Polymorphism and Structural Distortions of Mixed-Metal Oxide Photocatalysts Constructed with $\alpha$-$U_3O_8$ Types of Layers

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Abstract: A series of mixed-metal oxide structures based on the stacking of $\alpha$-$U_3O_8$ type pentagonal bipyramid layers have been investigated for symmetry lowering distortions and photocatalytic activity. The family of structures contains the general composition $A^{m+}((n+1)/m)B((3n+1)/8n+3)$ (e.g., $A = \text{Ag, Bi, Ca, Cu, Ce, Dy, Eu, Gd, K, La, Nd, Pb, Pr, Sr, Y}; B = \text{Nb, Ta}$; $m = 1–3$; $n = 1, 1.5, 2$), and the edge-shared BO$_7$ pentagonal pyramid single, double, and/or triple layers are differentiated by the average thickness, (i.e., $1 \leq n \leq 2$), of the BO$_7$ layers and the local coordination environment of the “A” site cations. Temperature dependent polymorphism has been investigated for structures containing single layered ($n = 1$) monovalent ($m = 1$) “A” site cations (e.g., $\text{Ag}_2\text{Nb}_4\text{O}_{11}$, $\text{Na}_2\text{Nb}_4\text{O}_{11}$, and $\text{Cu}_2\text{Ta}_4\text{O}_{11}$). Furthermore, symmetry lowering distortions were observed for the Pb ion-exchange synthesis of $\text{Ag}_2\text{Ta}_4\text{O}_{11}$ to yield $\text{PbTa}_4\text{O}_{11}$. Several members within the subset of the family have been constructed with optical and electronic properties that are suitable for the conversion of solar energy to chemical fuels via water splitting.

Keywords: photocatalysis; mixed-metal oxide; structural distortion

1. Introduction

Many properties and applications of inorganic materials are derived from a small number of reported structure types. Structural families of metal-oxides that have been commonly explored in the literature are ABO$_3$ pervoskites [1–5], layered Ruddelsden-Popper pervoskites [6–8], and spinel structures [9–11]. Metal-oxide materials can also be classified by their properties that can include superconductors [12–15], transparent conducting oxides [16–20], and photocatalysts [21–26]. Variations of compositions within homologous families of structures exhibit important structural transformations (i.e., structural distortions, polymorphism) which impact their optical properties (i.e., range of light absorption for photocatalysis). A family of structures based on the stacking of $\alpha$-$U_3O_8$ type layers constructed with pentagonal bipyramids is the focus of this review, wherein condensed MO$_7$ (M = Nb, Ta) polyhedra have been found to underlie interesting new polymorphism, structural distortions, and activity for photocatalytic water splitting.

The crystal structure of $U_3O_8$ was first proposed by Zachariasen [27], further investigations of the single crystal and neutron diffraction confirmed the orthorhombic crystal structure of $U_3O_8$ [28–30]. At room temperature two crystalline forms of $U_3O_8$ can be synthesized. The $\alpha$-$U_3O_8$ phase is the form obtained under typical synthetic conditions; however, under special circumstances the $\beta$-$U_3O_8$ form
can be crystalized [31]. The $\alpha$-U$_3$O$_8$ structure undergoes a phase transition from an orthorhombic unit cell to a hexagonal unit cell at $\approx$210 °C [32–34]. A polysomatic family of structures with the general composition $A^{m+((n+1)/m)}B_{(3n+1)}O_{(8n+3)}$ (e.g., $A = $ Ag, Bi, Ca, Cu, Ce, Dy, Eu, Gd, K, La, Nd, Pb, Pr, Sr, Y; $B = $ Nb, Ta; $n = 1, 1.5, 2; m = 1–3$) have been constructed with $\alpha$-U$_3$O$_8$ type layers comprised of mixed six-, seven-, and eight-coordination sites [35]. Synthesis and structural investigations of these systems were first described in detail by Jahnberg [36–38]. Furthermore, several of the structures in the system display symmetry lowering distortions, and unique optical and electronic properties that are viable for the direct conversion of solar energy into chemical fuels.

2. $\alpha$-U$_3$O$_8$ Type Structural Layers

The orthorhombic crystal structure of $\alpha$-U$_3$O$_8$ (space group Amm2 (n38) $a = 4.14(8)$ Å, $b = 11.96(6)$ Å, $c = 6.71(7)$ Å) consists of layers of edge-shared pentagonal bipyramids along the (110) direction [30]. In each layer a maximum of four edges can be shared, leaving one unshared edge per polyhedron [36]. An isolated UO$_7$ pentagonal bipyramid layer is built from U$_2$O$_{5+6/2}$ layers, where 6/2 are the six shared apical oxygen atoms between alternating layers, thereby yielding the U$_3$O$_8$ chemical composition [37]. The average interatomic distances between six nearby O atoms for U1 and U2 are between 2.07 Å–2.23 Å, with each U atom having a longer interatomic distance for a seventh O atom 2.44 Å (U1) and 2.71 Å (U2). An edge shared layer of UO$_7$ polyhedra and an isolated UO$_7$ pentagonal bipyramid labeled with average atomic distances and a single edge-shared polyhedra are shown in Figure 1a,b, respectively. This edge-shared pentagonal bipyramid layer is the principle building block for a polysomatic family of structures with the general composition $A^{m+((n+1)/m)}B_{(3n+1)}O_{(8n+3)}$ (e.g., $A = $ Ag, Bi, Ca, Cu, Ce, Dy, Eu, Gd, K, La, Nd, Pb, Pr, Sr, Y; $B = $ Nb, Ta; $n = 1, 1.5, 2; m = 1–3$). These ternary mixed-metal oxides are constructed from pentagonal bipyramidal layers, similar to the layers observed in $\alpha$-U$_3$O$_8$, where $n$ defines the average thickness (1 ≤ $n$ ≤ 2) of the BO$_7$ layers [35]. Furthermore, these structures are comprised of either 2, 7, or 8 coordination sites for the A-site cation, and layers of single, double, and triple layers of edge-shared pentagonal bipyramids. The crystal structures are comprised of edge-shared pentagonal bipyramidal polyhedra that stack in single, double, and triple layers, as shown in Figure 2.

