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Writing Reactions of Metals with Nitric Acid: A Mnemonic Device for Introductory Chemistry Students

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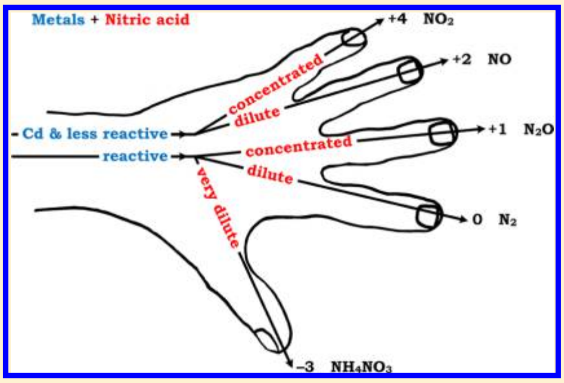
ABSTRACT: A mnemonic device has been designed for writing reactions of metals with nitric acid. The device utilizes a left hand and schematically indicates the product of reduction of nitric acid as a function of two factors: the activity of metal and the concentration of acid. Five different products can be retrieved with the help of the device. The integers represent the oxidation states of nitrogen in the resulting product of reduction. The device is particularly easy to memorize and use.



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Nitric acid is by far the most important of the acids containing nitrogen. Because it is both a strong acid and a strong oxidizing agent (HNO_3 represents nitrogen in its highest oxidation state +5), nitric acid will dissolve most metals.[1,2] The redox reactions of metals with nitric acid are more complicated than those with hydrochloric and sulfuric acids primarily due to five possible products of HNO_3 reduction including three nitrogen oxides (NO_2, NO, and N_2O), N_2, and NH_4NO_3. The above-mentioned products of HNO_3 reduction represent nitrogen in different oxidation states. The number of electrons gained by nitrogen of nitric acid in a redox reaction with metals (i.e., the extent nitrogen is reduced and hence the product of reduction) depends on two factors: (1) the activity of metal; (2) the concentration of acid. The activity of metal is considered to be the primary factor, as its value does not alter throughout the reaction, whereas the concentration of acid decreases.[3]

The difficulty is that in fact different metals react with nitric acid differently. For instance, the reaction between zinc and nitric acid yields any product of reduction depending on the HNO_3 concentration. Moreover, most reactions yield a number of products of reduction simultaneously and in various proportions. The only common trend is the following: the more active the metal is and the more dilute the acid is, the greater the extent to which nitrogen is reduced. Apparently, this often causes ambiguity among students during redox reaction exercises as it is unclear which product of reduction to choose. Therefore, it is necessary to design a scheme that would help students to cope with writing reactions of metals with nitric acid. The suggested scheme satisfies the following three requirements: (1) represents the nitric acid product of reduction as a function of the activity of metal and the concentration of acid; (2) is easy to memorize; (3) is easy to use.

THE TWO FACTORS THAT DETERMINE THE PRODUCT OF REDUCTION OF NITRIC ACID

The Activity of Metals

The standard reduction potentials measure the reducing strength of metals. With respect to reaction with nitric acid it is suggested to divide all metals into two groups: reactive and less reactive. A reasonable fixed point is cadmium's (Cd^{2+}/Cd) standard reduction potential (−0.4030 V). Metals with standard reduction potentials less than that of cadmium's are considered reactive, while the rest, including cadmium, are considered less reactive.

The Concentration of Acid

Commonly, it is suggested to distinguish concentrated nitric acid (up to 16 M or about 70 wt %), dilute nitric acid (3−6 M or 10−30 wt %), and very dilute nitric acid (0.1−3 M or less than 10 wt %). Hereinafter concentrated acid will be denoted by "C", dilute by "d", and very dilute by "vd".

THE SUGGESTED MNEMONIC DEVICE

Description of the Suggested Mnemonic Device

The use of mnemonic devices can enhance the memorizing of new information.[4−7] Several manual chemical mnemonic devices have been reported.[6,7] The suggested mnemonic device utilizes a left hand (Figure 1).

