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Chemical Salt Reactions as Algebraic Hyperstructures

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ABSTRACT

A salt metathesis reaction is a chemical process involving the exchange of bonds between two reacting chemical species, which results in the creation of products with similar or identical bonding affiliations. Hyperstructure theory is studied from the theoretical point of view and for its applications. In this paper, we provide some examples of hyperstructures associated with salt metathesis reactions, and we observe that these chemical reactions are examples of the phenomena when composition of two elements is a set of elements.

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1. INTRODUCTION

Hyperstructure theory, introduced in 1934 by F. Marty [13], is studied from the theoretical point of view and for its applications to many subjects of pure and applied mathematics, see [4, 12]. Algebraic hyperstructures are a generalization of classical algebraic structures. In a classical algebraic structure the composition of two elements is an element, while in an algebraic hyperstructure the composition of two elements is a non-empty set. One of motivations for the study of hyperstructures comes from chemical reactions. In [6], Davvaz and Dehghan-Nezhad provided examples of hyperstructures associated with chain reactions. In [8], Davvaz et al. introduced examples of weak hyperstructures associated with dismutation reactions. In [11], Davvaz et al. investigated the examples of hyperstructures and weak hyperstructures associated with redox reactions. Also, see [1, 2, 5, 10]. In [3], Chung et al. investigated mathematical structures of chemical reactions for three consecutive oxidation states of elements.

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Let H be a non-empty set. Then the map $\circ: H \times H \rightarrow P^*(H)$ is called a hyper operation when $P^*(H)$ is the family of non-empty subsets of H. The couple $(H,\circ)$ is called a hypergroupoid. The hyper product of tow subsets A and B of H defines as follows

$$A \circ B = \bigcup_{a\in A, b\in B} a \circ b; \;\; x \circ A = \{x\} \circ A \;\; and \;\; A \circ x = A \circ \{x\}.$$

The theory of H_v-structures has been introduced by Vougiouklis [17]. The concept of H_v-structures constitutes a generalization of the well-known algebraic hyperstructures (hypergroups, hyperrings, hypermodules). Actually, some axioms concerning the above hyperstructures are replaced by their corresponding weak axioms. Basic definitions and results about the H_v-structures and their applications can be found in [7, 15, 16].

Definition 1.1. The hypergroupoid $(H,\circ)$ is called

1. an *H_v-semigroup* if the *weak associativity* property holds that is for every $x, y, z \in H$ we have $x \circ (y \circ z) \cap (x \circ y) \circ z \neq \emptyset$;
2. a *semihypergroup* if the *associativity* property holds that is for every $x, y, z \in H$ we have $x \circ (y \circ z) = (x \circ y) \circ z$;
3. a *quasihypergroup* if *reproductive* axiom holds that is for every $x \in H$ we have $x \circ H = H = H \circ x$;
4. an *H_v-group* if it is an H_v-semigroup and quasihypergroup;
5. a *hypergroup* if it is a semihypergroup and quasihypergroup;
6. a *commutative hypergrpoid* if for every $x, y \in H$ we have $x \circ y = y \circ x$.

2. HYPERSTRUCTURES OF SALT REACTIONS

In a salt metathesis reaction, cations and anions exchange partners. This reaction usually takes place in aqueous solutions. Metathesis reaction is a type of chemical reactions, which include combination, decomposition, and displacement. When a soluble salt (like sodium chloride) is dissolved in water, it decomposes and becomes hydrated ions. If you pour two solutions of different electrolytes together, the mixture will have all ions from the two electrolytes. Ions of the same charge usually repel each other, but ions of opposite charge may form a stable molecule or solid. Cations of one electrolyte meat anions of the other. If they form a more stable substance such as a solid or neutral molecules, exchange or metathesis reaction takes place. The new couples form a precipitation, gas, or neutral molecules. (See [14] for more details.)

In the following lemma we construct a semihypergroup by a non-empty set of atoms X and an associative hyper operation $\circ$ on $X \times X$. The semihypergroup $(X \times X,\circ)$ is denoted by $\mathfrak{S}[X]$.