![Figure 1](image)

**Figure 1.** (a) Polyhedral view of the crystal structure of $\alpha$-U$_3$O$_8$ showing the edge-shared UO$_7$ pentagonal bipyramid layer in the (001) plane and (b) the local pentagonal bipyramidal coordination environment of a U cation annotated with interatomic distances.
Figure 2. The crystal structures constructed from $\alpha$-U$_3$O$_8$ type layers with the general composition $A^{m+}_{(n+1)/m}B_{3(n+1)}O_{8(n+3)}$ (a) single; (b) alternating single and double; (c) double; and (d) alternating single and triple layers of edge-shared pentagonal bipyramid polyhedra. These layers alternate with layers of isolated octahedra along the (001) direction. The grey (o) and black (p) striped polyhedra represent BO$_6$ octahedral and BO$_7$ layers, respectively.
2.1. Single Layers

Crystal structures comprised of single pentagonal bipyramidal layers have been observed for the subset of metal oxides with the general composition \( A^{m+ (2/m)} B_4 O_{11} \) (A = Ag, Ca, Cu, K, Na, Pb, Sr; B = Nb, Ta; \( m = 1, 2 \)) [37–39]. These layers of MO\(_7\) polyhedra alternate with layers of MO\(_6\) octahedra in a p–o–p–o (o = octahedra, p = pentagonal bipyramid) pattern, as shown in Figure 2a. Individual structural views of each type of layer are shown in Figure 3a–d. The apical O atoms of the single layers of edge-shared Nb/Ta pentagonal bipyramids form the intervening coordination environments (from above and below) for the layers of Nb/Ta octahedra and A-site cations. Each BO\(_6\) octahedral environment can accommodate either three (\( m = 2 \)) or six (\( m = 1 \)) A-site cations that are 2, 6, 7, or 8-coordinate depending on their oxidation state, size, and coordination preference. Linearly coordinated cations have solely been observed for Cu-containing compounds (e.g., Cu\(_2 Ta_4 O_{11}\)) where Cu vacancies are found to occur over 33% of the available Cu sites [40]. There are six nearest neighbor O atoms for coordination to the A-site cations in the Ag/K tantalates and the Ag/Na niobates. The coordination number for the Na/Pb cations in Na\(_2 Ta_4 O_{11}\) and Pb\(_2 Ta_4 O_{11}\) is 7, owing to an increase of a single nearest neighbor O atom in comparison to Na\(_2 Nb_4 O_{11}\). The crystal structure for CaTa\(_4 O_{11}\) is shown in Figure 3d, where the Ca\(^{2+}\) and Sr\(^{2+}\) cations are surrounded by eight nearest neighbor O atoms. Alternating octahedral and pentagonal bipyramidal layers are mirror images of one another; thus, upper and lower faces of the BO\(_6\) (B = Nb, Ta) octahedron cavity are formed from three oxygen atoms in the layer above and from three oxygen atoms in the layer below [36]. The layers are bridged through the apical vertices of BO\(_7\) (B = Nb, Ta) pentagonal bipyramids that are perpendicular to BO\(_6\) (B = Nb, Ta) octahedral layers. The interatomic distances for 7-coordinate Nb/Ta polyhedra are included in Table S1.

The rhombohedral R\(^3\)c space group is observed for members of the A\(^{m+ (2/m)} B_4 O_{11}\) subset of structures where the A-site cation is monovalent (\( m = 1 \)). Although the symmetry of the compositions Ag\(_2 Nb_4 O_{11}\), Ag\(_2 Ta_4 O_{11}\), Cu\(_2 Ta_4 O_{11}\), Na\(_2 Nb_4 O_{11}\), Na\(_2 Ta_4 O_{11}\), Na\(_2 Ta_4 O_{11}\), and K\(_2 Ta_4 O_{11}\) are similar, the coordination geometries of the A-site cations vary as previously mentioned. Babaryk et al., reported increasing the calculated polyhedral volume of MO\(_x\) (\( x = 6–8 \)) leads to successful transformations from centrosymmetric to noncentrosymmetric space groups [41]. However, Na\(_2 Nb_4 O_{11}\) and Ag\(_2 Nb_4 O_{11}\) are not polar at room temperature, and are classified in a rhombohedral R\(^4\)c and monoclinic C2/c space groups, respectively [42,43]. Table S2 in the Supporting Information indicates three general trends for extended structures with the composition A\(^{m+ (2/m)} B_4 O_{11}\): (1) an increase in the "A” site...
coordination number is directly correlated to decreasing $c$ lattice constant parameters; (2) members where $m = 1$ belong to centrosymmetric nonpolar space groups which contain an inversion center; and (3) members where $m = 2$ belong to noncentrosymmetric polar space that do not contain an inversion center. Symmetry-lowering structural distortions have been reported for the monovalent A-site niobate cations Na and Ag, as well as the monovalent “A” site Cu cation in the tantalate structures, which will be further discussed in a separate section of this review.

### 2.2. Alternating Single and Double Layers

The Cu$_5$Ta$_{11}$O$_{30}$ and Pr$_2$Nb$_{11}$O$_{30}$ compounds are members of the subgroup of structures that are comprised of alternating layers of single and double (Nb/Ta)$_7$ pentagonal bipyramids [44–46] shown in Figure 2b. The members of this subset of structures are arranged in a stacking scheme constructed with octahedral (o) and pentagonal bipyramid (p) layers in a p-o-p-p-o order. The edge-shared pentagonal bipyramid layers and layers of isolated BO$_6$ octahedra surrounded by 2- or 8-coordinated Cu (l) or Pr cations in Figure 3a,d, respectively. As previously observed for Cu-containing structures comprised of layers of edge-shared pentagonal bipyramids, the Cu atoms in Cu$_5$Ta$_{11}$O$_{30}$ are also linearly coordinated and contain Cu vacancies, where 5/6 of the Cu sites are occupied[44,47]. Furthermore, the Cu-containing phase with the theoretical composition Cu$_7$Ta$_{15}$O$_{41}$ was observed as a side product during the Cu$_5$Ta$_{11}$O$_{30}$ phase analysis study by Jahnberg [48] and indexed on a hexagonal unit cell in the P6$_3$/m space group. The Pr$_2$Nb$_{11}$O$_{30}$ compound is structurally related to Cu$_5$Ta$_{11}$O$_{30}$ and is the only known example that appears to be partially reduced (i.e., $\approx$9.1% Nb$^{4+}$ to $\approx$90.9% Nb$^{5+}$) within the Jahnberg structural family [49]. The structure is comprised of one symmetry unique Pr (III) cation coordinated to eight near-neighbor O atoms and three symmetry unique Nb cations, where Nb1 and Nb2 are edge shared NbO$_7$ polyhedra, and Nb3 is octahedrally coordinated to surrounding O atoms. Selected crystallographic information for Cu$_5$Ta$_{11}$O$_{30}$, Cu$_7$Ta$_{15}$O$_{41}$, and Pr$_2$Nb$_{11}$O$_{30}$ are included in Table S3 in the Supporting Information.

### 2.3. Double Layers

The subset of structures composed exclusively with double layers of edge-shared TaO$_7$ (B = Ta) pentagonal bipyramids occur with the general formula $\Lambda^{m-}_{(i(r+1)/m)}$Ta$_7$O$_{19}$ ($\Lambda$ = Bi, Cu, Ce, Dy, Eu, Gd, La, Nd, Sm, Y; $m = 1$, $n = 1.5$, 2) [35,40,46,50–53]. Members of this subset are constructed with octahedra (o) and pentagonal bipyramids (p) in the following stacking pattern p-p-o-p-p-o as shown in Figure 2c. Similar to the A-site cations in the sub-group of structures composed of single layers and alternating layers of single double pentagonal bipyramids, Cu-containing cations ($m = 1$) within the branch of structures composed of double layers of TaO$_7$ pentagonal bipyramids are linearly coordinated to O atoms as shown in Figure 3a. With the exception of Cu, the A-site cations, i.e., Bi, Ce, Eu, Dy, La, Y ($m = 3$), are coordinated to eight nearby O atoms within the layer containing isolated TaO$_6$ octahedra. Linearly coordinated Cu and 8-coordinated A-site cations are shown in Figure 3a. Similar to the single layered structures, the double-layered structure is constructed of mirrored images of alternating octahedral and pentagonal bipyramidal layers bridged through the apical vertices of the TaO$_7$. The interatomic distances for TaO$_7$ polyhedra of selected compounds are listed in Table S4.

