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# O<sub>2</sub> activation by core–shell Ru<sub>13</sub>@Pt<sub>42</sub> particles in comparison with Pt<sub>55</sub> particles: a DFT study†

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The reaction of O<sub>2</sub> with a Ru<sub>13</sub>@Pt<sub>42</sub> core–shell particle consisting of a Ru<sub>13</sub> core and a Pt<sub>42</sub> shell was theoretically investigated in comparison with Pt<sub>55</sub>. The O<sub>2</sub> binding energy with Pt<sub>55</sub> is larger than that with Ru<sub>13</sub>@Pt<sub>42</sub>, and O–O bond cleavage occurs more easily with a smaller activation barrier (*E<sub>a</sub>*) on Pt<sub>55</sub> than on Ru<sub>13</sub>@Pt<sub>42</sub>. Protonation to the Pt<sub>42</sub> surface followed by one-electron reduction leads to the formation of an H atom on the surface with considerable exothermicity. The H atom reacts with the adsorbed O<sub>2</sub> molecule to afford an OOH species with a larger *E<sub>a</sub>* value on Pt<sub>55</sub> than on Ru<sub>13</sub>@Pt<sub>42</sub>. An OOH species is also formed by protonation of the adsorbed O<sub>2</sub> molecule, followed by one-electron reduction, with a large exothermicity in both Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub>. O–OH bond cleavage occurs with a smaller *E<sub>a</sub>* on Pt<sub>55</sub> than on Ru<sub>13</sub>@Pt<sub>42</sub>. The lower reactivity of Ru<sub>13</sub>@Pt<sub>42</sub> than that of Pt<sub>55</sub> on the O–O and O–OH bond cleavages arises from the presence of lower energy in the d-valence band-top and d-band center in Ru<sub>13</sub>@Pt<sub>42</sub> than in Pt<sub>55</sub>. The smaller *E<sub>a</sub>* for OOH formation on Ru<sub>13</sub>@Pt<sub>42</sub> than on Pt<sub>55</sub> arises from weaker Ru<sub>13</sub>@Pt<sub>42</sub>–O<sub>2</sub> and Ru<sub>13</sub>@Pt<sub>42</sub>–H bonds than the Pt<sub>55</sub>–O<sub>2</sub> and Pt<sub>55</sub>–H bonds, respectively. The low-energy d-valence band-top is responsible for the weak Ru<sub>13</sub>@Pt<sub>42</sub>–O and Ru<sub>13</sub>@Pt<sub>42</sub>–OH bonds. Thus, the low-energy d-valence band-top and d-band center are important properties of the Ru<sub>13</sub>@Pt<sub>42</sub> particle.

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## 1. Introduction

The proton exchange membrane fuel cell (PEMFC) is a promising candidate for a clean and sustainable energy source to cope with the growing energy consumption and related environmental concerns. Pt particles are used as a catalyst for the oxygen reduction reaction (ORR) at the PEMFC cathode because of their incomparable catalytic activity and stability in acidic solution, as discussed in recent reviews;<sup>1–6</sup> we cite here reviews

from the last 5 years because many reviews have been published. However, their limited availability on earth and high cost still remain major obstacles for the wide use of PEMFCs. One of the promising methods to solve this problem is the use of core–shell Pt particles (M@Pt) consisting of Pt for the shell and abundant metals (M) for the core, because Pt content can be reduced in the catalyst by the use of a M core but the Pt shell exhibits high catalytic activity and stability in acid solution, as reviewed in the last few years.<sup>7–14</sup> Also, one can expect to improve the catalytic activity of the Pt shell by tuning the electronic structure of the Pt shell with the M core.

Recently, core–shell Ru@Pt particles have been reported as excellent ORR catalysts.<sup>15–20</sup> For instance, Adzic and co-workers demonstrated that the catalytic activity of Ru@Pt could be tuned by varying the Pt shell thickness; Ru@Pt<sub>2ML</sub> with two Pt layers was more active than Ru@Pt<sub>xML</sub> (*x* = 1 and 3).<sup>15</sup> Jackson and coworkers<sup>17,19</sup> and Takimoto and coworkers<sup>18</sup> reported that the catalytic activity of Ru@Pt for the ORR exceeded that of a commercial Pt electrode. Jackson and co-workers also interestingly obtained a volcano plot of the catalytic activity against the O binding energy, suggesting that both overly strong and overly weak O binding with the Pt surface is not good for ORR catalysts.<sup>17</sup> However, the relation between electronic structure and origin of the O binding energy has been unclear.

Many theoretical ORR studies reported so far discuss the relation between electronic structure of the catalyst and ORR activity.<sup>21–39</sup> In particular, the O–O bond activation has been

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† Electronic supplementary information (ESI) available: Possible adsorption structures of 2(O) species and (O)(OH) species (Scheme S1); total energies for Pt<sub>55</sub> and Pt<sub>42</sub>Ru<sub>13</sub> in different possible spin states using PBE-D3 method (Table S1); binding energies (*E<sub>b</sub>*, in eV) for O<sub>2</sub> and OOH species (Table S2); binding energies (*E<sub>b</sub>*, in eV) for O, OH, and H/x-binding species (Table S3); optimized structures of O<sub>2</sub>-binding species (Fig. S1), 2O-binding species (Fig. S2), OOH-binding species (Fig. S3), (O)(OH)-binding species (Fig. S4) and Cartesian coordinates of important optimized species discussed in the main text. The effect of box size for periodic calculation on the Fermi level (*ε<sub>F</sub>*, eV) and the d-valence band top (*ε<sub>VB, top</sub>*, eV) energies (Table S4). d-Valence band top energy (in eV) calculated using several different functionals and basis sets (Table S5). See DOI: 10.1039/d0ra05738j