Lemma 2.1. *Let X be a non-empty set and for every $(x_1, x_2), (y_1, y_2) \in X \times X$ define $(x_1, x_2) \circ (y_1, y_2) = \{(z, z) | z \in \{x_1, x_2, y_1, y_2\}\}$. Then, $\mathfrak{S}[X] = (X \times X, \circ)$ is a semihypergroup.*

Proof. Suppose that $a_i = (x_i, y_i) \in X \times X$, where $i = 1,2,3$. Then,

$$a_1 \circ (a_2 \circ a_3) = \{(x_i, x_i), (y_i, y_i) | 1 \leq i \leq 3\} = (a_1 \circ a_2) \circ a_3.$$

Therefore, $\mathfrak{S}[X]$ is a semihypergroup.

From now on, let A and C be cations, B and D be anions and AB, AD, CB and CD be salts. Based on the solubility of the reacting and produced salts we can consider the following four cases:

Case 1. *All ions and salts are soluble in water***.** Then the overall reaction is

$$\mathrm{AB_{(aq)} + CD_{(aq)} \rightarrow A + B + C + D}$$

This reaction takes place in following steps:

$$\mathrm{AB_{(aq)} \rightarrow A + B}$$
$$\mathrm{CD_{(aq)} \rightarrow C + D.}$$

All ions formed from these salts are soluble in water, consequently, all of them are bystander ions and no reaction takes place and we obtain the following hyper operation table:

Table 1: $\mathrm{AB + CD \rightarrow A + B + C + D}$

$\oplus$	A	B	C	D	AB	CD
A	A	A,B	A,C	A,D	A,B	A,C,D
B	A,B	B	B,C	B,D	A,B	B,C,D
C	A,C	B,C	C	C,D	A,B,C	C,D
D	A,D	B,D	C,D	D	A,B,D	C,D
AB	A,B	A,B	A,B,C	A,B,D	A,B	A,B,C,D
CD	A,C,D	B,C,D	C,D	C,D	A,B,C,D	C,D

Theorem 2.2. *Let $H := \{A, B, C, D, AB, CD\}$, where* A *and* C *are cations and* B *and* D *are anions. Let $x \oplus y$ be the chemical interaction of x and y for every $x, y \in H$. Then, $(H, \oplus)$ is a semihypergroup.*

Proof. Let $X = \{A, B, C, D\}$. Then, $\mathfrak{S}[X]$ is a semihypergroup by Lemma 2.1 and the mapping $\varphi: (H, \oplus) \rightarrow \mathfrak{S}[X]$ defined by

$$\varphi(z) = \begin{cases} (z, z) & z \in X \\ (A, B) & z = AB \\ (C, D) & z = CD \end{cases}$$

is a monomorphism. Therefore, $(H,\oplus)$ is isomorphic to a sub-semihypergroup of $\mathfrak{S}[X]$ and the proof is complete.

Example 1. What will be the reaction of sodium chloride and ammonium nitrate? These two salts are soluble and decompose to their ions.

$$NaCl_{(aq)} \rightarrow Na^{+} + Cl^{-}$$

$$NH_4NO_{3(aq)} \rightarrow NH_4^{+} + NO_3^{-}.$$

Since Na^{+}, Cl^{-}, NH_4^{+} and NO_3^{-} formed from these salts are soluble in water, then all of them are bystander ions and no reaction takes place:

$$NaCl_{(aq)} + NH_4NO_{3(aq)} \rightarrow Na^{+} + Cl^{-} + NH_4^{+} + NO_3^{-}$$

Then we have the following commutative H_v-semigroup:

Table 2: $NaCl_{(aq)} + NH_4NO_{3(aq)} \rightarrow Na^{+} + Cl^{-} + NH_4^{+} + NO_3^{-}$