The members constructed with double layers of TaO$_7$ pentagonal bipyramids can be classified to the hexagonal crystal systems, (i.e., P6$_3$/m, P6$_5$c2, and P6$_3$/mcm) as listed in Table S4. Very early investigations by Chretien and Bodit found that the rare earth tantalates, ATa$_7$O$_{19}$ ($\Lambda$ = Ce, Eu, Gd, La, Nd, Pr, Sm) are isostructural to CeTa$_7$O$_{19}$ indexed on a tetragonal unit cell, as found using powder X-ray diffraction [54,55]. Further powder X-ray and single crystal investigations by Rossel and Gatehouse concluded CeTa$_7$O$_{19}$ crystallizes in the hexagonal system, and includes the other known rare earth tantalates. [50,53,56]. Similarly, YTa$_7$O$_{19}$ was indexed on a hexagonal unit cell, space group determination among the P6$_3$/m, P6$_5$cm, and P6$_3$/mcm was not distinguishable [53]. Niobium containing chemical compositions with the general formula $\Lambda^{m-}_{(i(r+1)/m)}$Nb$_7$O$_{19}$ cations have also been found, and are composed of triple NbO$_7$ layers, as described below.
2.4. Alternating Single and Triple Layers

Hofmann and Gruehn synthesized and reported a subset of lanthanide rare earth structures with the general composition \( A^{m+}((n+1)/m)\text{Nb}_7\text{O}_{19} \) (\( A = \text{Ce, La}; m = 3; n = 2 \)) [57]. These rare earth mixed-metal oxide structures are comprised of triple \( \text{NbO}_7 \) pentagonal bipyramid layers alternating with 8-coordinated \( \text{La} \) and \( \text{Nb} \) octahedra, as shown in Figure 2d. A single crystal investigation of \( \text{LaNb}_7\text{O}_{19} \) confirmed that it crystallizes in the trigonal space group, \( P3 \) [57]. Its structure is composed of eight-coordinated \( \text{La}^{3+} \) cations that form distorted square antiprisms and \( \text{Nb} \) cations in distorted octahedra which are linked together via corner shared \( \text{O} \) atoms as shown in Figure 3. The \( \alpha\text{-U}_3\text{O}_8 \)-type layers of \( \text{NbO}_7 \) are mirror images of one another and alternate with the following stacking scheme \( p-o-p-p-p-o \) (\( p = \text{pentagonal bipyramid} \) and \( o = \text{octahedra} \)), as shown in Figure 4. Each type of niobate layer is constructed from its own symmetry unique \( \text{Nb} \) cation, where \( \text{Nb1}-4 \) are layers of pentagonal bipyramids and \( \text{Nb5} \) and \( \text{Nb6} \) are the layers of octahedra. The structures \( \text{LaNb}_7\text{O}_{19} \) and \( \text{CeNb}_7\text{O}_{19} \) are the first example of a trigonal member within the family of structures. A single crystal investigation was not carried out for \( \text{CeNb}_7\text{O}_{19} \), the assumption of an isotype with \( \text{LaNb}_7\text{O}_{19} \) is based on the consistency of the reflections from Guinean diagrams via powder X-ray diffraction [57]. From the investigation, it cannot be ruled out that \( \text{Ce}^{4+} \) may occupy the \( \text{La}^{3+} \) and \( \text{Nb}^{5+} \) sites. Furthermore, powder X-ray investigation for \( \text{NdNb}_7\text{O}_{19} \) and \( \text{PrNb}_7\text{O}_{19} \) were reported and the structural information is provided in Table S3 in the supporting information [46,58].

![Figure 4](image-url)

Figure 4. The crystal structure \( \text{LaNb}_7\text{O}_{19} \), with labels for the symmetry inequivalent \( \text{Nb} \) cations in each layer. The layers of \( \text{NbO}_7 \) pentagonal bipyramids are shown in black (\( \text{Nb1} \)), red (\( \text{Nb2} \)), blue (\( \text{Nb3} \)), and purple (\( \text{Nb4} \)) striped polyhedra. The \( \text{NbO}_6 \) octahedra are shown in orange (\( \text{Nb5} \)) and gold (\( \text{Nb6} \)) striped polyhedra.

3. Structural Distortion and Polymorphism

Symmetry-lowering distortions have been observed for several of the Nb- and Ta-containing structures constructed with \( \alpha\text{-U}_3\text{O}_8 \) type pentagonal bipyramid layers. For example, structures composed of single \( \text{MO}_7 \) pentagonal bipyramid layers (e.g., \( \text{Ag}_2\text{Nb}_4\text{O}_{11} \), \( \text{Cu}_2\text{Ta}_4\text{O}_{11} \), \( \text{Na}_2\text{Nb}_4\text{O}_{11} \),
PbTa$_2$O$_{11}$ have exhibited structural distortions under various conditions (e.g., as a function of temperature, composition, etc.). Second-order Jahn-Teller (SOJT) effects by d$^0$ cations in octahedral coordination environments can be the driving force for structural distortions and symmetry lowering transitions, such as leading to noncentrosymmetric structures [59]. The SOJT distortions have typically been found for octahedral d$^0$ cations with high valency, with the magnitude of the distortion increasing in the following order: Zr$^{4+}$ < Ta$^{5+}$ < Nb$^{5+}$ < W$^{6+}$ < V$^{5+}$ < Mo$^{6+}$ [59]. The magnitude of the distortions are expected to increase as the energy separation between the metal-based $t_{2g}$ d-orbitals and the non-bonding O 2p states decrease, owing to a greater mixing of the occupied (O based) and unoccupied (M based) crystal orbitals [60]. Another theory described by Kunz and Brown finds that the directions of the displacements of the d$^0$ cations are not primarily determined from the electronic SOJT effect [61], but rather the cation displacement is influenced more by bond network stresses (e.g., asymmetry in the bond network from the nearest neighbors). In addition, cation-cation repulsions from near-neighbor cations that share edges or faces also increase bond network stresses.

