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Topic 2.4: Structure of Metals and Alloys

Worksheet · AP Chemistry

Unit 2 · Compound Structure and Properties

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How to Use This Worksheet

Work through the sections in order. Section A checks the ideas, Section B builds fluency with atomic radii data and alloy classification, and Section C mixes everything the way an exam would.

For every alloy question, work in the same order: compare the two atomic radii first and calculate the percentage difference, then state where the added atoms sit, in lattice positions or in the gaps between them, and only then predict the effect on the properties. A classification with no size evidence behind it is only half finished.

Do not look at the answer key until you have attempted every question. The key gives full working, so compare your method, not just your final answer.

Section A: Recall and Concepts

A1. Describe the structure of a pure metal using the electron sea model, and explain why it is incorrect to say that its valence electrons belong to specific atoms.

A2. Explain why a metal conducts electricity in the solid state, naming the charge carriers, and explain why the metal still conducts after it has melted.

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A3. Explain, using the electron sea model, why a metal can be hammered into a sheet without breaking, while an ionic solid struck in the same way shatters.

A4. A student objects: "A metal is full of positive ions, and positive charges repel each other, so a piece of metal should push itself apart." Explain why the structure holds together.

A5. A student says: "Copper conducts electricity because the positive copper ions flow through the wire." Identify the error in this statement, and state what actually moves through the wire.

Section B: Core Practice

B1. Brass is an alloy of copper (atomic radius 128 pm) and zinc (atomic radius 134 pm). (a) Calculate the percentage difference between the two radii, relative to the radius of copper. (b) Use your answer to classify brass as an alloy type, and describe where the zinc atoms are located.

B2. Steel is an alloy of iron (atomic radius 126 pm) and carbon (atomic radius 77 pm). (a) Calculate by what percentage the radius of a carbon atom is smaller than the radius of an iron atom. (b) Explain why carbon atoms cannot take the place of iron atoms in the lattice, name the type of alloy steel is, and state where the carbon atoms are located. (c) Predict two ways in which the properties of steel differ from those of pure iron.

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B3. Two pairs of elements are being considered as alloys: silver (144 pm) with gold (144 pm), and titanium (147 pm) with hydrogen (37 pm). (a) Calculate the percentage difference in radii for each pair, relative to the larger atom. (b) State which pair can form a substitutional alloy and which pair would place the smaller atoms in the spaces between the larger atoms, giving a reason for each.

B4. Sodium atoms each contribute one valence electron to the electron sea and form Na^+ ions; sodium melts at 98 °C. Magnesium atoms each contribute two valence electrons and form Mg^{2+} ions; magnesium melts at 650 °C. (a) Calculate how many delocalized electrons 200 atoms of sodium contribute to the sea, and how many 200 atoms of magnesium contribute. (b) Use your answers, and the charges on the cations, to explain why magnesium melts so much higher than sodium.

B5. An unknown solid is malleable and ductile, conducts electricity both as a solid and as a liquid, and melts at 1,085 °C. (a) State the type of solid it most likely is. (b) State which single observation rules out an ionic solid most directly, and explain why. (c) Explain the ductility of the solid at the particulate level.

B6. A student models an alloy by dropping small marbles into a jar of large marbles, so that the small marbles settle into the gaps between the large ones. (a) Name the type of alloy the model represents, and name a real alloy it describes well. (b) A particulate diagram of a different alloy shows 250 atoms in a regular lattice. Of these, 25 atoms are of a second element, they sit in normal lattice positions, and their radius is within 5% of the host radius. Calculate the percentage of the atoms that belong to the second element, and classify this alloy.

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Section C: Exam Style

C1. Element X has an atomic radius of 130 pm, element Y a radius of 60 pm, and element Z a radius of 133 pm. (a) Calculate the percentage difference between the radii of X and Z, and the percentage by which the radius of Y is smaller than the radius of X. (b) State which pair, X with Z or X with Y, forms a substitutional alloy and which forms an interstitial alloy, justifying each answer. (c) Predict how the malleability of the X-Y alloy compares with that of pure X, and explain your prediction at the particulate level.

