Continued

Letter ^a	Chemical name	Probe	λ_{ex} (nm)	λ_{em}^{b} (nm)	Quenched ACN	Quenched ACN- TOLN ^c	Quenched ACN-EA ^d
Group IV—Nonalternant Acenaphthylene Derivatives							
A	Acenaphthylene	No	288	336	Yes	Yes	Yes
B	Aceanthrylene	No	360	427	Yes	Yes	Yes
C	Acephenanthrylene	No	300	355	Yes	Yes	Yes
D	Benz[e]aceanthrylene	No	360	402	Yes	Yes	Yes
E	3-Methylbenz[j]aceanthrylene	No	300	397	Yes	Yes	Yes
F	6-Methylbenz[j]aceanthrylene	No	300	426	Yes	Yes	Yes
G	Benzo[def]cyclopenta[hi]chrysene	No	300	410	Yes	Yes	Yes
H	Cyclopenta[cd]pyrene	No	336	377	Yes	Yes	Yes
I	Acenaphth[1,2a]acenaphthylene	No	406	435	Yes	Yes	Yes
Group V—Nonalternant Fluoranthene and Fluorenois							
A	Benz[def]indeno[1,2,3hi]chrysene	No	406	474	No ^f	No	No
B	Fluoreno[2,3,4,9defg]chrysene	No	315	478	No ^f	No	No
C	Benz[def]indeno[1,2,3qr]chrysene	No	408	490	No	No	No
D	Benzo[k]fluoranthene	Yes	306	408	Yes ^f	Yes	No
E	Dibenzo[a,e]fluoranthene	No	390	482	No ^f	No	No
F	Indeno[1,2,3cd]pyrene	No	326	474	No ^f	No	No
G	Naphtho[1,2b]fluoranthene	No	350	438	No ^f	No	No
H	Benzo[b]fluoranthene	No	346	446	No ^f	No	No
I	Benzo[j]fluoranthene	No	315	508	No ^f	No	No
J	Fluoranthene	No	300	461	No ^f	No	No
K	Benzo[ghi]fluoranthene	No	340	447	No	No	No
L	Naphtho[2,1a]fluoranthene	No	400	466	No ^f	No	No
M	Naphtho[2,3b]fluoranthene	Yes	316	422	Yes ^f	No	No
N	Benzo[a]fluoranthene	No	406	488	No	No	No
O	Dibenzo[ghi,mno]fluoranthene	No	290	433	No	No	No
P	Rubicene	No	370	542	No	No	No
Q	Diacenaphtho[1,2j:1',2'l]fluoranthene	No	374	502	Yes	Yes	Yes
Group VI—Nonalternant Fluoranthene Derivatives							
A	10-Methylbenzo[b]fluoranthene	No	347	445	No	No	No
B	3-Methoxybenzo[k]fluoranthene	No	312	456	Yes	Yes	Yes
C	3-Hydroxybenzo[k]fluoranthene	No	310	459	Yes	Yes	Yes

^a Molecular structures are given in Refs. 17–19, 23, 26, 30, and 31.

^b Emission wavelength used in the nitromethane quenching studies.

^c Quenching studies performed in a binary toluene/acetonitrile solvent mixture (40:60 percent by volume).

^d Quenching studies performed in a binary ethyl acetate/acetonitrile solvent mixture (40:60 percent by volume).

^e NA indicates that the PAC is unacceptable as a solvent polarity probe molecule because a common set of bands could not be assigned in all solvents studied. The molecule may exhibit selective enhancement of one (or more) fluorescence emission band(s).

^f Quenching studies performed in a binary aqueous/acetonitrile solvent mixture (20:80 percent by volume). Quenching of coronene and benzo[a]coronene fluorescence emission, after correction for primary inner-filtering and dilution, amounted to about a 20% reduction in signal intensity. Much larger reductions were observed for many of the other alternant PAHs studied.

nene derivatives, BNP and dinaphtho[2,1,8,7defg; 2',1',8',7'opqr]pentacene remain the only other major exceptions in the ethyl acetate/acetonitrile binary solvent mixture when compared to the more polar aqueous/acetonitrile system. Results of the present investigation clearly indicate that a solute's quenching behavior can be directly affected by the polarity of the surrounding solvent.

ACKNOWLEDGMENTS

This work is supported in part by grants from the National Science Foundation (Grant No. CTS-8922485), by the University of North Texas Research Council, and by a National Science Foundation Doctoral Research Fellowship awarded to S. A. Tucker.