3.1. Niobates

Symmetry lowering transitions that are a function of temperature have only been reported for the niobium-containing structures Ag$_2$Nb$_2$O$_{11}$ and Na$_2$Nb$_2$O$_{11}$ [42,43]. The Ag$_2$Nb$_2$O$_{11}$ phase transforms from the centrosymmetric R$3\overline{c}$ space group to the noncentrosymmetric R$3c$ space group upon cooling to $\approx$127 °C. The driving force of this symmetry-lowering transition has been described to arise from the displacement of Ag and Nb cations within the pentagonal bipyramid and the octahedral layers [43]. The Ag and Nb cations are shifted out of the center of the polyhedra towards the octahedral faces of the distorted Mo$_6$ (M = Ag, Nb) polyhedra, yielding a dipole moment along the c axis [43]. The Nb$^{5+}$ cations in pentagonal bipyramidal layers are displaced towards the apical O atoms in the polyhedra [43]. A second symmetry-lowering transition into the R$3$ space group is observed upon cooling to $\approx$73 °C and has been attributed to shifts in the equatorial O atoms of the NbO$_7$ pentagonal bipyramids are found to occur [43].

By comparison, the symmetry lowering distortions of Na$_2$Nb$_4$O$_{11}$ from R$5c$ to C2/c upon cooling to $\approx$107 °C yields a nonpolar centrosymmetric structure [43,62]. The structural relationship of the phase transformation between the monoclinic and hexagonal-rhombohedral unit cells has been previously described [42,63]. The origin of the structural distortion is primarily related to the displacement of the Nb cation within the plane of the pentagonal bipyramidal layer [42]. Below the transition temperature, two crystallographically distinct Nb cations, (i.e., Nb1 and Nb2) are generated in the pentagonal bipyramidal layer [42]. The longest interatomic distance between Nb1-O4 increases, causing its polyhedron to further distort in the layer, while the Nb2 polyhedron becomes a more regular pentagonal bipyramid [42].

3.2. Tantalates

3.2.1. Cu$_2$Ta$_4$O$_{11}$

The Cu$_2$Ta$_4$O$_{11}$ structure occurs in two polymorphs, namely, the monoclinic $\alpha$-Cu$_2$Ta$_4$O$_{11}$ phase and the rhombohedral $\beta$-Cu$_2$Ta$_4$O$_{11}$ [64,65], shown in Figures 5 and 6. At temperatures of $\approx$50 °C to room temperature, the monoclinic $\alpha$-Cu$_2$Ta$_4$O$_{11}$ phase is relatively stable. The rhombohedral $\beta$-Cu$_2$Ta$_4$O$_{11}$ phase emerges upon heating the monoclinic $\alpha$-Cu$_2$Ta$_4$O$_{11}$ phase to between 250 °C and 550 °C [64]. This symmetry-lowering distortion is driven by the edge-shared Ta d$^0$ cations that form the single pentagonal bipyramidal layers [64]. The direction of the out-of-center displacement of the Ta cations are towards the vertices of the polyhedra not shared by neighboring Ta cations, as illustrated in Figures 5 and 6 for the distorted and non-distorted structures, respectively [64]. Thus, it appears that the repulsion from nearest-neighbor cations directs the out-of-center displacement of Ta d$^0$ cations towards an edge of the polyhedron that is not shared by a neighboring Ta cation within the layer [64]. The longer interatomic distance between Ta2-O2 in the pentagonal bipyramidal
layer increases from 2.44 Å to 2.55 Å; thus, the Ta2 cation, coordinated to 7 O atoms in a pentagonal bipyramid, is transformed into a highly-distorted TaO6 octahedron within the tantalate layer [64].

**Figure 5.** The crystal structure of a single edge-sharing TaO7 pentagonal bipyramid layer of the rhombohedral β-Cu2Ta4O11 (A) a view of the edge sharing of Ta cations along the ab plane with the unit cell outline as a blue dashed line (B) a smaller segment from the uppermost three Ta cations, where the grey arrows indicate the out-of-center displacement of Ta; and (C–E) local views of the coordination environments of the Ta cations labeled 1, 2, and 3, respectively. Reproduced with permission from [64], published by Elsevier, 2014.

**Figure 6.** (A) Polyhedral view of a layer of edge-sharing TaO7 pentagonal bipyramids in the monoclinic α-Cu2Ta4O11, with the unit cell outline as a blue dashed line and the black line indicating the distortion of Ta2 into an octahedron; and (B–D) the local coordination environment of Ta3, Ta1, and Ta2, respectively. Reproduced with permission from [64], published by Elsevier, 2014.

An explanation of the phase transition observed in the rhombohedral β-Cu2Ta4O11 can be suggested from bond length arguments. The longer Ta-O interatomic distances observed in the TaO6 and TaO7 polyhedra in Cu2Ta4O11 are comparable to the Nb-O distances in Na2Nb4O11 and Ag2Nb4O11. Thus, these polyhedra are more flexible to accommodate an out-of-center displacement of the Ta/Nb cations. In the rhombohedral β-Cu2Ta4O11 structure, effects from cation-cation repulsion likely cause the nearest neighbor Ta 5d0 cations within three edge-shared TaO7 polyhedra to move out of the center of the polyhedra. The TaO7 pentagonal bipyramid layer distorts into a layer containing TaO6 and TaO7 polyhedra, where Ta3 and Ta1 maintain the TaO7 pentagonal bipyramid coordination environment and Ta2 centers a highly-distorted TaO6 octahedron [64]. The monoclinic α-Cu2Ta4O11
structure contains fewer edges that are shared as the Ta2-O2 interatomic distance lengthens to ≈2.55(3) Å, an increase of ≈0.13 Å as compared to the rhombohedral β-Cu2Ta4O11 structure [64]. Structural distortions to lower symmetry have not been observed for Ag2Ta4O11, which could be due to the slightly larger interatomic distances in the equatorial plane of edge-shared pentagonal bipyramids for Ta1-O3 in Cu2Ta4O11 as compared to those in Ag2Ta4O11, at 2.45(8) Å and 2.398(2) Å, respectively [43]. The TaO6 octahedron are also relatively larger, in the range of 1.92(7) Å–2.20(6) Å, as compared to those in Ag2Ta4O11 at 1.9845(5) Å [43].

3.2.2. PbTa4O11

Comparable to that described above for Cu2Ta4O11, distortions were observed for PbTa4O11 when it was prepared from Ag2Ta4O11 by a Pb-ion exchange reaction. Similar to the parent structure of Ag2Ta4O11 (R3c), the lower-symmetry PbTa4O11 (R3) exhibits two symmetry-unique layers of edge-shared TaO7 pentagonal bipyramids (Ta1 and Ta2), layers of TaO6 octahedra (Ta3 and Ta4), and Pb(II) cations (Pb1 and Pb2), as shown in Figure 7 [35]. Each of the isolated TaO6 octahedra is surrounded by three monocapped trigonal prismatic PbO7 polyhedron that alternate in their orientation, (i.e., [001] for Pb1 and [001] for Pb2) [35]. The PbO7 polyhedra are formed by six apical O atoms and one equatorial O atom (Pb1-O7, Pb2-O9) from the adjacent TaO7 layers that result in the asymmetric coordination environment [35]. Divalent Pb cations commonly undergo intra-polyhedral distortions due to their high degree of polarizability and their stereoactive electron lone pair, and thereby adopt stable asymmetric anion coordination environments (i.e., PbO7) [59,61,66–68]. The stabilization of the Pb(II) cations results in their displacement towards the Ta(V) cations, which in turn electrostatically repulse the Ta atoms (Ta1 and Ta2) from the center of their TaO7 polyhedra towards their apical O atoms [35]. Similarly, the Ta atoms in the TaO6 octahedra were displaced towards the octahedral faces away from the Pb(II) cations, analogous to the polar distortions reported for Ag2Nb4O11 (R3) [43]. Displacement of the Ta(V) and the Pb(II) cations along the c-axis culminated in alternating expanded and contracted TaO7 pentagonal bipyramidal interlayer distances [35].