$\oplus$	Na^{+}	Cl^{-}	NH_4^{+}	NO_3^{-}	$NaCl$	NH_4NO_3
Na^{+}	Na^{+}	Na^{+} Cl^{-}	Na^{+} NH_4^{+}	Na^{+} NO_3^{-}	Na^{+} Cl^{-}	Na^{+} NH_4^{+} NO_3^{-}
Cl^{-}	Na^{+} Cl^{-}	Cl^{-}	Cl^{-} NH_4^{+}	Cl^{-} NO_3^{-}	Na^{+} Cl^{-}	Cl^{-} NH_4^{+} NO_3^{-}
NH_4^{+}	Na^{+} NH_4^{+}	Cl^{-} NH_4^{+}	NH_4^{+}	NH_4^{+} NO_3^{-}	NH_4^{+} Na^{+} Cl^{-}	NH_4^{+} NO_3^{-}
NO_3^{-}	Na^{+} NO_3^{-}	Cl^{-} NO_3^{-}	NH_4^{+} NO_3^{-}	NO_3^{-}	NO_3^{-} Na^{+} Cl^{-}	NO_3^{-} NH_4^{+}
$NaCl$	Na^{+} Cl^{-}	Na^{+} Cl^{-}	NH_4^{+} Na^{+} Cl^{-}	NO_3^{-} Na^{+} Cl^{-}	Na^{+} Cl^{-}	Na^{+} Cl^{-} NO_3^{-} NH_4^{+}
NH_4NO_3	Na^{+} NH_4^{+} NO_3^{-}	Cl^{-} NH_4^{+} NO_3^{-}	NH_4^{+} NO_3^{-}	NO_3^{-} NH_4^{+}	Na^{+} Cl^{-} NO_3^{-} NH_4^{+}	NO_3^{-} NH_4^{+}

Case 2. *On of the reacting salts is soluble in water and the other is insoluble in water.* Let AB be soluble and CD be insoluble. Then the reaction is

$$AB + CD \rightarrow A + B + CD$$

and we obtain the following hyper operation table:

Table 3: $AB + CD \to A + B + CD$

$\oplus$	A	B	AB	CD
A	A	A,B	A,B	A,CD
B	A,B	B	A,B	B,CD
AB	A,B	A,B	A,B	A,B,CD
CD	A,CD	B,CD	A,B,CD	CD

Theorem 2.3. *Let* $H := \{A, B, AB, CD\}$, *where* A *is a cation and* B *is an anion and* $x \oplus y$ *is the chemical interaction of* x *and* y *for every* $x, y \in H$. *Then* $(H, \oplus)$ *is a semihypergroup.*

Proof. Similar to the proof of Theorem 2.2 we conclude that $\oplus$ is associative on $\{A, B, AB\}$. On the other hand for every $X, Y \in H$ we have

$$CD \oplus (X \oplus Y) = \{CD\} \cup X \oplus Y = (CD \oplus X) \oplus Y.$$

Therefore, the result holds.

Example 2. Sodium nitrate is soluble and silver chloride is not soluble in water

$$NaNO_{3(aq)} \to Na^+ + NO_3^-$$

$$AgCl_{(aq)} \to AgCl$$

$$NaNO_{3(aq)} + AgCl \to Na^+ + NO_3^- + AgCl_{(s)}$$

Table 4: $NaNO_{3(aq)} + AgCl \to Na^+ + NO_3^- + AgCl_{(s)}$

$\oplus$	Na^+	NO_3^-	$NaNO_3$	$AgCl$
Na^+	Na^+	Na^+ NO_3^-	Na^+ NO_3^-	Na^+ $AgCl$
NO_3^-	Na^+ NO_3^-	NO_3^-	Na^+ NO_3^-	NO_3^- $AgCl$
$NaNO_3$	Na^+ NO_3^-	Na^+ NO_3^-	Na^+ NO_3^-	Na^+ NO_3^- $AgCl$
$AgCl$	Na^+ $AgCl$	NO_3^- $AgCl$	Na^+ NO_3^- $AgCl$	$AgCl$

Case 3. *Both Salts are soluble in water but one anion-cation pair forms a solid and the other pair is soluble in water and remains in ion form.* Let AB and CD be soluble and AD be insoluble solid produced from the reaction. Then the reaction steps are

$$\mathrm{AB} \rightarrow \mathrm{A} + \mathrm{B}$$
$$\mathrm{CD} \rightarrow \mathrm{C} + \mathrm{D}$$
$$\mathrm{A} + \mathrm{B} + \mathrm{C} + \mathrm{D} \rightarrow \mathrm{AD} + \mathrm{B} + \mathrm{C}$$

and the overall reaction is

$$\mathrm{AB} + \mathrm{CD} \rightarrow \mathrm{AD} + \mathrm{B} + \mathrm{C}$$

and we obtain the following hyper operation table:

Table 5: $\mathrm{AB} + \mathrm{CD} \rightarrow \mathrm{AD} + \mathrm{B} + \mathrm{C}$