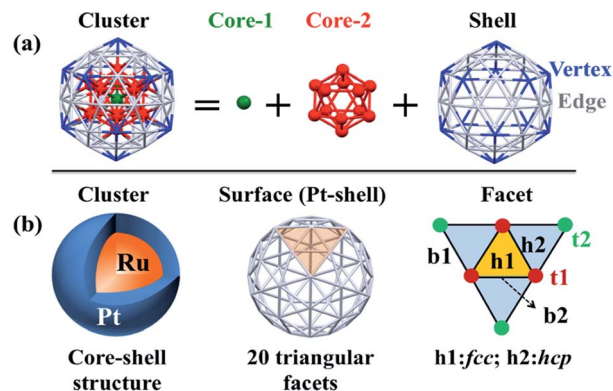
theoretically investigated in many works, as discussed by a recent review<sup>40</sup> and many works even after this review.<sup>41–46</sup> However, the theoretical study of Ru@Pt has been limited so far; for instance, the O and OH-binding energies with Ru<sub>13</sub>@Pt<sub>42</sub> and Pt<sub>55</sub> have been theoretically investigated,<sup>47</sup> but the O–O bond cleavage on Ru@Pt has not been investigated, despite the crucial importance of such O–O bond cleavage in the ORR. Considering that the theoretical study of nanoscale metal particles is still challenging and its development is needed even currently,<sup>48–50</sup> the theoretical study of the O<sub>2</sub> reaction on Ru@Pt and related metal particles is indispensable.

In this work, we theoretically investigated dioxygen (O<sub>2</sub>) adsorption and O–O bond cleavage by the Ru<sub>13</sub>@Pt<sub>42</sub> particle in comparison with the Pt<sub>55</sub> particle using DFT computations. In the O–O bond cleavage, two reaction courses are plausible; in one, the O–O bond of the adsorbed O<sub>2</sub> molecule is cleaved. In the other reaction course, OOH species are formed on the surface, followed by O–OH bond cleavage, because it is likely that the OOH species are easily formed in the presence of excess protons and enough supply of electrons to the electrode. Our purposes here are to explore O<sub>2</sub> adsorption, O–O bond cleavage, OOH formation, and O–OH bond cleavage, compare the reactivity between Ru<sub>13</sub>@Pt<sub>42</sub> and Pt<sub>55</sub>, find important factor(s) determining the reactivities of Ru<sub>13</sub>@Pt<sub>42</sub> and Pt<sub>55</sub>, and present a theoretical understanding of the differences between Ru<sub>13</sub>@Pt<sub>42</sub> and Pt<sub>55</sub>. We believe that the theoretical findings on these issues are valuable for understanding the chemistry of nanometal particles.

## 2. Computational methods and models

Spin-polarized periodic DFT calculations were carried out using the Vienna *Ab initio* Simulation Package (VASP),<sup>51,52</sup> where plane-wave basis sets were employed with an energy cutoff of 400 eV, and the projector-augmented-wave (PAW) pseudopotentials were used to represent core electrons. The PBE-D3 functional was employed in all calculations,<sup>53</sup> where “D3” represents the dispersion correction proposed by Grimme’s group.<sup>54,55</sup> Ru@Pt and Pt particles were placed in a large supercell (25 Å × 25 Å × 25 Å) to ensure enough separation by vacuum. Geometry optimization of equilibrium structure was carried out in gas phase using the energy threshold of 0.0001 eV and force threshold of 0.01 eV Å<sup>-1</sup>. Optimization of transition state (TS) was carried out using the climbing image nudged elastic band (CI-NEB) method with the VASP transition-state tools (VTST),<sup>56,57</sup> in which thresholds for convergence were set to 0.0001 eV for energy and 0.02 eV Å<sup>-1</sup> for force. To evaluate solvent effects, an implicit solvation model, which describes the effect of electrostatic interaction between solute and solvent, was employed as implemented in VASPsol,<sup>58,59</sup> where optimized geometry in gas phase was used.

Though Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub> particles are not very large compared to real catalysts, we employed these particles here as model nanoparticles because we have to optimize many intermediates and transition states. Also, the use of Pt<sub>55</sub> and



Scheme 1 (a) Geometry of the icosahedron (*I<sub>h</sub>*) 55-atom particle and (b) binding sites of the Pt<sub>42</sub> shell of the *I<sub>h</sub>* Ru<sub>13</sub>@Pt<sub>42</sub> core-shell particle.

Ru<sub>13</sub>@Pt<sub>42</sub> particles is not unreasonable, considering that subnanometer-scale metal particles with 55 metal atoms have been employed as model particle in theoretical studies of O<sub>2</sub> adsorption and O–O bond cleavage<sup>46,60–63</sup> and other catalytic reactions.<sup>64–69</sup> The number “55” is a magic number for icosahedral (*I<sub>h</sub>*) and cuboctahedral (*O<sub>h</sub>*) structures. Here, we employed the *I<sub>h</sub>*-like structure because the *I<sub>h</sub>* structure is more stable than *O<sub>h</sub>* in Ru<sub>13</sub>@Pt<sub>42</sub>; the relative stabilities of various spin states and comparison between core-shell and non-core-shell structures have been investigated recently.<sup>47</sup> As shown in Scheme 1, the Pt<sub>42</sub> surface of icosahedral Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub> consists of 20 triangular facets. Each facet has three different types of binding sites: top (t), bridge (b) and hollow (h). Adsorptions at these binding sites are classified as follows: (i) adsorption at the top site is denoted as t1 or t2, in which the adsorbate binds with one Pt atom at the edge or the vertex position. (ii) Adsorption in a bridging manner is denoted as b1 or b2, in which the adsorbate binds with two adjacent Pt atoms at either the edge and vertex positions or two adjacent edge positions. (iii) Adsorption at the hollow site is denoted as h1 or h2, in which the adsorbate binds at either the fcc-like position among three edge-Pt atoms or the hcp-like position among two edge-Pt atoms and one vertex-Pt atom. We explored all these possible adsorption sites.

## 3. Results and discussion

In this work, we firstly discuss O<sub>2</sub> adsorption to Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub>, followed by O–O bond cleavage, OOH formation from the adsorbed O<sub>2</sub> molecule, and O–OH bond cleavage on the Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub> surfaces. Next, we show the differences in reactivity between Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub> in these reactions and elucidate the reasons for the differences. Lastly, we unveil the characteristic feature(s) of Ru<sub>13</sub>@Pt<sub>42</sub> in comparison with Pt<sub>55</sub>.