1. J. Rein, C. M. Cork, and K. G. Furton, *J. Chromatogr.* **545**, 149 (1991).
2. B. W. Wright, S. R. Frye, D. G. McMinn, and R. D. Smith, *Anal. Chem.* **59**, 640 (1987).
3. S. B. Hawthorne and D. J. Miller, *J. Chromatogr.* **403**, 63 (1987).
4. S. B. Hawthorne, J. J. Langenfeld, D. J. Miller, and M. D. Burford, *Anal. Chem.* **64**, 1614 (1992).
5. B. W. Wright, C. W. Wright, R. W. Gale, and R. D. Smith, *Anal. Chem.* **59**, 38 (1987).
6. P. J. A. Fowle and T. L. Bulman, *Anal. Chem.* **58**, 721 (1986).
7. G. A. Junk and J. J. Richard, *Anal. Chem.* **58**, 962 (1986).
8. S. A. Wise, L. C. Sander, R. Lapouyande, and P. Garrigues, *J. Chromatogr.* **514**, 111 (1990).
9. L. C. Sander and S. A. Wise, *Anal. Chem.* **59**, 2309 (1987).
10. L. C. Sander and S. A. Wise, *J. High Resolut. Chromatogr. Chromatogr. Commun.* **11**, 383 (1988).
11. L. C. Sander and S. A. Wise, *Anal. Chem.* **61**, 1749 (1989).
12. J. C. Fetzer, in *Chemical Analysis of Polycyclic Aromatic Compounds*, T. Vo-Dinh, Ed. (John Wiley and Sons, New York, 1989), Chap. 3.
13. L. C. Sander, R. M. Parris, S. A. Wise, and P. Garrigues, *Anal. Chem.* **63**, 2589 (1991).
14. J. C. Fetzer and W. R. Biggs, *J. Chromatogr.* **386**, 87 (1987).
15. J. C. Fetzer and W. R. Biggs, *Chromatographia* **27**, 118 (1989).
16. G.-P. Blümer and M. Zander, *Fresenius Z. Anal. Chem.* **296**, 409 (1979).
17. S. A. Tucker, W. E. Acree, Jr., B. P. Cho, R. G. Harvey, and J. C. Fetzer, *Appl. Spectrosc.* **45**, 1699 (1991).
18. V. L. Amszi, Y. Cordero, B. Smith, S. A. Tucker, W. E. Acree, Jr., C. Yang, E. Abu-Shaqara, and R. G. Harvey, *Appl. Spectrosc.* **46**, 1156 (1991).
19. S. A. Tucker, H. Darmodjo, W. E. Acree, Jr., J. C. Fetzer, and M. Zander, *Appl. Spectrosc.* **46**, 1260 (1992).

20. H. Dreeskamp, E. Koch, and M. Zander, *Z. Naturforsch.* **30A**, 1311 (1975).
21. U. Breymann, H. Dreeskamp, E. Koch, and M. Zander, *Chem. Phys. Lett.* **59**, 68 (1978).
22. S. H. Chen, C. E. Evans, and V. L. McGuffin, *Anal. Chim. Acta* **246**, 65 (1991).
23. S. A. Tucker, H. C. Bates, V. L. Amszi, W. E. Acree, Jr., H. Lee, P. D. Raddo, R. G. Harvey, J. C. Fetzer, and G. Dyker, *Anal. Chim. Acta* **278**, 269 (1993).
24. D. C. Dong and M. A. Winnik, *Can. J. Chem.* **62**, 2560 (1984).
25. K. W. Street, Jr., and W. E. Acree, Jr., *Analyst* **111**, 1197 (1986).
26. S. A. Tucker, W. E. Acree, Jr., J. C. Fetzer, and J. Jacob, *Polycyclic Aromat. Compds.* **3**, 1 (1992).
27. S. A. Tucker, V. L. Amszi, and W. E. Acree, Jr., *J. Chem. Educ.* **69**, A8 (1992).
28. P. A. Peadar, M. L. Lee, Y. Hirata, and M. V. Novotny, *Anal. Chem.* **52**, 2268 (1980).
29. K. W. Street, Jr., and W. E. Acree, Jr., *J. Liq. Chromatogr.* **9**, 2799 (1986).
30. S. A. Tucker, W. E. Acree, Jr., J. C. Fetzer, R. G. Harvey, M. J. Tanga, P.-C. Cheng, and L. T. Scott, *Appl. Spectrosc.* **47**, 715 (1993).
31. W. E. Acree, Jr., S. A. Tucker, and J. C. Fetzer, *Polycyclic Aromat. Compds.* **1**, 75 (1991).