⊕	A	B	C	D	AB	CD	AD
A	A	A,B	A,C	AD	A,B	C,AD	A,AD
B	A,B	B	B,C	B,D	A,B	B,C,D	B,AD
C	A,C	B,C	C	C,D	C,A,B	C,D	C,AD
D	AD	B,D	C,D	D	B,AD	D,C	D,AD
AB	A,B	A,B	C,A,B	B,AD	A,B	AD,B,C	B,A,AD
CD	AD,C	B,C,D	C,D	C,D	AD,B,C	C,D	C,D,AD
AD	A,AD	AD,B	AD,C	AD,D	A,B,AD	C,D,AD	AD

Theorem 2.4. *Let $H := \{A, B, C, D, AB, CD, AD\}$, where* A *and* C *are cations and* B *and* D *are anions and $x \oplus y$ is the chemical interaction of x and y for every $x, y \in H$. Then $(H,\oplus)$ is an H_v-semigroup.*

Proof. Suppose that $x, y, z \in H$. If $\{x, y, z\} \subseteq \{A, B, C, AB\}$ or $\{x, y, z\} \subseteq \{B, C, D, CD\}$ then $x \oplus (y \oplus z) = (x \oplus y) \oplus z$ since, $(\{A, B, C, AB\},\oplus)$ and $(\{B, C, D, CD\},\oplus)$ are isomorphic to a sub-semihypergroup of $\mathfrak{S}[\{A, B, C\}]$ and $\mathfrak{S}[\{B, C, D\}]$, respectively. Otherwise, $AD \in x \oplus (y \oplus z) \cap (x \oplus y) \oplus z$. So, $(H,\oplus)$ is an H_v-semigroup.

Example 3. Sodium chloride and silver nitrate are soluble salts in water, and decompose to their constituent ions:

$$\mathrm{NaCl}_{(aq)} \rightarrow \mathrm{Na}^{+} + \mathrm{Cl}^{-}$$
$$\mathrm{AgNO}_{3(aq)} \rightarrow \mathrm{Ag}^{+} + \mathrm{NO}_3^{-}$$

When the silver ions and chloride ions meet in solution, they combine and form a solid, which appears as a white precipitate:

$$\mathrm{Ag}^{+} + \mathrm{Cl}^{-} \rightarrow \mathrm{AgCl}_{(s)}$$

Sodium and nitrate ions do not react (because sodium nitrate is a soluble salt) and they are called bystander (or spectator) ions. In result, we can write the overall reaction as:

$$\mathrm{AgNO}_{3(aq)} + \mathrm{NaCl(aq)} \rightarrow \mathrm{AgCl}_{(s)} + \mathrm{Na}^{+} + \mathrm{NO}_3^{-}$$

Table 6: $AgNO_{3(aq)} + NaCl(aq) \rightarrow AgCl_{(s)} + Na^+ + NO_3^-$

$\oplus$	Ag^+	NO_3^-	Na^+	Cl^-	$AgNO_3$	NaCl	AgCl
Ag^+	Ag^+	Ag^+ NO_3^-	Ag^+ Na^+	AgCl	Ag^+ NO_3^-	Na^+ AgCl	Ag^+ AgCl
NO_3^-	Ag^+ NO_3^-	NO_3^-	NO_3^- Na^+	NO_3^- Cl^-	NO_3^- Ag^+	NO_3^- Na^+ Cl^-	NO_3^- AgCl
Na^+	Ag^+ Na^+	NO_3^- Na^+	Na^+	Na^+ Cl^-	Na^+ Ag^+ NO_3^-	Na^+ Cl^-	Na^+ AgCl
Cl^-	AgCl	NO_3^- Cl^-	Na^+ Cl^-	Cl^-	NO_3^- AgCl	Cl^- Na^+	Cl^- AgCl
$AgNO_3$	Ag^+ NO_3^-	NO_3^- Ag^+	Na^+ Ag^+ NO_3^-	NO_3^- AgCl	Ag^+ NO_3^-	AgCl NO_3^- Na^+	NO_3^- Ag^+ AgCl
NaCl	Na^+ AgCl	NO_3^- Na^+ Cl^-	Na^+ Cl^-	Cl^- Na^+	AgCl NO_3^- Na^+	Cl^- Na^+	Cl^- Na^+ AgCl
AgCl	Ag^+ AgCl	NO_3^- AgCl	Na^+ AgCl	Cl^- AgCl	NO_3^- Ag^+ AgCl	Cl^- Na^+ AgCl	AgCl

