Explainer: Properties and Reactions of Iron and Iron Oxides

In this explainer, we will learn how to describe the properties and reactions of iron and its oxides.

Iron is the most abundant transition element in Earth's crust and an incredibly important metal to society. Although it is seemingly ubiquitous, it is very rarely pure iron metal that is being used around us and a huge amount of iron extracted from its ore is used to make many different alloys. The most common iron alloys include different forms of steel, which have a variety of properties and a great number of uses. However, pure iron is of little industrial importance due to its relative softness and low hardness.

Pure iron is malleable and ductile and has magnetic properties. It melts at 1 538°C and has a density of 7.87 g/cm^3 when solid. The exact physical properties of pure iron depend on the final purity of the metal. Any remaining impurities left from the ore from which it was extracted will affect its physical properties.

Example 1: Identifying the Physical Properties of Iron Metal

Which of the following properties is **not** correct for pure iron?

A. Pure iron is easily pulled or stretched into a thin wire.
B. Pure iron has a shining luster.
C. Pure iron is very soft with low hardness.
D. Pure iron has a low melting point.
E. Pure iron has magnetic properties.

Answer

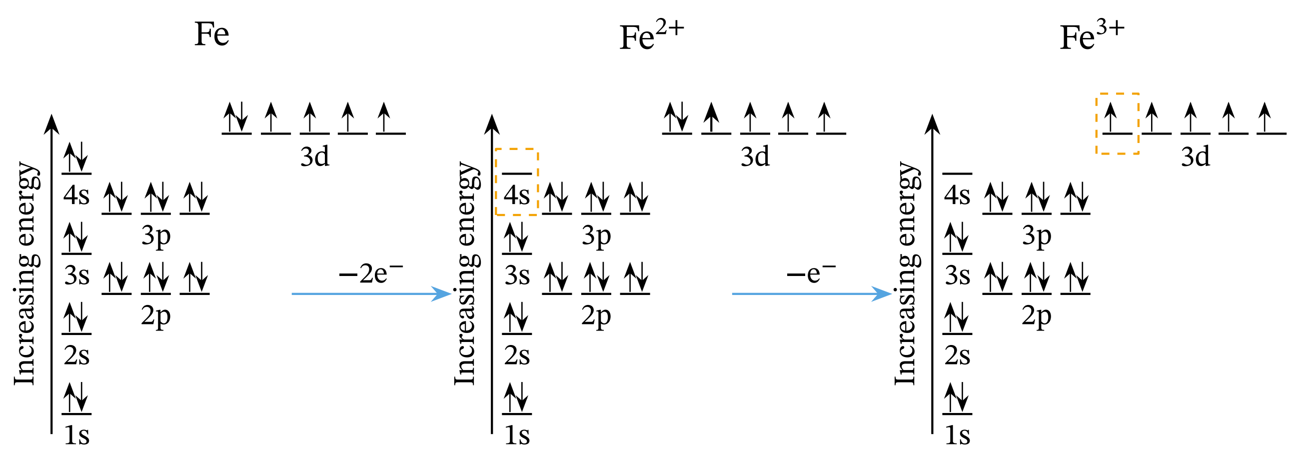
While some properties of iron are well known such as its magnetism, less well-known properties can be conceived from the general properties of metals; furthermore, some are specific to iron and must be remembered. Like many metals, iron is ductile and can be drawn into a wire, which discounts answer A. Also, like many metals, iron can be polished to give a shiny luster, which discounts answer B.

Physical properties specific to iron include the fact that it is magnetic, discounting answer E, and that it is a soft metal with low hardness, discounting answer C.

This leaves us with answer D, which states that pure iron has a low melting point. However, pure iron melts at 1 538°C, which would not be considered a low temperature, meaning that answer D is the correct answer.

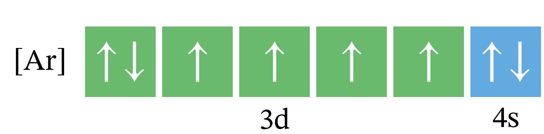
Iron shares some characteristic physical and chemical properties with other d-block metals in the same period. The oxidation states of iron, however, differ. Atoms of iron do not form the +8 oxidation state corresponding to the loss of all the electrons in the 3d and 4s orbitals. This is in contrast to the adjacent element manganese that can lose all its 3d and 4s electrons to form the +7 oxidation state. While iron can have oxidation states ranging from −4 to +7, its most common oxidation states are +2 and +3.

When forming ions, iron will lose two electrons from the 4s subshell, but it can also lose a third electron from its paired 3d orbital resulting in a +3 oxidation state.