C2. Pure gold is 24-karat. Fourteen-karat gold is an alloy of gold with silver and copper, and contains 14 parts gold out of 24 parts in total. Atomic radii: Au 144 pm, Ag 144 pm, Cu 128 pm. (a) Calculate the percentage of gold by mass in 14-karat gold. (b) Calculate the percentage difference between the radii of gold and copper, and state the percentage difference between the radii of gold and silver. Use both results to classify 14-karat gold as an alloy type. (c) Explain why 14-karat gold is harder and more durable than pure gold, and predict how its electrical conductivity compares with that of pure gold, giving a reason.

C3. Solid P conducts electricity in both the solid and liquid states and can be drawn into a wire. Solid Q has a high melting point, conducts electricity only when molten, and shatters when struck with a hammer. (a) Identify the type of structure present in solid P and in solid Q. (b) Explain the ductility of P and the brittleness of Q at the particulate level. (c) Both P and Q conduct electricity when liquid. Explain the conduction in each case, naming the charge carriers, and explain why the carriers are different.

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Answer Key

A1. In the electron sea model, a pure metal is a regular lattice of positive metal ions (cations) surrounded by a sea of delocalized valence electrons. Each atom contributes its valence electrons to the shared pool, and the electrostatic attraction between the cations and the negatively charged sea holds the structure together. The electrons do not belong to specific atoms because they are delocalized: they move freely throughout the whole crystal, so at any moment an electron near a given cation cannot be identified as having come from that atom. The valence electrons are a property of the whole structure, not of individual atoms.

A2. A metal conducts in the solid state because its delocalized valence electrons are mobile: when a potential difference is applied, the electrons drift through the lattice and carry the charge. The cations remain in their fixed lattice positions and play no part in carrying the current. When the metal melts, the regular arrangement of the cations becomes disordered, but the electron sea is still present and the electrons are still free to move through the liquid, so the liquid metal also conducts, for exactly the same reason as the solid.

A3. In a metal, hammering forces layers of cations to slide past one another into new positions. Because metallic bonding is non-directional, the delocalized electron sea redistributes itself around the shifted cations, and the attraction between the cations and the sea is maintained in the new arrangement. The bonding is never broken, so the metal changes shape instead of fracturing. In an ionic solid, shifting a layer by one ion position brings ions of the same charge face to face. The strong repulsion between those like charges forces the layers apart, so the crystal splits and shatters rather than deforming.

A4. The cations do repel each other, but every cation is simultaneously attracted to the negatively charged sea of delocalized electrons that surrounds it on all sides. Each cation is embedded in that sea, so it is pulled toward the electrons throughout the whole structure, and the total of these attractions is stronger than the cation to cation repulsions. The structure is held together by the balance of the two effects: repulsion between the cations, outweighed by the shared attraction of all the cations to the electron sea.

A5. The error is the identity of the moving particles. The copper cations do not flow through the wire: they occupy fixed positions in the lattice and can only vibrate about those positions. What actually moves is the sea of delocalized valence electrons, which drifts through the lattice when a potential difference is applied, and it is this movement of electrons that carries the current. If the cations themselves travelled through the wire, the wire would be consumed at one end and rebuilt at the other, which does not happen.

B1. (a) Difference in radii: 134 − 128 = 6 pm. Percentage difference relative to copper: (6 / 128) × 100 = 4.7%. (b) The two radii are comparable, differing by only 4.7%, comfortably within the

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roughly 15% range in which atoms can take each other's places. Brass is therefore a substitutional alloy: the zinc atoms occupy normal lattice positions, each one replacing a copper atom in the regular lattice.

B2. (a) Difference in radii: 126 − 77 = 49 pm. Percentage smaller: (49 / 126) × 100 = 38.9%. (b) A carbon atom is about 39% smaller than an iron atom, far outside the roughly 15% range for comparable radii, so a carbon atom cannot sensibly occupy an iron lattice position. Steel is an interstitial alloy: the iron atoms keep their normal lattice positions, and the much smaller carbon atoms fit into the interstices, the empty spaces between them. (c) Any two of: steel is harder than pure iron; steel is stronger than pure iron; steel is less malleable than pure iron; steel is slightly denser than pure iron. The carbon atoms obstruct the sliding of the iron layers, which is what raises the hardness and strength and lowers the malleability.

B3. (a) Silver and gold: 144 − 144 = 0 pm, a percentage difference of 0%. Titanium and hydrogen: 147 − 37 = 110 pm, and (110 / 147) × 100 = 74.8%. (b) Silver and gold form a substitutional alloy: their radii are identical, so gold atoms can replace silver atoms in the lattice (and the reverse) with no size problem at all. Titanium and hydrogen cannot form a substitutional alloy, because a hydrogen atom is about 75% smaller than a titanium atom; instead the hydrogen atoms occupy the interstitial spaces between the titanium atoms.