![Figure 7. Polyhedral view of the four symmetry-unique layers of PbTa4O11 that are composed of alternating layers of (a–b) isolated TaO6 octahedra surrounded by Pb(II) cations and (c–d) edge-sharing TaO7 pentagonal bipyramid layers. The unit cell is outlined in black with tan-colored TaO6 and TaO7 polyhedra, gray spheres for Pb, and red spheres for oxygen. Reproduced with permission from [35], published by Elsevier, 2015.](image-url)
Similar to the distortions along the c-axis between adjacent tantalate layers, electrostatic repulsion effects within the ab plane bring about two symmetry unique TaO$_7$ pentagonal bipyramid layers. The off-center displacement of the nearest-neighbor Ta atoms (Ta1 and Ta2) towards empty trigonal cavities within the TaO$_7$ layers relieves electrostatic strain caused by cation-cation repulsions. This resulted in two symmetry unique Ta atoms, six different Ta-O equatorial bond distances, and increased the TaO$_7$-TaO$_7$ nearest-neighbor distances, as shown in Figure 8 [35]. In comparison to the centrosymmetric Ag$_2$Ta$_4$O$_{11}$ structure, the TaO$_7$ layers are comprised of one symmetry unique Ta, two different Ta-O equatorial bond distances, and shorter TaO$_7$-TaO$_7$ nearest-neighbor distances [43]. The symmetry-lowering polar distortions from the centrosymmetric Ag$_2$Ta$_4$O$_{11}$ (R3c) to the noncentrosymmetric PbTa$_4$O$_{11}$ (R3) space group are characteristic of SOJT distortions that are typically observed for structures with high valent d$^0$ cations (i.e., Ta(V)) and cations containing filled valence s shells (i.e., Pb(II)). The SOJT distortion reduces the crystal symmetry and is the driving force for stabilizing ionic shifts [59,61,66–68].

**Figure 8.** Polyhedral view and local coordination environments of one layer of PbTa$_4$O$_{11}$. Shown are (a) a polyhedral view of the TaO$_7$ layer along the ab plane with the unit cell outline in black; (b) a smaller segment from the lower right cluster of three labeled Ta2 atoms, with red arrows indicating the atomic displacement; and (c–e) the local coordination of the labeled Ta2 atoms. Reproduced with permission from [35], published by Elsevier, 2015.

### 3.3. Niobates/Tantalates Solid Solution

The polymorphism of the (Na$_{1-x}$Ag$_x$)$_2$Nb$_4$O$_{11}$ solid solutions have been investigated as a function of chemical composition and temperature by the Woodward and West groups, which revealed a complex system with interesting structural transformations [69,70]. The (Na$_{1-x}$Ag$_x$)$_2$Nb$_4$O$_{11}$ structures were characterized using Rietveld refinements of variable temperature powder X-ray and neutron diffraction data, differential scanning calorimetry, and lattice parameter trends. The West group reported a monoclinic (C2/c) to rhombohedral (R3c) phase transformation upon heating compositions with $x \leq 0.25$, and a monoclinic C2/c ($x = 0.25$) to rhombohedral R3c phase transformation upon cooling below $\approx 107$ °C. Further, the rhombohedral and monoclinic phases coexist in a two-phase region at the phase boundary for compositions of 0.65 $\leq x \leq 0.8$. The origin of the rhombohedral R3c to monoclinic C2/c phase transition is related to distortions within the equatorial plane of the NbO$_7$ pentagonal bipyramids, as described below [69,70].

An interesting series of ferroelectric-paraelectric phase transformations was observed using variable temperature powder X-ray diffraction and lattice refinements. The transformation from R3 to R3c to R3c occurred upon heating to higher temperatures for compositions where $x \geq 0.85$. For example, upon cooling the R3c phase ($x = 0.875$) it transforms to R3c at $\approx 87$ °C and to R3 at $\approx -63$ °C. The series of ferroelectric-paraelectric phase transformations are related to the displacement of the Nb atoms in the NbO$_7$ pentagonal bipyramids towards the apical O atoms, as well as displacement of Nb...
atoms in NbO₆ and Na/Ag atoms towards their octahedral faces. A triclinic $\overline{P}T$ crystal structure was observed in the compositional range of $0.25 < x < 0.60$ in the temperature range $-273 \degree C$ to $3 \degree C$ [70]. Heating the low-temperature $\overline{P}T$ crystal structure resulted in the structural transformation to the monoclinic $P2_1/c$ at temperatures up to room temperature. At temperatures above room temperature the monoclinic $P2_1/c$ crystal structure transforms to the rhombohedral $R\bar{3}c$ crystal structure [70]. The triclinic distortions from the rhombohedral structure are the result of a combination of off-center displacement of the Nb atoms in the NbO₇ and NbO₆ polyhedra, as well as movement of the equatorial O atoms in the NbO₂ pentagonal bipyramid layers out of the equatorial plane [70].

The Na$_{2-x}$Cu$_x$Ta$_4$O$_{11}$ solid solutions were also investigated by the Maggard group with compositional limits between $0 \leq x \leq 0.78$ at a reaction temperature of $950 \degree C$ [71]. The solid solutions did not display any phase transformation; however, Wyckoff site substitution of Na cations and Cu cations in the $R\bar{3}c$ crystal structure of the solid solution were observed together with a significant decrease in bandgap size from $\approx 4.0$ eV to $\approx 2.65$ eV [71]. The origin of the differential site occupancy of the Ag and Cu cations is driven by the preferred coordination number of the Na/Cu cation to the surrounding O atoms [71]. The linearly coordinated Cu cation and 7-coordinate Na cation are located at the 18d and 12c Wyckoff crystallographic sites, respectively. By comparison, the use of nanoparticle reactants and lower reaction temperatures of $\approx 625 \degree C$ to $\approx 700 \degree C$ were found necessary to obtain the Cu-richest composition, i.e., Cu$_2$Ta$_4$O$_{11}$, in high crystalline purity [65]. This composition was found to undergo a transformation from a monoclinic structure (Cc) to a rhombohedral ($R\bar{3}c$) crystal structure upon heating, i.e., from $\alpha$-Cu$_2$Ta$_4$O$_{11}$ to $\beta$-Cu$_2$Ta$_4$O$_{11}$, as described above [64].

