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Reply to Comments on "Denitrogenation of Piperidine on Alumina, Silica, and Silica-Aluminas: The Effect of Surface Acidity"

Zdražil questioned the appropriateness of using the name *Hofmann elimination* for a surface reaction which involves the cleavage of C–N bonds without prior methylation of the nitrogen, followed by elimination of an amine and an alkene. Instead, he proposes to name it β-elimination. In order to throw some light on the issue—but perhaps not to completely resolve it—it is appropriate to briefly review the work of A. W. von Hofmann. In 1851, Hofmann (*1*) developed a process which is widely known as *Hofmann exhaustive methylation*. In this procedure, a primary, secondary, or tertiary amine is first treated with methyl iodide to convert it into the quaternary ammonium iodide. Then the iodide is transformed into hydroxide in the presence of silver oxide and water. Finally, the dry quaternary ammonium hydroxide is heated to produce C–N bond scission and the ensuing elimination of the tertiary amine and an alkene. Hence, most authors use the name *Hofmann exhaustive methylation* for an elimination reaction which involves the preparation of a quaternary ammonium compound by methylation, followed by either (i) pyrolysis of the corresponding hydroxide or (ii) direct pyrolysis of the compound in the presence of a base (*3*). Some authors call this reaction *Hofmann degradation*, although such a name is also given to the Hofmann hypobromite reaction, i.e., the Hofmann rearrangement of amides to amines with one less carbon (*3*). Finally, still others prefer to call the described reaction a *Hofmann elimination* since its net result and final objective is the cleavage of C–N bonds and the elimination of an amine (*3–8*). It is in this sense that the phrase *Hofmann elimination* was used in our paper (2).

To understand whether such a name is sufficiently justified for our reaction or if β-elimination would be a better term, let us further examine the related issues. Hofmann noted in his studies that nonsymmetrical quaternary ammonium hydroxides containing different primary alkyl groups decompose to give mainly ethylene if an ethyl group is present, or to give the least substituted alkene in general. This conclusion was known as the Hofmann rule. Much later, in 1927, Hanhart and Ingold (*9*) showed that this rule can be generalized as expressed in most textbooks: "In elimination reactions of ammonium compounds, the β-hydrogen atom is removed most readily if it is located in a CH_3 group, less so if it is in an RCH_2 group, and the least readily if it is in an R_2CH group" (*3, 5*). Hence the name Hofmann elimination for a β-elimination reaction whose mechanism obeys the Hofmann rule (*8, 10–13*).

It is pertinent to note that β-eliminations are of three main types: (1) E1 (unimolecular), (2) E2 (bimolecular), and (3) E1cB (unimolecular, conjugate base). Most of the Hofmann eliminations, however, follow an E2 mechanism, as first suggested by Hanhart and Ingold (*9*) for the Hofmann decomposition of quaternary ammonium hydroxides to olefins and tertiary amines. This reaction is second order, first order in the quaternary ammonium ion, and first order in the hydroxide ion (*14*), showing that the mechanism involves proton abstraction and leaving group departure in a concerted manner. This E2 mechanism also requires that the β-hydrogen and the nitrogen atom involved in the elimination be coplanar and in the *trans* conformation (*15*).

From the above discussion it is clear that

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the term Hofmann elimination implies two requirements for the reaction: (1) the type of elimination must be β and (2) the mechanism of reaction must be E2 (bimolecular). The piperidine denitrogenation over solid catalysts satisfies both of these criteria. Zdražil mentioned that the nitrogen must be quaternized with methyl groups for elimination to occur, but this is strictly true *in solution*; if the nitrogen atom were not fully methylated, the base that performs the β-hydrogen abstraction could move freely and attack the conjugate acid $-NH_2^+-$, resulting in neutralization. The scenario is different, however, when the reaction is carried out on a solid catalyst surface, where pairs of suitably spaced acidic and basic sites coexist. Here, the base is immobile (localized) and cannot attack the positively charged nitrogen. Hence, the base is free to abstract β-hydrogen, leading to elimination of amine or ammonia, as the case may be. Note that NH_3 ($pK_a = 9.25$) and $N(CH_3)_3$ ($pK_a = 9.81$) have approximately equal efficiency as leaving groups. Thus this reaction has all of the ingredients of Hofmann elimination except that nitrogen is not completely methylated, but as explained, this is an unnecessary requirement for this solid acid–base surface reaction. A quote attributed to Cope and Trumbull (*3*) also supports our assertion as to the most important requirements for a Hofmann elimination: "The general requirements of the Hofmann elimination reaction suggests that a moderately strong base, a β-hydrogen atom, and a positively charged nitrogen center are involved and are usually necessary."

