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Stable 3-Imino-2,3-dihydroindazol-1-yl Radicals

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Dedicated to Professor Siegfried Hünig on the occasion of his 90th birthday

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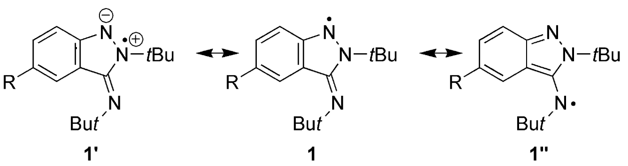
Oxidation of 2-*tert*-butyl-3-(*tert*-butylamino)-2*H*-indazoles with lead(IV) oxide yields red, stable radicals, which can be distilled under high vacuum and recrystallized. They revert to their precursors on Pd-catalysed hydrogenation. Configuration and atomic distances were obtained by X-ray diffraction analysis. EPR hfc constants were assigned with the help of ^{15}N labeling and exchange of a phenyl hydrogen atom for a *tert*-butyl group. The X-ray and EPR results show that the novel radicals are to be considered as cyclic hydrazyl radicals, modified by delocalization of the unpaired electron involving the exocyclic imino group and the benzene ring.

Introduction

Since more than one century, stable radicals play important roles in may areas of organic chemistry.[1–3] So far, all stable *N*-radicals devoid of heteroatoms other that nitrogen belong to the families[3,4] of aminyl ($R_2N^{\cdot}$)[5] and hydrazyl radicals ($R_2N–N^{\cdot}–R$) (both types being acyclic or having the radical moiety built into a cyclic skeleton like phenazinyl, 1,2,4-triazolinyl, and 1,4-dihydrobenzo-1,2,4-triazinyl radicals), and symmetric, resonance-delocalized hydrazidinyl radicals, viz., tetraazapentenyl ($R_2N–N^{\cdot}–CR=N–NR_2$), tetrazolinyl, and verdazyl radicals.[6] In the general framework of Hünig's two-step reversible redox systems,[7] the intermediate neutral radical $R_2N–(CH=CH)_n–N^{\cdot}–R$ between the corresponding reduced and oxidized forms is exemplified by hydrazyl ($n = 0$) and several heterocyclic *N*-radicals, e.g., phenazinyl ($n = 1$) and 1,4-dihydrobenzo-1,2,4-triazinyl radicals ($n = 1$). A number of *N*-radicals are known whose stabilization by one or more structural features, viz., steric protection, spin delocalization, nitrogen atoms as carriers of spin densities, and charge distribution by electronic effects of substituents,[3] permitted characterization by X-ray crystallography.[8] Here we report on a novel type of such *N*-radicals, the (*E*)-3-imino-2,3-dihydroindazol-1-yl radicals **1**.



a: R = H, **b**: R = *t*Bu

Results and Discussion

A host of 3-amino-2*H*-indazoles are known.[9] However, none of them has been considered as source of a radical. In reactions conceived as syntheses of aryl-substituted 3-iminodiaziridines, we obtained, surprisingly, blue fluorescent 3-amino-2*H*-indazoles **7** as main products besides small amounts of isomeric 3-(arylimino)diaziridines **3** and 2-aminobenzimidazoles **6**.[10] 1,3-Elimination of sulfuric acid from *N*-hydroxyguanidine *O*-sulfonic acids **2** under the influence of strong bases afforded red mixtures of isomers **3**, **6**, **7**. Likewise, chlorination/1,3-dehydrochlorination at low temperature of guanidine **5** gave a red mixture consisting mainly of **3a** and **7a** (Scheme 1). The same red color was observed on heating of solutions of **3a** under rigorous exclusion of molecular oxygen.[11] As 3-iminodiaziridines are weak oxidants,[12] we suspected that the red color was due to oxidation of small amounts of one of the products **6a** or **7a**. Indeed, oxidation of **7a** in benzene solution with lead(IV) oxide or silver oxide[5,6] gave a red, under high vacuum distillable oil (75% yield), which slowly crystallized to afford deep-red crystals (**1a**), m.p. 39–40 °C. In a similar experiment, **7b** furnished a 78% yield of black-red crystals (**1b**), m.p. 102 °C after recrystallization from acetonitrile. Whereas **1a** was not completely stable but slowly formed a blue-violet EPR-silent dimer when kept at room tempera-