4. Photocatalysis

4.1. Background

Among renewable energy sources, solar energy is the largest, exploitable resource that could meet current and future human energy demand, with an estimation that $\approx 0.015\%$ of solar energy reaching the earth would be enough to support human civilization [72–75]. The capture and conversion of solar energy to drive photocatalytic hydrogen production would provide a clean alternative energy solution that can be used to generate useful chemical fuels Honda and Fujishima were the first to demonstrate the decomposition of H$_2$O into H$_2$ and O$_2$ using TiO$_2$ as an $n$-type photocatalyst [76]. Since this groundbreaking work, semiconductor-based photocatalytic water splitting to produce hydrogen has been considered one of the most important approaches to solving the world energy crisis [77]. Semiconductors have also been used in practical application for the photocatalytic degradation of organic pollutants in water [78–81]. The photoelectrolysis of water using semiconductors as both light absorber and energy converter (i.e., catalyst) to store the solar energy in the simplest bond, H$_2$, has been described as the “Holy Grail” of solar energy conversion and storage [74,82–84].

Photocatalysis for water splitting can be divided into four mechanistic steps: (a) absorption of photons to excite electrons from the valence band to the conduction band; (b) charge separation electrons and holes; (c) diffusion of the photoexcited electrons and holes to the surfaces as driven by the space-charge layer, and (d) surface chemical reactions between the charge carriers and the adsorbates [85–89]. The illustration in Figure 9 shows a photocatalyst particulate and the four basic steps, where (d) also includes the competing volume and surface recombination processes. An efficient photocatalyst must have band gap energies capable of the absorption of visible light energies and possess energetic band positions suitable for driving water reduction and oxidation reactions (i.e., $E_g \geq 1.23$ eV) [90]. The valence and conduction band energies of several semiconductors are plotted in Figure 10, and shown relative to the water redox couples for water splitting. Additionally, the photocatalyst must be stable in aqueous solution under solar irradiation. The use of co-catalysts on semiconductors has proven to be an effective approach to promote charge separation, transfer, and to suppress recombination and back-reactions during photocatalysis [91]. The electronic structure of the semiconductor also determines the functionality and efficiency of a photocatalyst. This is not
limited to the space charge width alone, which is composed of the accumulation layer, depletion layers, and inversion layer. The carrier diffusion lengths, and charge carrier mobility are also critical to the material’s photocatalytic performance [85,92–95]. In addition, selecting a suitable doping strategy is essential to enhancing photocatalytic properties [96]. Common challenges for achieving water splitting with heterogeneous photocatalysts include rapid recombination of electrons/holes [97], hole/electron collection at particle surfaces [98], and improvement of the photocatalytic rates [99,100].

**Figure 9.** An illustration of a particulate photocatalyst, showing the processes of (a) light absorption; (b) charge separation; (c) charge migration; (d) recombination; and (e) redox reaction.

**Figure 10.** The bandgap energies (red for n-type, black for p-type) are shown with respect to the reversible hydrogen electrode and the water oxidation redox couple (assuming Nernstian behavior for the band-edge energies with respect to the electrolyte pH). The contribution of the valence and conduction band orbitals are outlined in blue and grey, respectively. Reproduced with permission from [101], published by Macmillian Publishers Limited, Part of Springer Nature, 2016.

Evaluation of photocatalysts under experimental conditions suitable for water splitting is dependent upon the following: the evolution of O2 and H2 gases, stability over time, as a function of wavelength (i.e., ultraviolet or visible light), and overall efficiency of the system [101–105]. Depending upon the overall configuration of the photocatalytic measurements, (i.e., whether in the form of
suspended particles or as a polycrystalline film) various parameters are important to assess solar-to-fuel energy conversion, including the photocurrent density, turnover frequency, overall quantum yield,

\[
\text{Overall Quantum Yield} = \frac{\text{rate of reaction}}{\text{rate of absorption of radiation}} = \frac{N_{\text{mol}}}{N_{\text{ph}}} \tag{1}
\]

and the incident photon-to-current-efficiency (IPCE). The photoelectrochemical properties of polycrystalline films of the Cu(I) tantalates of this structural family (e.g., Cu₅Ta₁₁O₃₀) have been recently reviewed [85], and this current review will focus on their photocatalytic activity as suspended powders in aqueous solutions.

For investigations where solid photocatalysts particles are suspended in an aqueous solution and irradiated, the rate of hydrogen and/or oxygen production and the quantum yield are commonly reported. A turnover number can be calculated from the moles of evolved H₂ and the number of surface active sites of the photocatalyst. The latter can be approximated from surface area measurements and a knowledge of the crystalline structure, and this is typically reported in units of \(\mu\text{mol} \cdot \text{h}^{-1} \cdot \text{g}^{-1}\). The overall quantum yield, listed in Equation (1), is defined as the number of molecules produced relative to the total number of incident photons in a reaction vessel [83]. The number of molecules \(N_{\text{mol}}\) undergoing an event (conversion of reactants or formation of products) relative to the number of quanta (photons) \(N_{\text{ph}}\) absorbed by the reactants or photocatalyst is determined based on the \(\text{cm}^3\) per seconds (cm/s) of the reactions.

Heterogeneous photocatalysts for water reduction or oxidation are common among many metal-oxide systems, which include binary oxides (i.e., TiO₂, Cu₂O, Fe₂O₃, WO₃), oxynitride systems (i.e., TaO₃Nₓ, BaTaO₂Nₚ, LaTiO₂Nₚ), layered oxides (K₄Nb₁₈O₄₇, Na₂W₄O₁₃, RbLaNb₂O₇), and mixed-metal oxides (BiVO₄, CuFeO₂, CuWO₄) [106–113]. In addition perovskite-based photocatalysts have been extensively studied and various strategies have been employed for enhancing photocatalytic performance [90,114,115]. The use of mixed-metal compositions is critical to lowering the bandgap sizes of simpler metal oxides into the visible region [116]. Layered oxide systems are also of importance in photocatalytic systems due to their unique interlayer spaces in which reduction sites are separated from oxidation sites, yielding among the highest rates for hydrogen and oxygen production from solar energy [117–119]. However, the incorporation of secondary transition metals into the interlayer sites, (i.e., to lower their bandgap sizes into the visible range) is typically not a stable configuration in aqueous solutions where the layers can delaminate. Thus, the family of layered structures based pentagonal bipyramid layers serve as an alternative for achieving efficient water splitting activity in aqueous solutions. In addition, several members within the system are comprised of early and late transitions metals (i.e., Cu¹⁺/Ta⁵⁺, Ag¹⁺/Ni²⁺, Ag¹⁺/Ta⁵⁺) which possess lower visible-light band gaps that are suitable for use with the solar spectrum and capable of driving the water splitting reactions.

The Maggard group has extensively investigated the visible and ultraviolet photocatalytic activity of members from the \(A^{m+}[(n+1)/m]B_{(3n+1)}O_{(8n+3)}\) (e.g., \(A = \text{Na, Ag, Cu, Pb, Bi; } B = \text{Nb, Ta} \)) family of structures as both suspended particles and polycrystalline films for water splitting [92,116,120,121]. Improved charge separation and photocatalytic/photoelectrochemical redox reactions have been proposed to be enhanced in these structures due to the preferential anisotropic diffusion of charge carriers along the BO₇ pentagonal bipyramid layers. The anisotropic charge diffusion is a result of the delocalization of the Nb 4d and the Ta 5d lowest-energy unoccupied crystal orbitals across the BO₇ pentagonal bipyramid layers, as confirmed by electronic structure calculations which show the largest band dispersion in these crystallographic directions [35,47,64,65,71,122–128].