### 3.1 Dioxygen (O<sub>2</sub>) adsorption

The binding energy  $E_b(\text{O}_2)$  of dioxygen molecule (O<sub>2</sub>) increases (becomes more negative) following the order O<sub>2</sub>-η<sup>1</sup>/h1 < O<sub>2</sub>-η<sup>1</sup>/t1 < O<sub>2</sub>-η<sup>1</sup>/t2 < O<sub>2</sub>-μ<sub>2</sub>/b2 < O<sub>2</sub>-μ<sub>3</sub>/h2 < O<sub>2</sub>-μ<sub>3</sub>/h1 < O<sub>2</sub>-μ<sub>2</sub>/b1 for pure Pt<sub>55</sub> and O<sub>2</sub>-η<sup>1</sup>/h1 < O<sub>2</sub>-μ<sub>2</sub>/b2 < O<sub>2</sub>-η<sup>1</sup>/t1 < O<sub>2</sub>-μ<sub>3</sub>/h2 < O<sub>2</sub>-μ<sub>3</sub>/h1 <



$O_2-\eta^1/t_2 < O_2-\mu_2/b_1$  for  $Ru_{13}@Pt_{42}$ , as shown in Fig. S1 in the ESI,<sup>†</sup> where  $h_1, t_1$  etc., represent the adsorption site shown in Scheme 1 and “A- $\mu_2/x$ ” represents the interaction of adsorbate A with Pt at the x binding site in a  $\mu_2$  manner, hereinafter. Obviously,  $O_2$  is preferentially adsorbed at the  $b_1$  site of both  $Pt_{55}$  and  $Ru_{13}@Pt_{42}$  in a  $\mu_2$ -side-on manner ( $O_2-\mu_2/b_1$ ). This is the most stable  $O_2$  adsorption structure. The coordination number of the surface Pt atom is one of the important factors for stabilization of  $O_2$  adsorption: because the coordination number of the vertex Pt atom is 6 but that of the edge Pt is 7, the  $O_2$  molecule tends to interact with the vertex Pt atom compared to the edge Pt atom. However, the  $O_2$  molecule cannot interact with two vertex Pt atoms because the vertex Pt is far from the neighboring vertex Pt. Thus,  $O_2$  interacts with one vertex Pt and one edge Pt in a bridging manner, as seen by the  $O_2-\mu_2/b_1$  structure.

In the most stable  $O_2-\mu_2/b_1$ -binding species (2), the O–O distance of  $Pt_{55}(O_2)$   $2^{Pt}$  is moderately longer than that of  $Ru_{13}@Pt_{42}(O_2)$   $2^{RuPt}$ , and the Pt–O distance of  $2^{Pt}$  is moderately shorter than that of  $2^{RuPt}$ , as shown in Fig. 1. The  $E_b(O_2-\mu_2/b_1)$  value is  $-1.85$  ( $-1.70$ ) eV for  $Pt_{55}$  and  $-1.07$  ( $-0.95$ ) eV for  $Ru_{13}@Pt_{42}$ , as shown in Fig. 2, where the figures in parentheses represent the binding energy in gas phase. The larger binding energy of the  $O_2$  molecule with  $Pt_{55}$  than with  $Ru_{13}@Pt_{42}$  is consistent with such geometrical features as the shorter Pt–O and longer O–O distances in  $2^{Pt}$  than in  $2^{RuPt}$ . The reasons for the stronger  $O_2$  adsorption with  $Pt_{55}$  than with  $Ru_{13}@Pt_{42}$  are discussed below. It is also noted that solvation by water enhances  $O_2$  binding with these metal particles.

### 3.2 O–O bond cleavage

Starting from  $2^{Pt}$  and  $2^{RuPt}$ , O–O bond cleavage occurs *via* transition states  $TS2/3a^{Pt}$  and  $TS2/3a^{RuPt}$  to afford  $Pt_{55}(O)_2$   $3a^{Pt}$  and  $Ru_{13}@Pt_{42}(O)_2$   $3a^{RuPt}$ , respectively, as shown in Fig. 1. In  $TS2/3a^{Pt}$ , the O–O distance is considerably elongated to 1.835 Å, by 0.451 Å, and the Pt–O distances become shorter to 1.825 Å and 1.845 Å, by 0.144 and 0.152 Å (Fig. 1). In  $TS2/3a^{RuPt}$ , the O–O distance is more elongated to 1.939 Å (by 0.565 Å) than in  $TS2/3a^{Pt}$ , indicating that  $TS2/3a^{Pt}$  is more reactant-like than  $TS2/3a^{RuPt}$ . Consistent with the O–O bond elongation, the Pt–O distances become shorter in  $TS2/3a$ . Though they are almost the same between  $TS2/3a^{Pt}$  and  $TS2/3a^{RuPt}$ , the average of Pt–O distances is moderately shorter in  $3a^{Pt}$  than in  $3a^{RuPt}$ , suggesting the stronger binding energy of the O atom with  $Pt_{55}$  than with  $Ru_{13}@Pt_{42}$ , as discussed below. The activation barrier ( $E_a$ ) relative to 2 is 0.31 (0.33) eV and 0.35 (0.49) eV for  $TS2/3a^{Pt}$  and  $TS2/3a^{RuPt}$ , respectively, and the reaction energy ( $\Delta E$ ) relative to 2 is  $-0.90$  ( $-0.83$ ) eV and  $-0.95$  ( $-0.85$ ) eV, for  $3a^{Pt}$  and  $3a^{RuPt}$ , as shown in Fig. 2, where a negative  $\Delta E$  value represents exothermicity. The smaller  $E_a$  for the O–O bond cleavage on  $Pt_{55}$  than on  $Ru_{13}@Pt_{42}$  is consistent with the more reactant-like  $TS2/3a^{Pt}$  than  $TS2/3a^{RuPt}$ . The moderately smaller  $\Delta E$  in the  $Pt_{55}$  case than in the  $Ru_{13}@Pt_{42}$  case is seemingly inconsistent with the smaller  $E_a$  of the former case than in the latter. But, this is not unreasonable because the  $O_2$  binding energy with  $Pt_{55}$  is overly larger than that with  $Ru_{13}@Pt_{42}$ . It is noted that the  $E_a$  is smaller and  $\Delta E$  is more negative in water than in gas phase, because CT is generally enhanced by polar solvents.