Nelson and Levy (*16*) were the first to use Hofmann's name in relation to hydrodenitrogenation. They stated in their paper that the reactions involved in hydrodenitrogenation are *similar to classical Hofmann degradation*. It is erroneous to point this out as a "misleading reference to Hofmann elimination." Later, many scientists who studied the HDN mechanism used Hofmann's name in phrases such as Hofmann elimination (*17–19*), Hofmann-type elimination (E2) (*20, 21*), Hofmann mechanism (*17*), Hofmann-type mechanism (*18*), Hofmann β-elimination reaction mechanism (*22*), classical Hofmann degradation mechanism (*23*), and Hofmann-type degradation (*19*).

In conclusion, β-elimination or 1,2-elimination is a generic description that may apply to many reactions, such as dehydrations, hydrodesulfurizations, hydrodechlorinations, etc., following an E1, E2, or E1cB mechanism, in accordance with the type of catalyst, substrate structure, reaction conditions, and other factors (*15*). In our paper we specifically contend that denitrogenation of piperidine over silica–aluminas presents all of the main characteristics of an E2 β-elimination involving a positively charged nitrogen, a strong base, and a β-hydrogen, which are the main requirements of a Hofmann elimination.

One of the papers (*24*) related to the present work was unintentionally omitted. Our sincere thanks to Zdražil for bringing it to our attention.

REFERENCES

1. Hofmann, A. W., *Liebigs. Ann. Chem.* **78,** 253 (1851); **79,** 11 (1851).
2. Rajagopal, S., Grimm, T. L., Collins, D. J., and Miranda, R., *J. Catal.* **137,** 453 (1992).
3. Cope, A. C., and Trumbull, E. R., *in* "Organic Reactions" (A. C. Cope, Ed.), Vol. 11, p. 317, Wiley, New York, 1960.
4. White, E. H., and Woodcock, D. J., *in* "The Chemistry of the Amino Group" (S. Patai, Ed.), p. 407. Interscience, New York, 1968.
5. Streitwieser, Jr. A., and Heathcock, C. H., "Introduction to Organic Chemistry," 2nd ed. Macmillan, New York, 1976.
6. Bentley, K. W., *in* "Elucidation of Organic Structures by Physical Methods," 2nd ed. (K. W. Bentley and G. W. Kirby, Eds.), p. 255. Wiley–Interscience, New York, 1973.
7. Morrison, R. T., and Boyd, R. N., "Organic Chemistry," 5th ed. Allyn and Bacon, Boston, 1987.
8. Solomons, T. W. G., "Organic Chemistry," 2nd ed. p. 843. Wiley, New York, 1980.
9. Hanhart, W., and Ingold, C. K., *J. Chem. Soc.*, 997 (1927).
10. March, J., "Advanced Organic Chemistry: Reactions, Mechanisms, and Structure," 4th ed. Wiley, New York, 1992.
11. Lowry, T. H., and Richardson, K. S., "Mecha-

nism and Theory in Organic Chemistry," 3rd ed. Harper and Row, New York, 1987.

12. Carey, F. A., and Sundberg, R. J., "Advanced Organic Chemistry. Part A. Structure and Mechanisms," 3rd ed. Plenum, New York, 1991.
13. Bunnett, J. F., *Agnew. Chem. Int. Ed. Engl.* **1,** 225 (1962).
14. Hughes, E. D., and Ingold, C. K., *J. Chem. Soc.*, 523 (1933).
15. Beránek, L., and Kraus, M., *in* "Comprehensive Chemical Kinetics" (C. M. Bamford and C. F. H. Tipper, Eds.), Vol. 20, p. 263. Elsevier, Amsterdam, 1978.
16. Nelson, N., and Levy, R. B., *J. Catal.* **58,** 485 (1979).
17. Ledoux, M. J., and Djellouli, B., *Appl. Catal.* **67,** 81 (1990).
18. Ledoux, M. J., and Djellouli, B., *J. Catal.* **115,** 580 (1989).
19. Olalde, A., and Perot, G., *Appl. Catal.* **13,** 373 (1985).
20. Perot, G., *Catal. Today* **10,** 447 (1991).
21. Vivier, L., Dominguez, V., Perot, G., and Kasztelan, S., *J. Mol. Catal.* **67,** 267 (1991).
22. Lequitte, M., Figueras, F., Moreau, C., and Hub, S., *Appl. Catal. A* **84,** 155 (1992).
23. Portefaix, J. L., Cattenot, M., Guerriche, M., and Breysse, M., *Catal. Lett.* **9,** 127 (1991).
24. Sedláček, J., and Koubek, J., *Collect. Czech. Chem. Commun.* **48,** 755 (1983).

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