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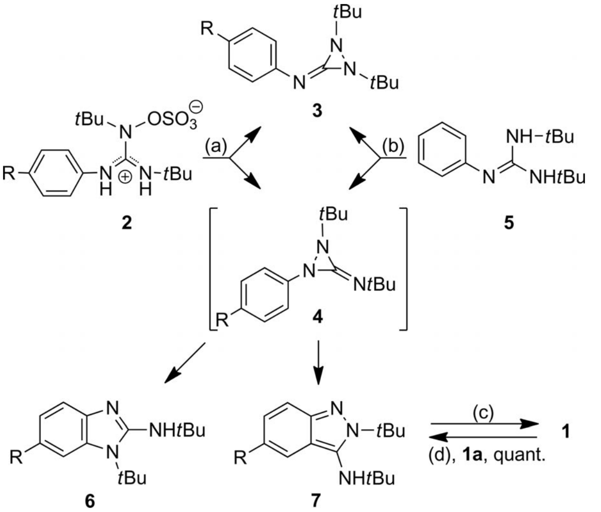
ture, the crystals of **1b** survived for years, obviously owing to the enhanced steric protection by the additional *tert*-butyl group at the benzene ring.[5] We did not observe reactions with molecular oxygen or moisture, a reluctance not often found among radicals.



Scheme 1. Synthesis of the stable *N*-radicals **1** and hydrogenation of **1a**. (a) 40% KOH in methanol/petroleum ether, yield **7a** 74%, **7b** 51%; (b) (1) *t*BuOK, diethyl ether, –78 °C, (2) *t*BuOCl, (3) → 20 °C, yield **7a** 42–50%; (c) PbO_2, K_2CO_3, benzene, 25 °C, 15 min, yield **1a** 75%, **1b** 78%; (d) $PdCl_2/CaCO_3$, DMF, 25 °C, 10 min, H_2 (735 Torr), yield **7a** quant.

The radical structures **1** of the deeply colored oxidation products of **7** were based on elemental analyses and spectroscopic evidence: mass spectra, lack of NH bands in IR spectra, UV/Vis spectra, strong EPR signals and, of course, the failure to record NMR spectra. The UV/Vis spectra show a broad, structured long-wavelength absorption in the visible region (Figure 1), which is more pronounced than in the case of 1,2,4-triazolinyl[13] and 1,4-dihydro-1,2,4-benzotriazinyl[14] radicals.

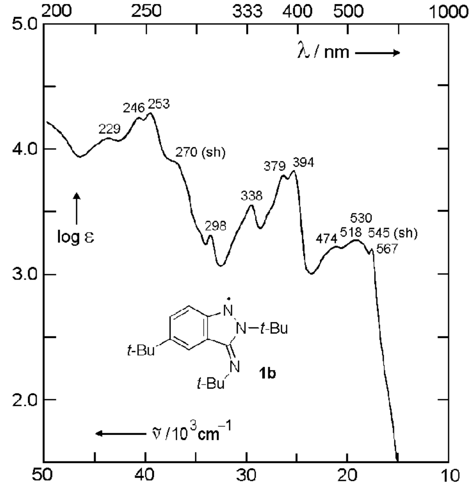


Figure 1. UV/Vis spectrum recorded for a solution of **1b** in heptane.