The short Pt–Pt distance of the surface has been discussed as one important factor for high catalytic activity.<sup>70–73</sup> The surface

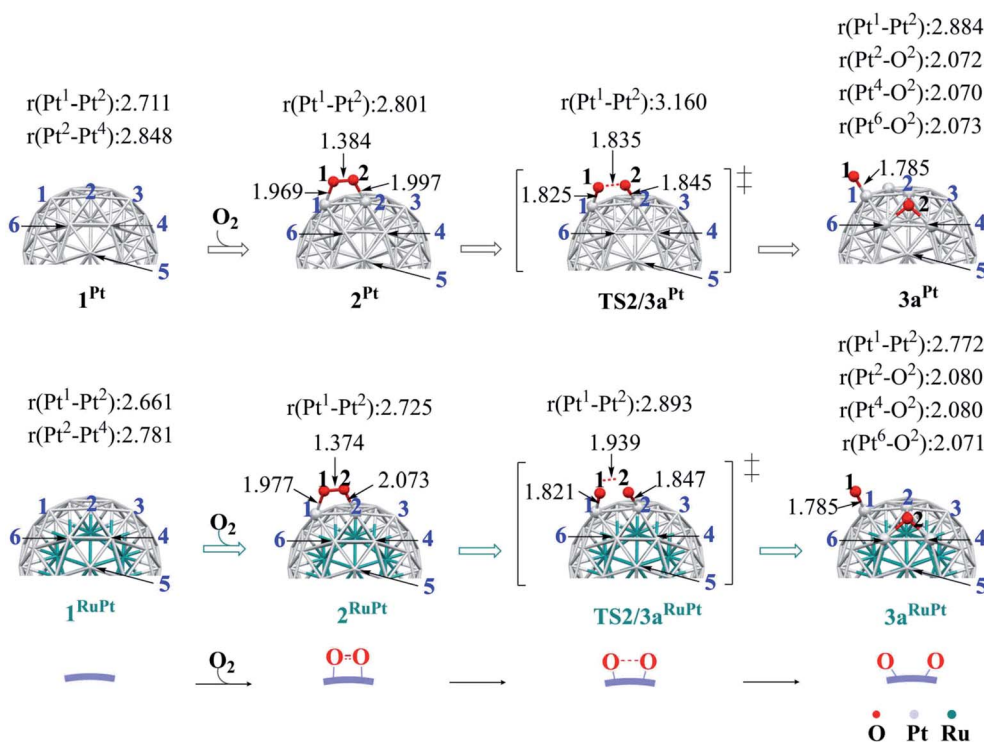


Fig. 1 Geometry changes in  $O_2$  adsorption followed by O–O bond cleavage on  $Pt_{55}$  and  $Ru_{13}@Pt_{42}$ . Values represent bond distance in angstrom.



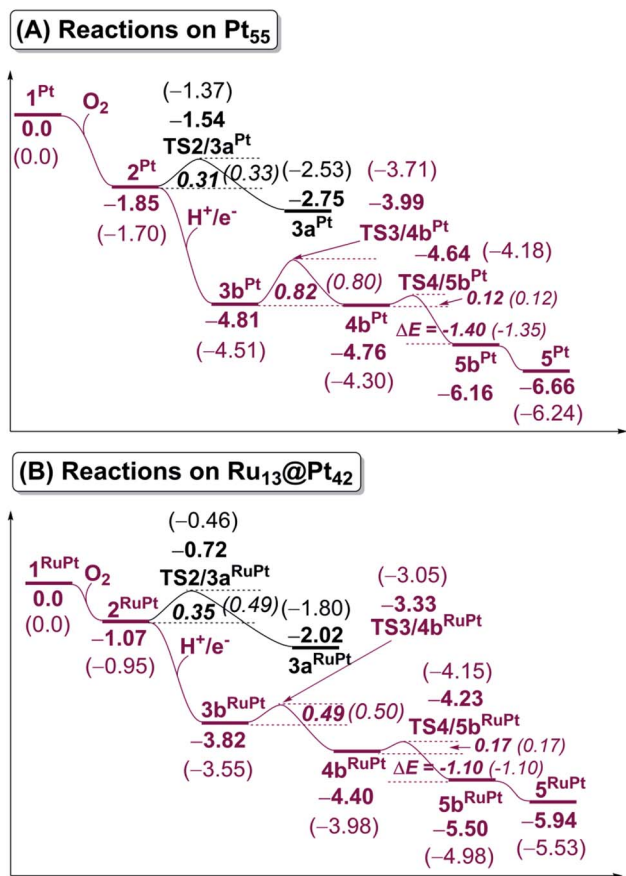


Fig. 2 Energy changes in  $\text{O}_2$  adsorption followed by O–O bond cleavage and OOH formation, followed by O–OH bond cleavage, on (A)  $\text{Pt}_{55}$  and (B)  $\text{Ru}_{13}@Pt_{42}$ . Values represent energy (in eV) relative to  $\text{Pt}_{55}$  or  $\text{Ru}_{13}@Pt_{42}$ . In parentheses are values for energy in gas phase.

$\text{Pt}^1\text{--Pt}^2$  distance becomes longer by the  $\text{O}_2$  adsorption and the O–O bond cleavage in both  $\text{Pt}_{55}$  and  $\text{Ru}_{13}@Pt_{42}$  (Fig. 1), suggesting that the short Pt–Pt distance of the surface is not beneficial to these processes. The other important factor is flexibility of the Pt surface. Actually, the energy destabilization of  $\text{Pt}_{55}$  is much smaller than that of  $\text{Ru}_{13}@Pt_{42}$  when surface Pt–Pt distance is elongated; it is 1.0 kcal mol<sup>-1</sup> in  $\text{Pt}_{55}$  and 7.5 kcal mol<sup>-1</sup> in  $\text{Ru}_{13}@Pt_{42}$  for the Pt–Pt elongation by 0.4 Å, where we employed rather arbitrarily the elongation of 0.4 Å because the Pt–Pt distance is elongated by about 0.3–0.4 Å at  $\text{TS2}/3a^{\text{Pt}}$  of the O–O bond cleavage on  $\text{Pt}_{55}$ . These results suggest that the longer Pt–Pt distance and the larger flexibility of  $\text{Pt}_{55}$  than those of  $\text{Ru}_{13}@Pt_{42}$  are favorable for  $\text{O}_2$  adsorption and O–O bond cleavage; in other words, the discussion that short Pt–Pt distance is good for high catalytic activity is not useful when these processes are rate-determining. In addition, it should be noted that the flexibility of the Pt surface is a crucially important factor besides Pt–Pt distance.