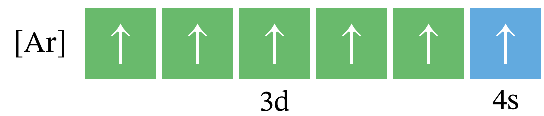


Example 2: Identifying the Electronic Configuration of an Ion of Iron

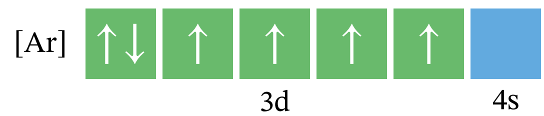
Considering the electronic configuration of iron metal represented in the diagram, what is the electronic configuration of the Fe^{2+} ion?



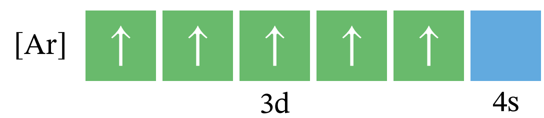
A.



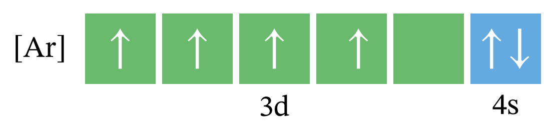
B.



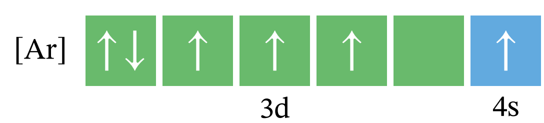
C.



D.



E.



Answer

In a similar fashion to other transition metals, atoms of iron will preferentially lose electrons from the 4s subshell prior to losing electrons from the 3d orbitals. As such, in this question, we are looking for responses where both electrons have been lost from the 4s subshell. This leaves us with response B and response C as possible correct answers. An atom of the element iron has 26 protons, and as such, an Fe^{2+} ion will have 24 electrons. Argon has 18 electrons, meaning that the 3d subshell must contain 6 electrons to give us 24 electrons in total. Another way to discount C would be to compare the initial diagram in the question and notice that 3 electrons have been lost in C. With C discounted, the correct answer is B.

Iron reacts in a similar way to most metals, but care must be taken to ensure that the iron species produced have the desired oxidation state.

One of the simplest reactions involves red-hot iron reacting with either dry air or oxygen to produce magnetic iron(II, III) oxide:

$$3\,Fe(s) + 2\,O_2(g) \xrightarrow{\Delta} Fe_3O_4(s)$$

Red-hot iron, at around 500°C, will also react with water vapor to also produce magnetic iron(II, III) oxide as well as hydrogen gas:

$$3\,\mathrm{Fe}(s) + 4\,\mathrm{H_2O}(g) \xrightarrow{500^\circ\mathrm{C}} \mathrm{Fe_3O_4}(s) + 4\,\mathrm{H_2}(g)$$

Iron can also react with nonmetals to produce the respective binary compound; although again, care must be taken to correctly identify the oxidation state of the iron product:

$$2\,\mathrm{Fe}(s) + 3\,\mathrm{Cl_2}(g) \xrightarrow{\Delta} 2\,\mathrm{FeCl_3}(s)$$
$$\mathrm{Fe}(s) + \mathrm{S}(s) \xrightarrow{\Delta} \mathrm{FeS}(s)$$

We should note at this point some of the names that can be used to describe iron compounds. The chloride compound formed above, which would formally be named as iron(III) chloride, can also be referred to as ferric chloride. The term *ferric* relates to iron in a +3 oxidation state. In contrast, iron(II) sulfide (FeS) could also be referred to as ferrous sulfide. Here, the term ferrous relates to an iron compound where iron has a +2 oxidation state.

When iron metal is oxidized by dilute mineral acids, iron(II) salts are produced:

$$\mathrm{Fe}(s) + \mathrm{H_2SO_4}(aq) \longrightarrow \mathrm{FeSO_4}(aq) + \mathrm{H_2}(g)$$
$$\mathrm{Fe}(s) + 2\,\mathrm{HCl}(aq) \longrightarrow \mathrm{FeCl_2}(aq) + \mathrm{H_2}(g)$$

However, when reacting iron metal with concentrated sulfuric acid, some of the iron(II) ions are further oxidized to iron(III) ions, resulting in a mixture of products that includes ferrous sulfate, ferric sulfate, sulfur dioxide gas, and water vapor:

$$3\,\mathrm{Fe}(s) + 8\,\mathrm{H_2SO_4}(l) \xrightarrow[\text{conc. } \mathrm{H_2SO_4}]{\Delta} \mathrm{FeSO_4}(aq) + \mathrm{Fe_2(SO_4)_3}(aq) + 4\,\mathrm{SO_2}(g) + 8\,\mathrm{H_2O}(g)$$

Example 3: Recalling the Products of the Reaction between Iron Metal and Dilute Mineral Acids

Which of the following statements is correct?