Case 4. *Both salts are soluble in water but ions form insoluble solids. Let AB and CD be soluble but AD and CB be insoluble produced solids.* By pouring AB and CD into water the reaction steps are as follows:

$$AB \rightarrow A + B$$
$$CD \rightarrow C + D$$
$$A + B + C + D \rightarrow AD + CB$$

The overall reaction is

$$AB + CD \rightarrow AD + CB$$

and we obtain the following hyper operation table:

Table 7: $AB + CD \rightarrow AD + CB$

$\oplus$	A	B	C	D	AB	CD	AD	CB
A	A	A,B	A,C	AD	A,B	C,AD	A,AD	A,CB
B	A,B	B	CB	B,D	A,B	CB,D	B,AD	B,CB
C	A,C	CB	C	C,D	CB,A	C,D	C,AD	C,CB
D	AD	B,D	C,D	D	B,AD	D,C	D,AD	D, CB
AB	A,B	A,B	A,CB	B,AD	A,B	AD,CB	B,A,AD	A,B,CB
CD	AD,C	CB,D	C,D	C,D	AD,CB	C,D	C,D,AD	C,D,CB
AD	A,AD	AD,B	AD,C	AD,D	A,B,AD	C,D,AD	AD	CB,AD
CB	A,CB	B,CB	C,CB	D,CB	A,B,CB	C,D,CB	AD,CB	CB

Theorem 2.5. *Let* $H := \{A, B, C, D, AB, CD, AD, CB\}$*, where* A *and* C *are cations and* B *and* D *are anions and* $x \oplus y$ *is the chemical interaction of* x *and* y *for every* $x, y \in H$*. Then* $(H, \oplus)$ *is an* H_v*-semigroup.*

Proof. Suppose that $x, y, z \in H$ and consider the following cases:

Case 1. If $\{x, y, z\} \subseteq \{A, C\}$, then $x \oplus (y \oplus z) = (x \oplus y) \oplus z$ since $(\{A, C\}, \oplus)$ is isomorphic to a sub-semihypergroup $\mathfrak{S}[\{A, C\}]$.

Case 2. If $\{x, y, z\} \subseteq \{B, D\}$, then $x \oplus (y \oplus z) = (x \oplus y) \oplus z$ since $(\{B, D\}, \oplus)$ is isomorphic to a sub-semihypergroup $\mathfrak{S}[\{B, D\}]$.

Case 3. If $\{x, y, z\} \subseteq \{A, B, AB\}$, then $x \oplus (y \oplus z) = (x \oplus y) \oplus z$ since $(\{A, B, AB\}, \oplus)$ is isomorphic to a sub-semihypergroup $\mathfrak{S}[\{A, B\}]$.

Case 4. If $\{x, y, z\} \subseteq \{C, D, CD\}$, then $x \oplus (y \oplus z) = (x \oplus y) \oplus z$ since $(\{C, D, CD\}, \oplus)$ is isomorphic to a sub-semihypergroup $\mathfrak{S}[\{C, D\}]$.

Case 5. If $AD \in \{x, y, z\}$, then $AD \in x \oplus (y \oplus z) \cap (x \oplus y) \oplus z$.

Case 6. If $CB \in \{x, y, z\}$, then $CB \in x \oplus (y \oplus z) \cap (x \oplus y) \oplus z$.

Otherwise, $\{AD, CB\} \cap (x \oplus (y \oplus z) \cap (x \oplus y) \oplus z) \neq \emptyset$. Therefore, $(H, \oplus)$ is an H_v-semigroup.