### 3.3 OOH formation followed by O–OH bond cleavage

In ORR, it is likely that the proton is adsorbed easily to the cathode surface because protons exist in excess in solution. Also, electrons are always supplied to the cathode. These

features suggest that H species is formed on the cathode surface. Actually, the reactions of adsorbed H atoms with oxygen-containing species were discussed in recent works,<sup>25,74–76</sup> which indicate they correspond to the Langmuir–Hinshelwood pathway. First, we investigated the formation of OOH species from the adsorbed  $\text{O}_2$  molecule and H atom on the surface; the adsorption sites of OOH and H are shown in Fig. S3, Tables S2 and S3 in the ESI.†

The  $\text{H}^+/\text{e}^-$  addition occurs with significant exothermicity in  $2^{\text{Pt}}$  and  $2^{\text{RuPt}}$  to afford  $\text{Pt}_{55}(\text{O}_2)(\text{H}^1) 3b^{\text{Pt}}$  and  $\text{Ru}_{13}@Pt_{42}(\text{O}_2)(\text{H}^1) 3b^{\text{RuPt}}$ , as shown in Fig. 2, where one-half of  $\Delta E$  of the eq.  $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ , was taken as the energy of  $\text{H}^+/\text{e}^-$ ; it is noted that this step can be tuned experimentally by the cell voltage. In  $3b^{\text{Pt}}$  and  $3b^{\text{RuPt}}$ ,  $\text{H}^1$  takes the position bridging two Pt atoms, as shown in Fig. 3 and 4. Starting from  $3b^{\text{Pt}}$  and  $3b^{\text{RuPt}}$ , the  $\text{H}^1$  reacts with the adsorbed  $\text{O}_2$  via transition states  $\text{TS3}/4b^{\text{Pt}}$  and  $\text{TS3}/4b^{\text{RuPt}}$  to afford an OOH species adsorbed on the Pt surface  $\text{Pt}_{55}(\text{OOH}) 4b^{\text{Pt}}$  and  $\text{Ru}_{13}@Pt_{42}(\text{OOH}) 4b^{\text{RuPt}}$ , respectively (Fig. 3 and 4). In the transition state, the  $\text{H}^1$  is approaching the  $\text{O}^2$ , keeping a bonding interaction with one Pt, and simultaneously, the  $\text{O}^2$  is leaving the  $\text{Pt}_{42}$  surface. Though the Pt– $\text{O}^2$  distance is very long in  $\text{TS3}/4b^{\text{Pt}}$ , the  $\text{O}^2\text{--H}^1$  distance is still long (1.414 Å), and the  $\text{O}^1\text{--O}^2$  distance is moderately elongated. In  $\text{TS3}/4b^{\text{RuPt}}$ , the  $\text{O}^2\text{--H}^1$  distance is much longer (2.006 Å) than that of  $\text{TS3}/4b^{\text{Pt}}$ , suggesting that  $\text{TS3}/4b^{\text{RuPt}}$  is more reactant-like than  $\text{TS3}/4b^{\text{Pt}}$ , in contrast to the more product-like  $\text{TS2}/3a^{\text{RuPt}}$  than  $\text{TS2}/3a^{\text{Pt}}$ . This contrast is reasonable according to the Hammond rule because the O–O bond cleavage occurs with smaller  $E_a$  (relative to  $2^{\text{Pt}}$ ), but the OOH formation occurs with larger  $E_a$  on  $\text{Pt}_{55}$  than on  $\text{Ru}_{13}@Pt_{42}$ . In  $4b^{\text{Pt}}$  and  $4b^{\text{RuPt}}$ , the  $\text{O}^1\text{--O}^2$  distance is 1.451 Å and 1.456 Å, respectively, which is moderately shorter than that (1.471 Å, the PBE-D3-optimized value) of free HOOH. The surface  $\text{Pt}^1\text{--Pt}^2$  distance becomes longer in this reaction, suggesting that the short Pt–Pt distance of the Pt surface is not favorable for this step, either.

We explored here another OOH formation pathway in which adsorbed  $\text{O}_2$  molecule undergoes protonation followed by one-electron reduction, as proposed by several works.<sup>77–79</sup> This reaction corresponds to the Eley–Rideal pathway. We compared the energy change in this pathway with that of the Langmuir–Hinshelwood pathway, as shown in Scheme 2. In the  $\text{Pt}_{55}$  case, the energy changes differ little between these two pathways, suggesting that the OOH formation occurs via both pathways. In  $\text{Ru}_{13}@Pt_{42}$ , the  $\text{H}^+/\text{e}^-$  addition to the adsorbed  $\text{O}_2$  molecule is more exothermic than that to the  $\text{Pt}_{42}$  surface (Scheme 2), indicating that the Eley–Rideal pathway is more favorable than the Langmuir–Hinshelwood pathway from the viewpoint of reaction energy. Also, Scheme 2 strongly suggests that the OOH formation occurs more easily on  $\text{Ru}_{13}@Pt_{42}$  via the Eley–Rideal pathway than that on  $\text{Pt}_{55}$  via both the Langmuir–Hinshelwood and Eley–Rideal pathways. Here, we need to mention that the reaction pathway significantly depends on the coverage of Pt surface by  $\text{O}_2$  molecules; the Langmuir–Hinshelwood pathway preferentially occurs at low coverage. On the other hand, the Eley–Rideal pathway preferentially occurs at high coverage from the viewpoint of possibility, while the Eley–Rideal pathway becomes less easy at high coverage than at low coverage, from