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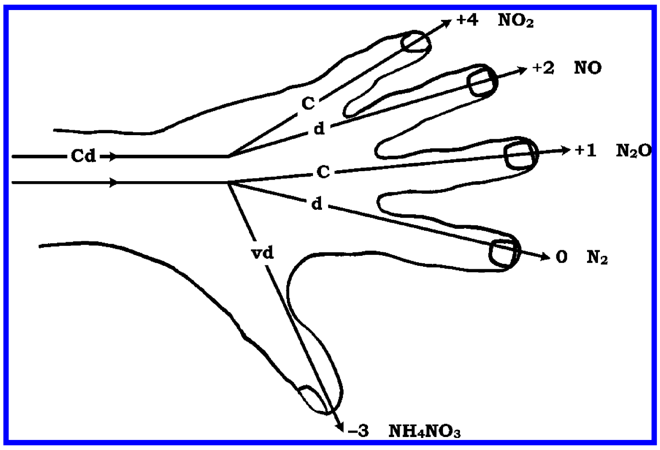

Figure 1. Suggested mnemonic device schematically indicates the product of reduction of nitric acid as a function of two factors: the activity of metal and the concentration of acid.

The mnemonic device has two inputs and five outputs for every finger and should be read from left to right. The upper input corresponds to less reactive metals and hence is denoted "Cd". The lower input corresponds to reactive metals. The outputs correspond to the nitric acid concentrations and are denoted accordingly. Coincidentally, the denotations "C" and "d" together form the symbol of the chemical element cadmium, making it easier to memorize the order "C", "d", "C", "d", "vd". Each output gives the appropriate oxidation state of the product of reduction of nitric acid. The oxidation states are ordered from top to bottom in a decreasing sequence from +4 to −3, thus emphasizing that the more electrons are gained, the greater the extent to which N^{+5} is reduced, with N^{-3} being the most significant reduction possible. Moreover, the angle between the outputs slightly correlates with the difference between resulting oxidation states (the angle between "0" and "−3" is considerably larger than the rest). The resulting oxidation states are followed by the respective products of reduction: $N^{+4}O_2$ (nitrogen dioxide), $N^{+2}O$ (nitric oxide), $N^{+1}{}_2O$ (nitrous oxide), $N^0{}_2$ (nitrogen), and $N^{-3}H_4NO_3$ (ammonium nitrate).

The suggested mnemonic device makes use of the arbitrary choice of cadmium's standard reduction potential as the dividing point between reactive and less reactive metals as the letters in the symbol can be used to remind students of the relative concentration effects.

Utilization of the Suggested Mnemonic Device

Given a chemical reaction to complete, a student should first determine the activity of metal as compared with cadmium with the help of the table of standard reduction potentials and, second, the concentration of acid. A good example is the reaction between copper and concentrated nitric acid. Copper's standard reduction potential (Cu^{2+}/Cu) is +0.3419 V, thus it is considered less reactive, and the upper input of the mnemonic device is to be used. Since the acid is concentrated, the "C" output is used, which yields nitrogen dioxide:

$$\text{Cu (less reactive)} + HNO_3\text{ (concentrated)} \rightarrow Cu(NO_3)_2 + NO_2\uparrow + H_2O$$

Other examples for each of the several presented cases include the following:[8]

$$\text{Hg (less reactive)} + HNO_3\text{ (dilute)} \rightarrow Hg(NO_3)_2 + NO\uparrow + H_2O$$

$$\text{Mg (reactive)} + HNO_3\text{ (concentrated)} \rightarrow Mg(NO_3)_2 + N_2O\uparrow + H_2O$$

$$\text{Fe (reactive)} + HNO_3\text{ (dilute)} \rightarrow Fe(NO_3)_2 + N_2\uparrow + H_2O$$

$$\text{Al (reactive)} + HNO_3\text{ (very dilute)} \rightarrow Al(NO_3)_3 + NH_4NO_3 + H_2O$$

Advantages and Limitations of the Suggested Mnemonic Device

The suggested mnemonic device successfully works for most of the common reactions between metals and nitric acid. It has already been used for one year, and students find it particularly easy to memorize and use. During the exam students are observed holding their left hands and counting down to the appropriate oxidation state.

The device is limited to the main two factors that influence the products of HNO_3 reduction (the activity of metal and the concentration of acid) and does not take into account the temperature, nor does it cover the few cases of liberation of H_2 (hydrogen), and it indicates only the prevailing product of reduction.

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Notes

The authors declare no competing financial interest.

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