On palladium-catalysed hydrogenation, stable *N*-radicals like 1,2,4-triazolinyl,[8d] 1,4-dihydro-1,2,4-benzotriazinyl,[14] tetraazapentenyl, and verdazyl radicals,[6] rapidly consume half a mol of hydrogen to afford the corresponding reduced radical precursors. Similarly, hydrogenation of **1a** consumed the calculated amount of hydrogen and produced **7a** in quantitative yield, thus providing unequivocal structural evidence.

The configuration of **1b** in the solid state was revealed by X-ray diffraction analysis (Figure 2).[15] As expected on steric grounds, **1b** adopts the more favorable (*E*) configuration. More important, the atomic distances provided the clue to the electronic structure and thus supported the assignment of the nitrogen hyperfine coupling (hfc) constants (see below): the length of the bond to the exocyclic nitrogen atom amounts to only 128.7 pm. This value is very close to the length of a normal carbon–nitrogen double bond.[16,17] The distances (N-1)–(C-7a) and (C-3)–(C-3a) correspond to normal single bonds between sp^2 atoms.[16] Consequently, the new radical is best represented by the two hydrazyl resonance structures **1** and **1′** with an only small contribution by the *ortho*-quinonoid 1,5-diazapentadienyl resonance structure **1′′**. The hydrazyl character of **1** is confirmed by the length of the N–N bond, which is exactly as long as in 1,2,4-triazolinyl **8**[8d] and very close to the length of the N–N bond in Goldschmidt's radical 2,2-diphenyl-1-picrylhydrazyl (133.4 pm).[8a] These N–N distances correspond to about 50% double bond character.

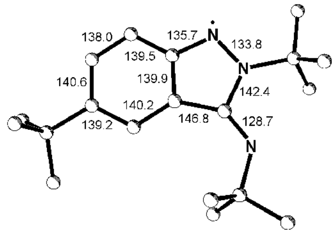


Figure 2. Configuration of **1b** in the solid state and selected atomic distances [pm] as calculated from the data reported in ref.[15] The complete set of atomic distances is given in the Supporting Information.

Owing to significant line broadening, the EPR spectrum recorded for a solution of **1a** in benzene shows only 58 lines instead of 432, calculated for three different nitrogen and four different hydrogen atoms (Figure 3). The line broadening results from unresolved couplings to the 18 hydrogen atoms of the *tert*-butyl groups. This is demonstrated by the EPR spectrum of [D_{18}]-**1a** (Figure 4). Perdeuteration of *tert*-alkyl groups has been used already for a long time in radical chemistry to improve the resolution of EPR spectra.[18]

Evaluation of the X-band EPR spectra by using standard techniques afforded the hfc constants compiled in Table 1. To aid the assignment, position 1 of **7a** was labeled with ^{15}N to afford radical [^{15}N]-**1a** and the EPR spectrum of Figure 5. In addition, the *tert*-butyl group at the benzene ring of **1b** simplified the EPR spectrum of **1a** by eliminating

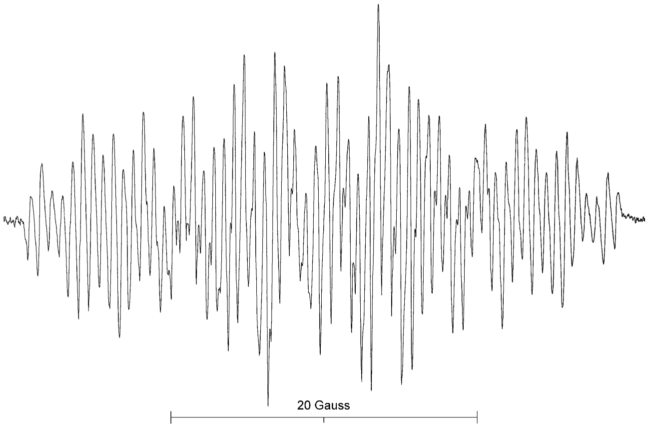


Figure 3. First derivative of the EPR spectrum recorded for a solution of **1a** in benzene.