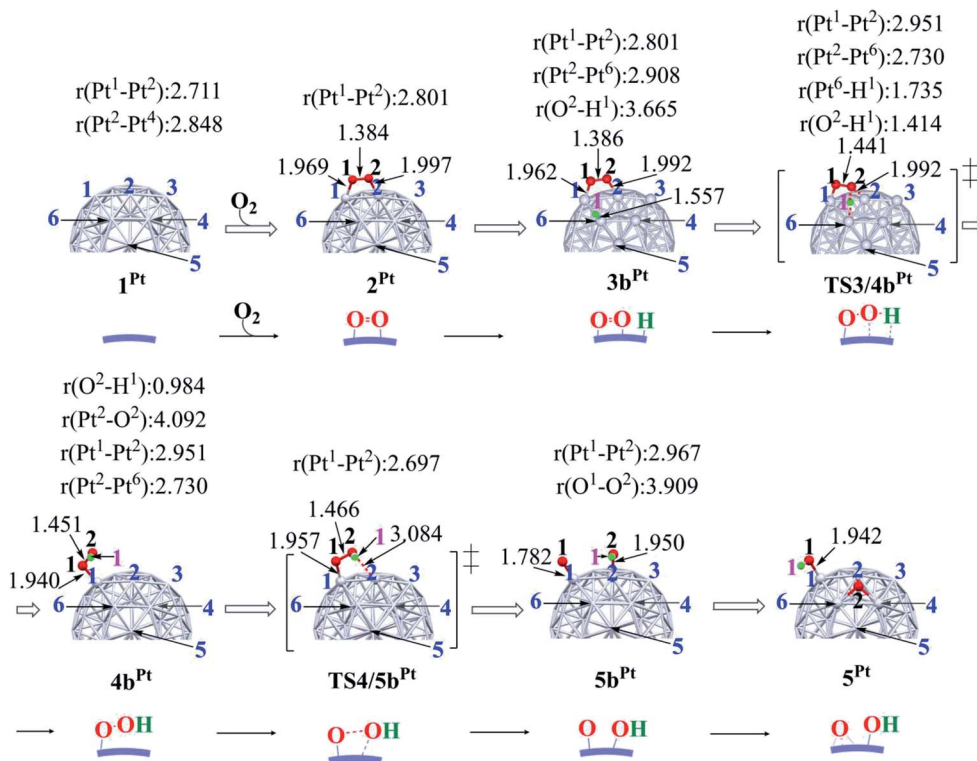


Fig. 3 Geometry changes in OOH formation through the reaction between adsorbed  $\text{O}_2$  molecule and H atom, followed by O–OH bond cleavage on  $\text{Pt}_{55}$  particle. Numbers represent bond distance in angstrom.

the viewpoint of reactivity of adsorbed  $\text{O}_2$  molecule, because the adsorbed  $\text{O}_2$  molecule becomes less negatively charged at high coverage. The mechanism of OOH formation significantly depends on reaction conditions, which must be investigated

carefully in the near future. In both pathways, it is reasonably concluded that OOH formation is an easy process on  $\text{Pt}_{55}$  and  $\text{Ru}_{13}@\text{Pt}_{42}$  particles.

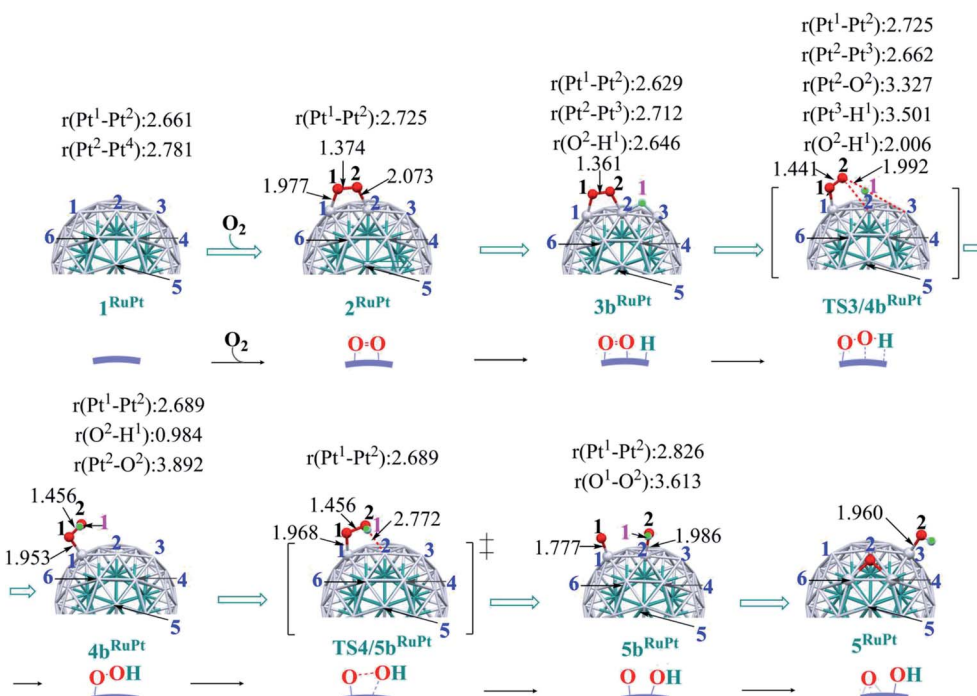
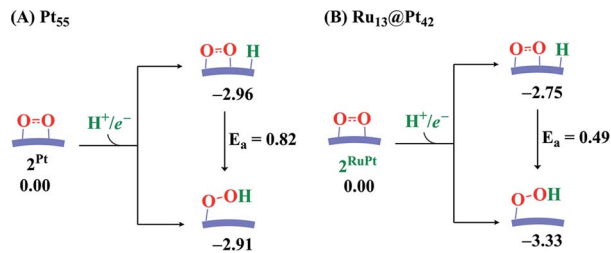


Fig. 4 Geometry changes in OOH formation through the reaction between adsorbed  $\text{O}_2$  molecule and H atom, followed by O–OH bond cleavage on  $\text{Ru}_{13}@\text{Pt}_{42}$  particle. Numbers represent bond distance in angstrom.





Scheme 2 Comparison of energy change between  $\text{H}^+/\text{e}^-$  addition to the  $\text{Pt}_{42}$  surface (the Langmuir–Hinshelwood pathway) and the adsorbed  $\text{O}_2$  molecule (the Eley–Rideal pathway).