4.2. Photocatalysts with Single MO₇ Layers

The first system investigated in this family of structures for photocatalytic activity was the natrotaantite compound, Na₂TaO₄₁, which showed activity for hydrogen production under ultraviolet-visible light of \(\approx 13.4\) to \(\approx 34\ \mu\text{mol H}_2 \cdot \text{h}^{-1} \cdot \text{g}^{-1}\) [127]. Owing to its large bandgap size of \(\approx 4.3\ e\text{V}\), its activity was limited to ultraviolet light wavelengths. The variation in H₂ gas rates were

---

**Equation 1**

\[
\text{Overall Quantum Yield} = \frac{\text{rate of reaction}}{\text{rate of absorption of radiation}} = \frac{N_{\text{mol}}}{N_{\text{ph}}} \tag{1}
\]
dependent upon the synthetic conditions and the particle sizes and surface areas of the polycrystalline powders [127]. The particle sizes varied with a wide distribution from \( \approx 100 \text{ nm} \) to \( \approx 1000 \text{ nm} \) among all of the products that were investigated by scanning electron microscopy, with low total surface areas from \( \approx 0.8 \) to \( \approx 1.0 \text{ m}^2/\text{g} \). Notably, the highest photocatalytic rates for hydrogen production were found for crystallites with highly faceted and nanoterraced surfaces. These rates were stable over the course of several hours during the photocatalytic reactions [127]. Similarly, the Ag(I) analogues, i.e., Ag\(_2\)M\(_4\)O\(_{11}\) (\( A = \text{Ta, Nb} \)), have been investigated as photocatalysts for water splitting and organic dye degradation [124,126,129]. The Ag\(_2\)Nb\(_4\)O\(_{11}\) composition has a smaller band gap of \( \approx 3.1 \text{ eV} \), while for Ag\(_2\)Ta\(_4\)O\(_{11}\) it is \( \approx 3.9 \text{ eV} \). As a suspended powder, the Ag\(_2\)Ta\(_4\)O\(_{11}\) compounds show photocatalytic activity for hydrogen production of \( \approx 23 \text{ \( \mu \)mol} \text{ H}_2/\text{h} \cdot \text{g}^{-1} \). This is similar in rate to that found for Na\(_2\)Ta\(_4\)O\(_{11}\). However, the activity for oxygen production was significantly higher \( \approx 165 \text{ \( \mu \)mol} \text{ O}_2/\text{h} \cdot \text{g}^{-1} \), and higher compared to that for Na\(_2\)Ta\(_4\)O\(_{11}\) of \( \approx 110 \text{ \( \mu \)mol} \text{ O}_2/\text{h} \cdot \text{g}^{-1} \). Both compounds crystallize in the same centrosymmetric rhombohedral space group, which suggests the higher activity for oxygen production arises from the new Ag-based valence band in Ag\(_2\)Ta\(_4\)O\(_{11}\), shown in Figure 11. By comparison, the Ag\(_2\)Nb\(_4\)O\(_{11}\) compound is ferroelectric and crystallizes in the polar R\(_3\)c space group at room temperature. While the Ag\(_2\)Nb\(_4\)O\(_{11}\) compound has been found active for photocatalytic dye degradation [129], there are currently no reports of its photocatalytic activity for water reduction or oxidation.

More recently, the solid solutions of Na\(_2\)Ta\(_{4-y}\)Nb\(_y\)O\(_{11}\) (\( 1 \leq y \leq 4 \)) were investigated for hydrogen production [125]. All solid solution compositions investigated were photocatalytically active for the generation of hydrogen and exhibited higher rates for hydrogen production in comparison to Na\(_2\)Ta\(_4\)O\(_{11}\) and Ag\(_2\)Ta\(_4\)O\(_{11}\) [125], as shown in Figure 12. Mott-Schottky measurements were evaluated in order to determine the positions of the conduction and valence band edges for selected samples in the Na\(_2\)Ta\(_{4-y}\)Nb\(_y\)O\(_{11}\) solid solution. The conduction band energies followed a trend toward more positive potentials and resulted in a red-shift in the absorption edge owing to the increase in lower energy Nb 4d orbitals [125]. The bandgap size decreased across the solid solution series from \( \approx 4.3 \text{ eV} \) for Na\(_2\)Ta\(_4\)O\(_{11}\) to \( \approx 3.6 \text{ eV} \) for Na\(_2\)Nb\(_4\)O\(_{11}\). The highest photocatalytic rate for hydrogen production was exhibited by Na\(_2\)Nb\(_4\)O\(_{11}\), which generated 84 \( \mu \text{mol} \text{ H}_2/\text{h} \cdot \text{g}^{-1} \) under ultraviolet-visible light.

![Figure 11](image-url). The densities-of-states (DOS; right) and electron density plots (left) of Ag\(_2\)Ta\(_4\)O\(_{11}\). The individual atomic contributions are projected out in the DOS, and the electron density at the top of the valence band and bottom of the conduction band are shaded red and blue, respectively. Reprinted with permission from [126]. Copyright 2013 American Chemical Society.
At a wavelength of 230 nm [125]. At an x ≈ 2.7 to 3.0, (i.e., ≈ 67% to ≈ 70% Nb content) the structural transformation from the rhombohedral to monoclinic space groups occurs, as described above, both of which are centrosymmetric. However, the general trends in bandgap size and photocatalytic activity do not show any discontinuities, but rather, both gradually shift and result in lower band energies and higher photocatalytic activities with increasing Nb content [125]. This suggests the higher activities are the result of increased light absorption, and are not significantly impacted by this specific structural transformation. The further substitution of Sn (II) cations into the structure was partially successful, resulting in a Sn (II) content that varied between ≈ 11% to ≈ 21%. Significant red-shifting of the bandgap size occurred down to ≈ 2.3 eV into the visible light energies, as well as higher photocatalytic activities for hydrogen formation of up to ≈ 124 μmol H2 h−1 g−1 under ultraviolet and visible-light energies, as shown in Figure 12 [125]. Further, the conduction and valence band energies were both found to maintain suitable positions for driving both the reduction and oxidation of water. However, further research is necessary to elucidate any structural changes and the crystallographic location of the Sn(II) cations, as well as the preparation of a fully Sn(II) exchanged composition (i.e., SnTa4O11 in analogy with PbTa4O11).

Figure 12. Photocatalytic hydrogen production (μmol H2) versus time (h) for (a) Na2Ta4−yNb4O11 and (b) Na2−2xSn2Ta4−yNb4O11 under ultraviolet-visible (λ > 230 nm) irradiation. Reprinted with permission from [125]. Copyright 2016 American Chemical Society.