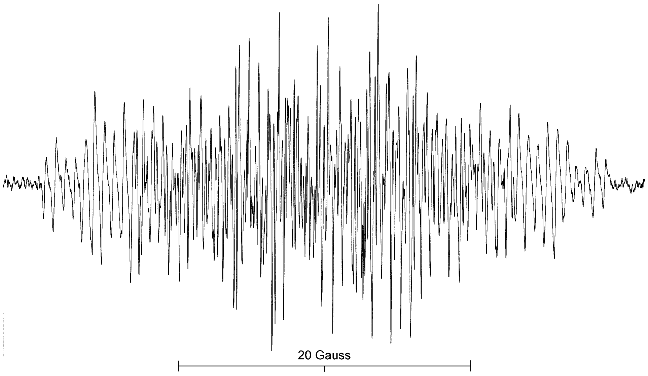
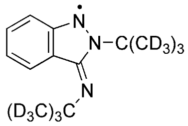
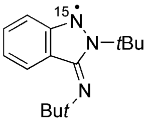


Figure 4. First derivative of the EPR spectrum recorded for a solution of [D_{18}]-**1a** in benzene.



[D_{18}]-**1a**



[^{15}N]-**1a**

the coupling to 5-H (→ EPR spectrum of Figure 6) and thus proved the assignment of the corresponding hfc constant a(5-H).

Table 1. Hyperfine coupling constants a [Gauss] obtained from EPR spectra recorded for solutions of **1** in benzene.

	1a (Figure 3)	[^{15}N]-**1a** (Figure 5)	**1b** (Figure 6)
a(N-1)	6.24	8.86	6.34
a(N-2)	6.49	6.56	6.41
a(=N)	3.32	3.36	3.24
a(4-H)[a]	0.75	0.74	0.75
a(5-H)	2.71	2.62	–
a(6-H)[a]	0.61	0.64	0.63
a(7-H)	2.01	2.07	2.03

[a] The assignment may be exchanged.

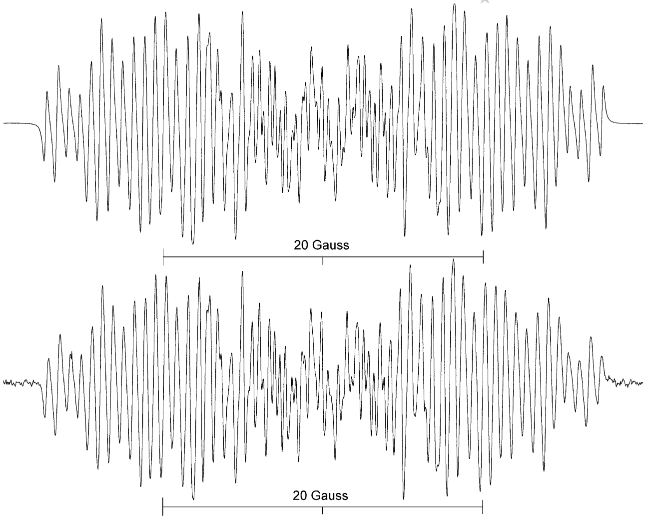


Figure 5. First derivative of the EPR spectrum recorded for a solution of [^{15}N]-**1a** in benzene (bottom) and spectrum simulated by using the hfc constants listed in Table 1 (top).