A. Iron can be dissolved in diluted hydrochloric acid, producing iron(III) chloride and water.

B. Iron can be dissolved in diluted hydrochloric acid, producing iron(II) chloride and hydrogen gas.

C. Iron can be dissolved in diluted hydrochloric acid, producing iron(II) chloride and water.

D. Iron can be dissolved in diluted hydrochloric acid, producing iron(III) chloride and hydrogen gas.

Answer

One of the chemical properties that iron shares with most metals is its reaction with dilute acid. Metals, when they react with acids, form salts and hydrogen gas, and so answers A and C, where water is one of the products, are both incorrect.

When iron metal reacts with dilute acids, iron(II) salts are produced. Iron(III) salts are only produced in reactions with concentrated mineral acids. This then leaves us with the correct answer, B.

One particularly interesting reaction involving iron and nitric acid is an example of a physical chemistry and engineering process known as passivation. When concentrated nitric acid reacts with iron metal, a thin layer of iron oxide is formed on the surface of the metal. This layer of oxide then prevents any further acid molecules from reaching the surface of the iron and therefore provides protection against corrosion. However, this oxide coating can be removed by the addition of dilute hydrochloric acid or through abrasion with glass paper.

One of the more interesting groups of iron compounds are the oxides. Iron forms three different oxides with varying physical and chemical properties.

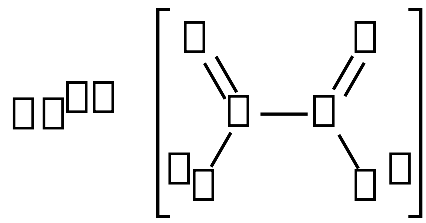
Iron(II) oxide, FeO

- Ferrous oxide
- Found in the mineral wüstite

Iron(III) oxide, Fe_2O_3
- Ferric oxide
- Found in the mineral hematite

Iron(II, III) oxide, Fe_3O_4
- Ferrous ferric oxide
- Found in the mineral magnetite

Iron(II) oxide is found in the mineral wüstite but can be formed chemically from the decomposition of iron oxalate in the absence of air:



$$FeC_2O_4(s) \xrightarrow[\text{(absence of air)}]{\Delta} FeO(s) + CO(g) + CO_2(g)$$

Iron(II) oxide can also be formed by reducing oxides of iron in a higher oxidation state such as iron(III) oxide and iron(II, III) oxide:

$$Fe_2O_3(s) + H_2(g) \xrightarrow{400\text{–}700°C} 2\,FeO(s) + H_2O(g)$$

$$Fe_3O_4(s) + H_2(g) \xrightarrow{400\text{–}700°C} 3\,FeO(s) + H_2O(g)$$

However, it should be noted that while these reactions of FeO occur in theory, in practice, the FeO produced is unstable below 570°C and readily oxidizes back to Fe_3O_4 or can be oxidized from iron(II) oxide to iron(III) oxide as per the following equation:

$$4\,FeO(s) + O_2(g) \xrightarrow{\Delta} 2\,Fe_2O_3(s)$$

Iron(II) oxide can react with a mineral acid to form the relevant salt and water:

$$FeO(s) + H_2SO_4(aq) \longrightarrow FeSO_4(aq) + H_2O(l)$$

The ore hematite, Fe_2O_3, is a common iron oxide found in Earth's crust. Frequently reddish-brown in color, Fe_2O_3 can be used as a red pigment in paint. The oxide can also be chemically isolated through the reaction of ferric chloride and hydroxide solutions to form the insoluble iron(III) hydroxide, which can then thermally decompose to form iron(III) oxide. For example, ferric chloride can react with ammonium hydroxide:

$$FeCl_3(aq) + 3\,NH_4OH(aq) \longrightarrow Fe(OH)_3(s) + 3\,NH_4Cl(aq)$$

$$2\,Fe(OH)_3(s) \xrightarrow{\text{above } 200°C} Fe_2O_3(s) + 3\,H_2O(g)$$

Iron(III) oxide can also be formed by heating iron(II) sulfate; however, care should be taken with this reaction in the laboratory due to the production of harmful sulfur gases:

$$2\,FeSO_4(s) \xrightarrow{\Delta} Fe_2O_3(s) + SO_2(g) + SO_3(g)$$

A final example of the chemical properties of iron(III) oxide involves the reaction with hot concentrated mineral acids, such as sulfuric acid, to form iron(III) salts and steam:

$$Fe_2O_3(s) + 3\,H_2SO_4(l) \longrightarrow Fe_2(SO_4)_3(aq) + 3\,H_2O(g)$$

Example 4: Identifying Iron Oxide Produced from the Reaction of Unknown Salt with an Alkali Solution