B4. (a) Sodium: 200 atoms × 1 electron each = 200 delocalized electrons. Magnesium: 200 atoms × 2 electrons each = 400 delocalized electrons. (b) Per atom, magnesium puts twice as many electrons into the sea as sodium, and its cations carry a +2 charge against sodium's +1. Both factors strengthen the electrostatic attraction between the cations and the electron sea: there are more electrons pulling, and each cation is pulled twice as strongly. The metallic bonding in magnesium is therefore much stronger, and far more thermal energy is needed to break the lattice down into a liquid, so magnesium melts at 650 °C against sodium's 98 °C.

B5. (a) A metal or an alloy: a substance with metallic bonding. (The melting point of 1,085 °C is that of copper.) (b) Conducting electricity in the solid state. An ionic solid can match the high melting point, and it conducts when molten, but it never conducts as a solid, because its ions are locked in fixed lattice positions and it contains no free electrons. Only mobile delocalized electrons, the signature of metallic bonding, allow solid state conduction. (c) When the solid is drawn into a wire, layers of cations slide past one another. The electron sea is non-directional and flows around the cations as they move, so the attraction holding the structure together is maintained throughout the deformation, and the solid stretches instead of snapping.

B6. (a) An interstitial alloy. The large marbles are the host metal lattice and the small marbles sit in the interstices between them, exactly as carbon atoms sit in the gaps in the iron lattice in steel. (b) Percentage of second element atoms: (25 / 250) × 100 = 10%. The second element atoms occupy normal lattice positions and their radius is within 5% of the host radius, well inside the comparable range, so this is a substitutional alloy.

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C1. (a) X and Z: 133 − 130 = 3 pm, and (3 / 130) × 100 = 2.3%. Y against X: 130 − 60 = 70 pm, and (70 / 130) × 100 = 53.8%, so Y is about 54% smaller than X (its radius is less than half of X's). (b) X with Z forms a substitutional alloy: the radii differ by only 2.3%, so Z atoms can replace X atoms in the lattice. X with Y forms an interstitial alloy: Y is far too small to occupy an X lattice position, so the Y atoms fit into the spaces between the X atoms instead. (c) The X-Y alloy is less malleable than pure X. In pure X the layers of atoms slide past each other while the electron sea keeps the structure bound, but the Y atoms lodged in the interstices obstruct that sliding and distort the lattice, so the layers move less easily and the material resists deformation.

C2. (a) (14 / 24) × 100 = 58.3% gold by mass. (b) Gold and copper: 144 − 128 = 16 pm, and (16 / 144) × 100 = 11.1%. Gold and silver: both radii are 144 pm, so the difference is 0%. Both added elements have radii comparable to gold (0% and 11.1%, within the roughly 15% range), so silver and copper atoms substitute for gold atoms in the lattice: 14-karat gold is a substitutional alloy. (c) In pure gold the lattice is perfectly regular and its layers slide easily, which is why pure gold is soft. Replacing some gold atoms with silver and copper atoms slightly distorts the lattice, and the distortion hinders the sliding of the layers, so the alloy is harder and resists wear better in jewellery. Its electrical conductivity is lower than that of pure gold, because the irregular lattice scatters the delocalized electrons as they move through it.

C3. (a) P has metallic bonding: a lattice of cations in a sea of delocalized electrons. Q is an ionic solid: a lattice of alternating cations and anions. (b) P is ductile because its bonding is non-directional: layers of cations can slide past one another while the electron sea redistributes and keeps them bound, so the solid stretches into a wire without the bonding breaking. Q is brittle because its lattice depends on the strict alternation of opposite charges: shifting a layer by one ion position aligns like charges, and their repulsion splits the crystal apart. (c) In liquid P the charge carriers are still the delocalized electrons: melting disorders the cation arrangement but the electron sea remains, and the electrons stay mobile. In molten Q the carriers are the ions themselves: melting breaks down the lattice that held the ions in fixed positions, so the cations and anions become free to move and carry the charge in opposite directions. The carriers differ because the two solids hold their charges differently: P's mobile charges are electrons that were never attached to individual atoms, while Q's charges are whole ions that can only carry current once they are free to move.

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