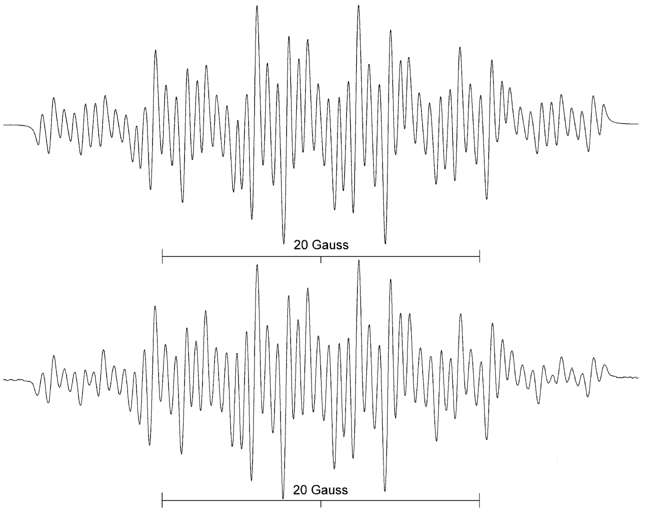
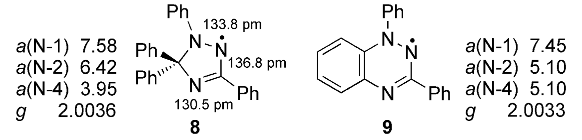


Figure 6. First derivative of the EPR spectrum recorded for a solution of **1b** in benzene (g = 2.0035, bottom) and spectrum simulated by using the hfc constants listed in Table 1 (top).

The hydrazyl character of **1**, as indicated by the X-ray diffraction results, suggested a comparison of **1** with related heterocyclic radicals, viz., Neugebauer's 1,2,4-triazolinyl **8**[8c,13] and Blatter's radical **9**.[14,19] The size of the g factor of **1b** (2.0035) falls into the range of the g factors of these two radicals. In both radicals, the largest hfc constants measure the coupling to the threefold coordinated nitrogen atoms (N-1) of the hydrazyl moieties (Scheme 2). By analogy, we assign the largest hfc constants in the EPR spectra of **1** to the analogous nitrogen atoms (N-2) of the indazole rings. Obviously, the polar resonance structure **1′** contributes strongly to the delocalized system. The smallest nitrogen hfc constant is attributed to the exocyclic nitrogen atom, in accord with the minor importance of resonance structure **1′′** as indicated by the short C=N distance. The π-SOMO of **1** is mainly localized on the pyrazole ring and less on the exocyclic nitrogen atom. However, the hfc constants *a*(5-H) and *a*(7-H), being larger than the corresponding constants for **9** [*a*(5-H) = –1.30 G, *a*(7-H) = –1.79 G],[14] indicate delocalization of the unpaired electron into the benzene ring.



Scheme 2. Reported atomic distances of **8**[8d] and nitrogen hfc constants [Gauss] and *g* factors for **8**[13] and **9**.[14]

Conclusions

The present study uncovers the rare case of a novel type of stable *N*-radicals. The bulky substituents of the two examples **1a** and **1b** certainly contribute to their exceptional stability. However, numerous, perhaps somewhat less stable *N*-radicals of this type may be conceived and, probably, prepared from the host of known 3-amino-2*H*-indazoles.

Experimental Section

2-(*tert*-Butyl)-3-(*tert*-butylimino)-2,3-dihydro-1*H*-indazol-1-yls 1. General Procedure: A mixture of 3-amino-2*H*-indazole **7** (10 mmol), PbO_2 (24 g, 0.10 mol) and K_2CO_3 (24 g, 0.17 mol) in dry benzene (250 mL) was stirred at room temp. for 15 min. The solid material was removed by filtration, followed by distillation of the solvent under vacuum. The remaining dark red oil was distilled at room temp./5×10^{-6} Torr in a sublimation apparatus, whose cold finger was kept at –30 °C, to afford a deep-red oil, which crystallized under N_2 overnight.