Table 1 Changes of the Bader charges in  $\text{O}_2$  adsorption and O–O bond cleavage<sup>a</sup>

	2	TS2/3a	3a
<b>Pt<sub>55</sub></b>			
$\text{O}^1$	–0.305 (–0.273) <sup>b</sup>	–0.496 (–0.434)	–0.610 (–0.509)
$\text{O}^2$	–0.300 (–0.259)	–0.480 (–0.406)	–0.706 (–0.684)
$\text{Pt}_{55}$	+0.605 (+0.532)	+0.976 (+0.840)	+1.316 (1.193)
$\Delta(\text{CT})^c$	0.0 (0.0)	0.371 (0.308)	0.711 (0.661)
<b>Ru<sub>13</sub>@Pt<sub>42</sub></b>			
$\text{O}^1$	–0.326 (–0.289)	–0.519 (–0.445)	–0.640 (–0.536)
$\text{O}^2$	–0.320 (–0.268)	–0.506 (–0.427)	–0.719 (–0.689)
$\text{Ru}_{13}$ @Pt <sub>42</sub>	+0.646 (+0.557)	+1.025 (0.872)	+1.359 (+1.225)
$\Delta(\text{CT})^c$	0.0 (0.0)	0.379 (0.315)	0.713 (0.668)

<sup>a</sup> A positive value represents positive atomic charge, and *vice versa*.

<sup>b</sup> Values in parentheses represent the Bader charge in gas phase. <sup>c</sup> A positive value represents the increase in charge transfer from the metal particle to  $\text{O}^1$  and  $\text{O}^2$  atoms.

Starting from  $4\text{b}^{\text{Pt}}$  and  $4\text{b}^{\text{RuPt}}$ , the O–OH bond is cleaved through transition states  $\text{TS4/5b}^{\text{Pt}}$  and  $\text{TS4/5b}^{\text{RuPt}}$  to afford  $\text{Pt}_{55}(\text{O})(\text{OH}) 5\text{b}^{\text{Pt}}$  and  $\text{Ru}_{13}\text{@Pt}_{42}(\text{O})(\text{OH}) 5\text{b}^{\text{RuPt}}$ , respectively (Fig. 3 and 4). In the transition state, the  $\text{O}^2$  is approaching the  $\text{Pt}^2$ , while the  $\text{Pt}^2\text{–O}^2$  distance is still long, and the  $\text{O}^1\text{–O}^2$  distance changes little from those in  $4\text{b}^{\text{Pt}}$  and  $4\text{b}^{\text{RuPt}}$ , indicating that the transition state is reactant-like. These transition states

differ little from each other except for moderately different  $\text{Pt–O}^2$  and  $\text{O}^1\text{–O}^2$  distances.

The OOH formation from adsorbed  $\text{O}_2$  and H species occurs with a smaller  $E_a$  of 0.49 (0.50) eV on  $\text{Ru}_{13}\text{@Pt}_{42}$  than on  $\text{Pt}_{55}$  ( $E_a = 0.82$  (0.80) eV), as shown in Fig. 2. The smaller  $E_a$  in the reaction on  $\text{Ru}_{13}\text{@Pt}_{42}$  than on  $\text{Pt}_{55}$  is consistent with the more reactant-like  $\text{TS3/4b}^{\text{RuPt}}$  than  $\text{TS3/4b}^{\text{Pt}}$ . The O–OH bond cleavage occurs with a very small  $E_a$  on both  $\text{Pt}_{55}$  ( $E_a = 0.12$  (0.12) eV) and  $\text{Ru}_{13}\text{@Pt}_{42}$  ( $E_a = 0.17$  (~0) eV; Fig. 2). The very small  $E_a$  for the O–OH bond cleavage is consistent with the reactant-like transition states  $\text{TS4/5b}^{\text{Pt}}$  and  $\text{TS4/5b}^{\text{RuPt}}$ . Though the  $E_a$  is moderately smaller in the reaction on  $\text{Pt}_{55}$  than on  $\text{Ru}_{13}\text{@Pt}_{42}$ , the difference is small, and therefore, the geometry of  $\text{TS4/5b}^{\text{Pt}}$  differs little from that of  $\text{TS4/5b}^{\text{RuPt}}$ .

It should be noted that the O–OH bond cleavage occurs with a smaller  $E_a$  than the O–O bond cleavage of the adsorbed  $\text{O}_2$  molecule on both  $\text{Pt}_{55}$  and  $\text{Ru}_{13}\text{@Pt}_{42}$ . This is not surprising because the O–O bond of the adsorbed  $\text{O}_2$  molecule is weaker than the original O–O double bond of free  $\text{O}_2$  molecule, as shown by the elongated O–O bond, but still stronger than the O–O single bond of the OOH species. Another result to be noted is that the  $E_a$  of the OOH formation from adsorbed  $\text{O}_2$  and H species is larger in the  $\text{Pt}_{55}$  case than in the  $\text{Ru}_{13}\text{@Pt}_{42}$  case, but the  $E_a$  for O–O bond cleavage is smaller in the  $\text{Pt}_{55}$  case than in the  $\text{Ru}_{13}\text{@Pt}_{42}$  case. These findings are discussed below in more detail on the basis of electronic structure.

### 3.4 Electronic process in $\text{O}_2$ adsorption, O–O bond cleavage, OOH formation, and O–OH bond cleavage

As shown in Table 1, the  $\text{O}_2$  moiety is negatively charged in  $\text{Pt}_{55}(\text{O}_2) 2^{\text{Pt}}$  and  $\text{Ru}_{13}\text{@Pt}_{42}(\text{O}_2) 2^{\text{RuPt}}$ , because  $\text{O}_2$  adsorption occurs with charge-transfer (CT) from metal particle to  $\text{O}_2$  molecule. This CT is enhanced by the polar solvent (water), as expected. Notably, the  $\text{O}_2$  molecule is more negatively charged in  $2^{\text{RuPt}}$  than in  $2^{\text{Pt}}$ . Seemingly, this result is inconsistent with the larger adsorption energy of the  $\text{O}_2$  molecule with  $\text{Pt}_{55}$  than with  $\text{Ru}_{13}\text{@Pt}_{42}$ , which is discussed below. In the O–O bond cleavage ( $2 \rightarrow 3\text{a}$ ), both  $\text{O}^1$  and  $\text{O}^2$  atoms become much more negatively charged, as well known. A moderately larger CT