The red–brown precipitate shown in the picture is produced in the reaction between an iron salt and a dilute alkali solution. When the precipitate is isolated and dried and then heated in an ignition tube, water vapor was found to be present along with another iron compound, X. What is a possible identity of X?

Answer

Iron salts react with dilute alkali solutions, specifically the hydroxide ions, to form either iron(II) hydroxide or iron(III) hydroxide depending on the starting iron salt. Heating iron hydroxide results in the dehydration of the hydroxide to form iron oxide, and in this case, we know that the resulting precipitate is iron(III) oxide, Fe_2O_3, due to the red–brown color shown within the picture.

The final oxide we will discuss in this explainer is the black, magnetic oxide also known as ferrous ferric oxide. This oxide is found predominantly in the ore magnetite and can be considered to be a mixture of iron(II) oxide and iron(III) oxide. It can be prepared in a laboratory through the reduction of iron(III) oxide by carbon monoxide as well as through the oxidation of iron metal:

$$3\,\mathrm{Fe_2O_3}(s) + \mathrm{CO}(g) \xrightarrow{230\text{–}300^\circ\mathrm{C}} 2\,\mathrm{Fe_3O_4}(s) + \mathrm{CO_2}(g)$$

$$3\,\mathrm{Fe}(s) + 4\,\mathrm{H_2O}(g) \xrightarrow{500^\circ\mathrm{C}} \mathrm{Fe_3O_4}(s) + 4\,\mathrm{H_2}(g)$$

In a similar fashion to iron metal, when iron(II, III) oxide reacts with concentrated sulfuric acid, a mixture of iron(II) and iron(III) salts are formed, supporting the rationale of considering this oxide to be a mixture of iron(II) and iron(III) oxides:

$$\mathrm{Fe_3O_4}(s) + 4\,\mathrm{H_2SO_4}(l) \xrightarrow[\text{conc. }\mathrm{H_2SO_4}]{\Delta} \mathrm{FeSO_4}(aq) + \mathrm{Fe_2(SO_4)_3}(aq) + 4\,\mathrm{H_2O}(g)$$

This can be further illustrated as well through reduction reactions previously discussed and the fact that iron(II, III) oxide can also be oxidized to iron(III) oxide:

$$Fe_3O_4(s) + H_2(g) \xrightarrow{400\text{–}700^\circ C} 3\,FeO(s) + H_2O(g)$$

$$2\,Fe_3O_4(s) + \frac{1}{2}O_2(g) \xrightarrow{\Delta} 3\,Fe_2O_3(s)$$

In summary, iron and its oxides have a wide range of physical and chemical properties that are important for chemists to understand due to the importance of this element to our society. Iron(II) oxide is a black solid that is insoluble in water and is easily oxidized by hot air. Iron(III) oxide is also insoluble in water and reacts with hot concentrated mineral acids to form iron(III) salts and water. The final oxide we examined in this explainer is iron(II, III) oxide, which also reacts with hot concentrated acids and is a strong magnet.

Let's summarize what has been learned in this explainer.

Key Points

- Pure iron has little industrial importance; however, alloys such as steel are very important.
- Iron has similar general properties to those one would attribute to most metals.
- Common chemical reactions of iron relate to iron in either a +2 or +3 oxidation state.
- Iron metal reacts with air, water vapor, nonmetals, and acid.
- Iron forms three different oxides: iron(II) oxide, iron(III) oxide, and iron(II, III) oxide.
- Iron(II) oxide can be formed from the decomposition of iron oxalate or by reducing iron(III) oxide or iron (II,III) oxide.
- Iron(III) oxide can be formed from the thermal decomposition of iron(III) hydroxide and iron(II) sulfate.
- Iron (II, III) oxide can be formed from the reaction between iron(III) oxide and carbon monoxide as well as by reacting iron metal with water.
- Iron(II, III) oxide can be considered a mixture of iron(II) oxide and iron(III) oxide, and it can be both oxidized and reduced to produce iron(III) oxide and iron(II) oxide respectively.