Among the divalent cations of this family, CaTa4O11 and the related solid solution Ca1−xSr2Ta4O11, 0 ≤ x ≤ 0.3, has been investigated for suspended particle photocatalysis [130]. The bandgap size across this series ranged from ≈ 4.4 eV to ≈ 4.2 eV with increasing Sr content, photocatalytic activities were limited to ultraviolet irradiation. The rate of hydrogen production varied, from ≈ 502 μmol/h with a NiO cocatalyst to ≈ 20–30 μmol/h without a cocatalyst [130]. Photocatalytic activity was dependent upon the preparation of the sample, co-catalyst, and loading methods of the cocatalyst. Generally, no apparent trends were observed in the rates for increasing amounts of Sr substitution into the compound [130]. The samples were prepared using either a polymerized complex method or impregnation method [130]. For pure CaTa4O11, rates for hydrogen production were found to be ≈ 403 μmol/h of H2 when loaded with 0.5 wt % of NiO co-catalyst in comparison to a rate ≈ 62 μmol/h of H2 when RuO2 was used as the co-catalyst. The solid solution with the highest activity also had the highest Sr content, (i.e., Ca0.7Sr0.3Ta4O11) yielded ≈ 575 μmol/h of H2 in the presence of NiO co-catalysts on the surface of the photocatalyst and ≈ 16 μmol/h of H2 without the addition of a co-catalyst [130]. The cited reason for the higher activity was the relaxation of the structural distortion when substituting the larger Sr cation into the structure. The rates for oxygen production followed generally similar trends, which peaked varied between ≈ 11 μmol/h to
were partially attributed to the higher amounts of Pb

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≈300 µmol/h. Thus, relatively high rates of both hydrogen and oxygen production are found, and a high quantum yield of ≈5.8% was measured under 254 nm irradiation for total water splitting for Ca0.5Sr0.5Ta4O11 with 0.5 wt % of NiO as a surface co-catalyst.

The photocatalysis of PbTa4O11 for hydrogen and oxygen production was investigated under ultraviolet-visible light irradiation, shown in Figure 13. The PbTa4O11 phase was prepared in high purity by Pb(II) exchange of either Ag2Ta4O11 or the Na2Ta4O11 compounds and shows a symmetry-lowering to a polar space group [35,126]. The PbTa4O11 phase exhibits a relatively high rate for hydrogen production of ≈175 µmol H2·g−1·h−1 when prepared from the Ag2Ta4O11 precursor, and a lower rate of ≈72 µmol H2·g−1·h−1 when prepared from Na2Ta4O11 [126]. These differences were partially attributed to the higher amounts of Pb2+ cations at the surfaces of PbTa4O11 prepared from Ag2Ta4O11. By comparison, both Na2Ta4O11 and Ag2Ta4O11 gave lower rates of ≈10 to ≈35 µmol H2·g−1·h−1 [126]. However, a further comparison of these rates with those for Ca1−xSrxTa4O11 is not possible owing to the different testing conditions and surface co-catalysts. Shown in Figure 13 (left), the photocatalytic rates for O2 production were calculated from the initial rates over 1 h for the PbTa4O11 phase and its precursor, Ag2Ta4O11. The rates of O2 production decreased over time as Ag(s) is deposited onto the particles’ surfaces owing to its reduction as a sacrificial reagent. The oxygen production of the PbTa4O11 phase was found to be ≈84 µmol O2·g−1·h−1, while its precursor Ag2Ta4O11 exhibited a higher rate of ≈165 µmol O2·g−1·h−1 [126]. The PbTa4O11 phase with a 1 wt % platinum co-catalyst exhibited an overall water splitting rate, i.e., for both hydrogen and oxygen production, at a rate of ≈34 µmol gas·g−1·h−1 in deionized water under ultraviolet-visible irradiation [126]. The bandgap size of Ag2Ta4O11 and PbTa4O11 are relatively the same (≈3.8 eV). The symmetry-lowering structural distortions and resulting electronic distortions in the PbTa4O11 phase are associated with its relatively higher photocatalytic rates for hydrogen generation compared to other undistorted single-layered structures (i.e., Na2Ta4O11 and Ag2Ta4O11). Out-of-center distortions of d⁰ transition metal cations have been reported to result in the generation of internal electric fields that can aid in electron/hole charge separation in polar noncentrosymmetric metal oxides, similar to that observed in the PbTa4O11 phase [61,131,132]. The improved electron/hole charge separation due to the internal electric fields can aid in mitigating the effects of recombination and back-reaction, and act to increase photocatalytic hydrogen generation [35].

Figure 13. Photocatalytic oxygen production (µmol O2: left) and hydrogen (µmol H2: right) versus time (h) for the M2Ta4O11, (M = Ag, Ta), and Pb2Ta4O11, Pb3Ta4O13, and PbTa2O6 phases under ultraviolet-visible (λ > 230 nm) irradiation. Adapted with permission from [126]. Copyright 2013 American Chemical Society.
4.3. Double MO\textsubscript{7} Layered Photocatalysts

The double-layered BiTa\textsubscript{2}O\textsubscript{19} phase has exhibited hydrogen production under ultraviolet-visible light irradiation in 20% methanol solution as a suspended particle photocatalyst with a rate of \( \approx 194 \, \mu \text{mol} \cdot \text{H}_2 \cdot \text{g}^{-1} \cdot \text{h}^{-1} \). Similar to PbTa\textsubscript{4}O\textsubscript{11} [126], analogous to the PbTa\textsubscript{4}O\textsubscript{11} phase, the photocatalytic rates for O\textsubscript{2} production were calculated from the initial 1 h rate for BiTa\textsubscript{2}O\textsubscript{19}. The BiTa\textsubscript{2}O\textsubscript{19} phase was found to exhibit a rate of \( \approx 140 \, \mu \text{mol} \cdot \text{O}_2 \cdot \text{g}^{-1} \cdot \text{h}^{-1} \). The BiTa\textsubscript{2}O\textsubscript{19} phase with a 1 wt% platinum co-catalyst exhibited total water splitting in deionized water under ultraviolet-visible irradiation with octahedral layers, Table S5: selected members comprised with single and triple pentagonal bipyramid layers.

Author Contributions:
Nacole King and Jonathan Boltersdorf conceived the concept for the feature article; Nacole King wrote the manuscript, prepared figures, analyzed data; Jonathan Boltersdorf, Paul A. Maggard, Winnie Wong-Ng co-wrote and revised the manuscript.

Conflicts of Interest:
The authors declare no conflict of interest.

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Supplementary Materials: The following are available online at www.mdpi.com/2073-4352/7/5/145/s1, Table S1: Selected members comprised with single pentagonal bipyramid layers alternating with octahedral layers, Table S2: General trends for extended structure comprised with single pentagonal bipyramid layers, Table S3: Selected members comprised with single and double pentagonal bipyramid layers alternating with octahedral layers, Table S4: Selected members comprised with double pentagonal bipyramid layers alternating with octahedral layers, Table S5: selected members comprised with single and triple pentagonal bipyramid layers alternating with octahedral layers.
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