Example 4. The zinc sulfate and barium hydroxide are both soluble salts in water. By pouring them into water, they decompose:

$$\mathrm{ZnSO_4} \rightarrow \mathrm{Zn^{2+}} + \mathrm{SO_4^{2-}}$$
$$\mathrm{Ba(OH)_2} \rightarrow \mathrm{Ba^{2+}} + 2\mathrm{OH^-}$$

The cation $\mathrm{Zn^{2+}}$ and the anion $\mathrm{OH^-}$ can form an insoluble salt of $\mathrm{Zn(OH)_2}$ and form a precipitate. The same reaction also takes place between $\mathrm{Ba^{2+}}$ and $\mathrm{SO_4^{2-}}$. So, the overall reaction will result in two solids:

$$\mathrm{ZnSO_{4(aq)}} + \mathrm{Ba(OH)_{2(aq)}} \rightarrow \mathrm{Zn(OH)_{2(s)}} + \mathrm{BaSO_{4(s)}}.$$

3. CONCLUSION AND FUTURE WORK

In this paper, we have provided some examples of hyperstructures associated with salt metathesis reactions that are examples of the phenomena when composition of two elements is a set of elements. In Theorems 2.2 and 2.3 it is shown that the considered chemical system forms a semihypergroup. In Theorems 2.4 and 2.5 we have an H_v-semigroup. Although the obtained results are interesting, more investigation on the application of this study in chemistry is required and should be considered in the future work.

Table 8: $ZnSO_{4(aq)} + Ba(OH)_{2(aq)} \to Zn(OH)_{2(s)} + BaSO_{4(s)}$

$\oplus$	Zn^{+2}	SO_4^{-2}	Ba^{+2}	OH^-	$ZnSO_4$	$Ba(OH)_2$	$Zn(OH)_2$	$BaSO_4$
Zn^{+2}	Zn^{+2}	Zn^{+2} SO_4^{-2}	Zn^{+2} Ba^{+2}	$Zn(OH)_2$	Zn^{+2} SO_4^{-2}	Ba^{+2} $Zn(OH)_2$	Zn^{+2} $Zn(OH)_2$	Zn^{+2} $BaSO_4$
SO_4^{-2}	Zn^{+2} SO_4^{-2}	SO_4^{-2}	$BaSO_4$	SO_4^{-2} OH^-	SO_4^{-2} Zn^{+2}	OH^- $BaSO_4$	SO_4^{-2} $Zn(OH)_2$	SO_4^{-2} $BaSO_4$
Ba^{+2}	Zn^{+2} Ba^{+2}	$BaSO_4$	Ba^{+2}	Ba^{+2} OH^-	$BaSO_4$ Zn^{+2}	Ba^{+2} OH^-	Ba^{+2} $Zn(OH)_2$	Ba^{+2} $BaSO_4$
OH^-	$Zn(OH)_2$	SO_4^{-2} OH^-	Ba^{+2} OH^-	OH^-	$Zn(OH)_2$	OH^- Ba^{+2}	OH^- $Zn(OH)_2$	OH^- $BaSO_4$
$ZnSO_4$	Zn^{+2} SO_4^{-2}	SO_4^{-2} Zn^{+2}	$BaSO_4$ Zn^{+2}	$Zn(OH)_2$	Zn^{+2} SO_4^{-2}	$Zn(OH)_2$ $BaSO_4$	Zn^{+2} SO_4^{-2} $Zn(OH)_2$	SO_4^{-2} Zn^{+2} $BaSO_4$
$Ba(OH)_2$	Ba^{+2} $Zn(OH)_2$	OH^- $BaSO_4$	Ba^{+2} OH^-	OH^- Ba^{+2}	$Zn(OH)_2$ $BaSO_4$	Ba^{+2} OH^-	Ba^{+2} OH^- $Zn(OH)_2$	Ba^{+2} OH^- $BaSO_4$
$Zn(OH)_2$	Zn^{+2} $Zn(OH)_2$	SO_4^{-2} $Zn(OH)_2$	Ba^{+2} $Zn(OH)_2$	OH^- $Zn(OH)_2$	Zn^{+2} SO_4^{-2} $Zn(OH)_2$	Ba^{+2} OH^- $Zn(OH)_2$	$Zn(OH)_2$	$Zn(OH)_2$ $BaSO_4$
$BaSO_4$	Zn^{+2} $BaSO_4$	SO_4^{-2} $BaSO_4$	Ba^{+2} $BaSO_4$	OH^- $BaSO_4$	$BaSO_4$ SO_4^{-2} Zn^{+2}	Ba^{+2} OH^- $BaSO_4$	$Zn(OH)_2$ $BaSO_4$	$BaSO_4$

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