2-(*tert*-Butyl)-3-(*tert*-butylimino)-2,3-dihydro-1*H*-indazol-1-yl (1a): Dark red, shining crystals (1.83 g, 75%, m.p. 39–40 °C), which formed a blue-violet EPR-silent dimer at room temp. during 30 d. IR (neat oil): $\tilde{\nu}$ = 1665 (w), 1595 (m) cm^{-1}. UV/Vis (hexane): λ_{max} ($\log\varepsilon$) = 555 (3.18), 515 (3.20), 478 (3.14), 394 (3.84), 376 (3.83), 337 (3.52), 296 (3.33), 268 (sh, 3.85), 249 (4.20), 241 (4.22) nm. EI MS (70 eV): *m*/*z* (%) = 245 (12) [$(M + 1)^+$], 244 (8) [M^+], 229 (1), 189 (10), 188 (26), 174 (12), 173 (16), 158 (10), 133 (85), 132 (100), 104 (18), 103 (23). $C_{15}H_{22}N_3$ (244.4): calcd. C 73.73, H 9.08, N 17.20; found C 73.80, H 9.18, N 17.42.

Dimer of 1a: 1a was kept in a sublimation apparatus at room temp. for 30 d. The volatile components (small amounts of a red oil and a white solid) were removed by sublimation at room temp./10^{-5} Torr. The residue was suspended in petroleum ether to afford dark blue-violet crystals. UV/Vis (hexane): λ_{max} ($\log\varepsilon$) = 631 (3.46), 600 (sh, 3.42), 583 (3.44), 406 (3.65), 392 (3.58), 383 (3.62), 320 (sh, 3.92), 305 (sh, 4.01), 285 (4.16), 214 (4.61) nm. EI MS (70 eV): *m*/*z* (%) = 488 (14) [M^+], 432 (4), 431 (23), 375 (1), 319 (2), 263 (3), 251 (1), 245 (13), 189 (3), 174 (4), 133 (100).

2,5-Bis(*tert*-butyl)-3-(*tert*-butylimino)-2,3-dihydro-1*H*-indazol-1-yl (1b): Black-red shining cubes (2.34 g, 78%, m.p. 102 °C, from acetonitrile), which survived unchanged for years under ambient conditions. IR (KBr): $\tilde{\nu}$ = 1596 (w) cm^{-1}. UV/Vis (heptane): λ_{max} ($\log\varepsilon$) = 567 (3.191), 545 (sh, 3.212), 530 (3.262), 518 (3.264), 474 (3.212), 394 (3.81), 379 (3.77), 338 (3.54), 298 (3.36), 270 (sh, 3.89), 253 (4.28), 246 (4.24), 229 (4.10) nm. EI MS (70 eV): *m*/*z* (%) = 301 (1), 300 (7), 299 (4). $C_{19}H_{30}N_3$ (300.5): calcd. C 75.95, H 10.06, N 13.98; found C 74.98, H 10.19, N 13.94.

Hydrogenation of 1a: A vigorously stirred suspension of $PdCl_2$ on $CaCO_3$ (2.6%, 200 mg) in dry dimethylformamide (DMF) was hydrogenated in a quantitative micro hydrogenation apparatus (NORMAG, Hofheim am Taunus, Germany). A solution of **1a** (246 mg, 1.005 mmol) in DMF (15 mL) was added, followed by stirring until the consumption of H_2 was complete (10 min). The volume of of H_2 consumed at 735 Torr was 12.5 mL (0.495 mmol, 99%). The catalyst was removed by filtration and the solvent distilled at 10^{-3} Torr to afford a residue, which was identical with **7a** (^1H NMR).

EPR Spectra: EPR quartz sample tubes were charged with weighted amounts of **1** and attached to a vacuum line (10^{-5} Torr). Solvents were stored over $LiAlH_4$, degassed by several freeze-pump-thaw cycles, and condensed into the sample tubes, which were sealed under a vacuum of 10^{-5} Torr.

Supporting Information (see footnote on the first page of this article): General experimental and analysis of EPR spectra (1 page), syntheses of [D_{18}]-**7a** and [^{15}N]-**7a** (2 pages), UV/Vis spectra of **1a** and **7b** (2 pages), IR spectra of **1** and **7** (2 pages), EPR spectra of **1** in various solvents (3 pages), atomic distances of **1b** (1 page).

Acknowledgments

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