Table 2 Changes of the Bader charges in OOH formation from adsorbed  $\text{O}_2$  and H species and O–OH bond cleavage

	3b	TS3/4b	4b	TS4/5b	5b
<b>Pt<sub>55</sub></b>					
$\text{O}^1$	–0.295 (–0.263) <sup>a</sup>	–0.246 (–0.218)	–0.371 (–0.339)	–0.669 (–0.630)	–1.016 (–0.935)
$\text{O}^2$	–0.289 (–0.250)	–0.252 (–0.197)	–0.624 (–0.575)	–0.384 (–0.349)	–0.615 (–0.511)
H	–0.035 (–0.037)	0.198 (0.204)	0.683 (0.609)	0.727 (0.653)	0.676 (0.610)
$\text{Pt}_{55}$	0.619 (0.550)	0.300 (0.211)	0.312 (0.305)	0.326 (0.326)	0.955 (0.836)
<b>Ru<sub>13</sub>@Pt<sub>42</sub></b>					
$\text{O}^1$	–0.312 (–0.261)	–0.260 (–0.235)	–0.401 (–0.367)	–0.945 (–0.671)	–1.182 (–1.138)
$\text{O}^2$	–0.278 (–0.245)	–0.210 (–0.140)	–0.800 (–0.728)	–0.401 (–0.367)	–0.708 (–0.680)
H	0.008 (0.007)	0.069 (0.083)	0.872 (0.782)	1.000 (0.675)	0.822 (0.789)
$\text{Ru}_{13}\text{@Pt}_{42}$	0.582 (0.499)	0.401 (0.292)	0.329 (0.313)	0.346 (0.363)	1.068 (1.029)

<sup>a</sup> Values in parentheses represent the Bader charge in gas phase.



occurs unexpectedly in  $\text{Ru}_{13}@Pt_{42}$  than in  $\text{Pt}_{55}$ , despite the larger  $E_a$  in  $\text{Ru}_{13}@Pt_{42}$  than in  $\text{Pt}_{55}$ .

In the OOH formation *via* the reaction between the adsorbed  $\text{O}_2$  molecule and H atom ( $3b \rightarrow \text{TS3/4b} \rightarrow 4b$ ), the H atom becomes more positively charged, the  $\text{O}^1$  and  $\text{O}^2$  atoms become more negatively charged, and the positive charges of  $\text{Pt}_{55}$  and  $\text{Ru}_{13}@Pt_{42}$  decrease. However, these population changes are not simple. The positive charges of  $\text{Pt}_{55}$  and  $\text{Ru}_{13}@Pt_{42}$  decrease when going from  $3b$  to  $\text{TS3/4b}$  but change little after  $\text{TS3/4b}$ , suggesting that the CT from  $\text{O}_2$  and H to the metal particle mostly occurs in step  $3b \rightarrow \text{TS3/4b}$  but little after  $\text{TS3/4b}$ . In this  $3b \rightarrow \text{TS3/4b}$  step, the H atomic charge becomes considerably positive, but the  $\text{O}^1$  and  $\text{O}^2$  atomic charges moderately change, suggesting that the H atom mainly participates in the CT to the metal particle. As it goes from  $\text{TS3/4b}$  to  $4b$ , the  $\text{O}^1$  becomes more negatively charged, the  $\text{O}^2$  is much more negatively charged, and the H atom becomes much more positively charged. Because the CT occurs little to metal particle in this step ( $\text{TS3/4b} \rightarrow 4b$ ), as discussed above, the change in electron distribution mainly occurs in the  $\text{O}^2\text{H}$  moiety, suggesting that the  $\text{O}^{\delta-}-\text{H}^{\delta+}$  polarization becomes strong in this step. It is noted that the positive charges of  $\text{Pt}_{55}$  and  $\text{Ru}_{13}@Pt_{42}$  change to a lesser extent in this OOH formation than in the  $\text{O}_2$  adsorption, O–O bond cleavage, and O–OH bond cleavage, as shown in Tables 1 and 2. These features suggest that not only CT but also some other factors

play important roles in this OOH formation, as discussed below.

In the  $\text{O}^1-\text{O}^2\text{H}$  bond cleavage ( $4b \rightarrow \text{TS4/5b} \rightarrow 5b$ ), the  $\text{O}^2\text{H}$  group becomes considerably positive at  $\text{TS4/5b}$  and then returns to moderately positive at  $5b$ , while the negative charge of the  $\text{O}^1$  atom and the positive charges of  $\text{Pt}_{55}$  and  $\text{Ru}_{13}@Pt_{42}$  increase when going from  $4b$  to  $5b$ . These population changes indicate that this step occurs with CT from the metal particle to the OOH moiety. These population changes resemble those by the oxidative addition in organometallic chemistry.<sup>80</sup> This is reasonable because the  $\sigma$ -bond cleavage needs CT from the metal to the  $\sigma^*$ -antibonding orbital. Because the CT deeply relates to the electronic structure of the metal particle, the next task is to elucidate the electronic structures of  $\text{Pt}_{55}$  and  $\text{Ru}_{13}@Pt_{42}$ .

### 3.5 Electronic structures of $\text{Pt}_{55}$ and $\text{Ru}_{13}@Pt_{42}$ , M–X bond energy (M = $\text{Pt}_{55}$ and $\text{Ru}_{13}@Pt_{42}$ ; X = H, O, OH, and OOH), and their relation to $\text{O}_2$ activation

The 5d-valence band-top and d-band center of the  $\text{Pt}_{42}$  shell are calculated at higher energy in  $\text{Pt}_{55}$  than in  $\text{Ru}_{13}@Pt_{42}$ , but the d-conduction band-bottom of the  $\text{Pt}_{42}$  shell is calculated at lower energy in  $\text{Pt}_{55}$  than in  $\text{Ru}_{13}@Pt_{42}$  (Fig. 5A and B), where the d-band center was calculated using d-valence bands and the DOS energy was corrected according to Baldereschi and coworkers.<sup>81</sup> We checked if the box size for periodic calculation

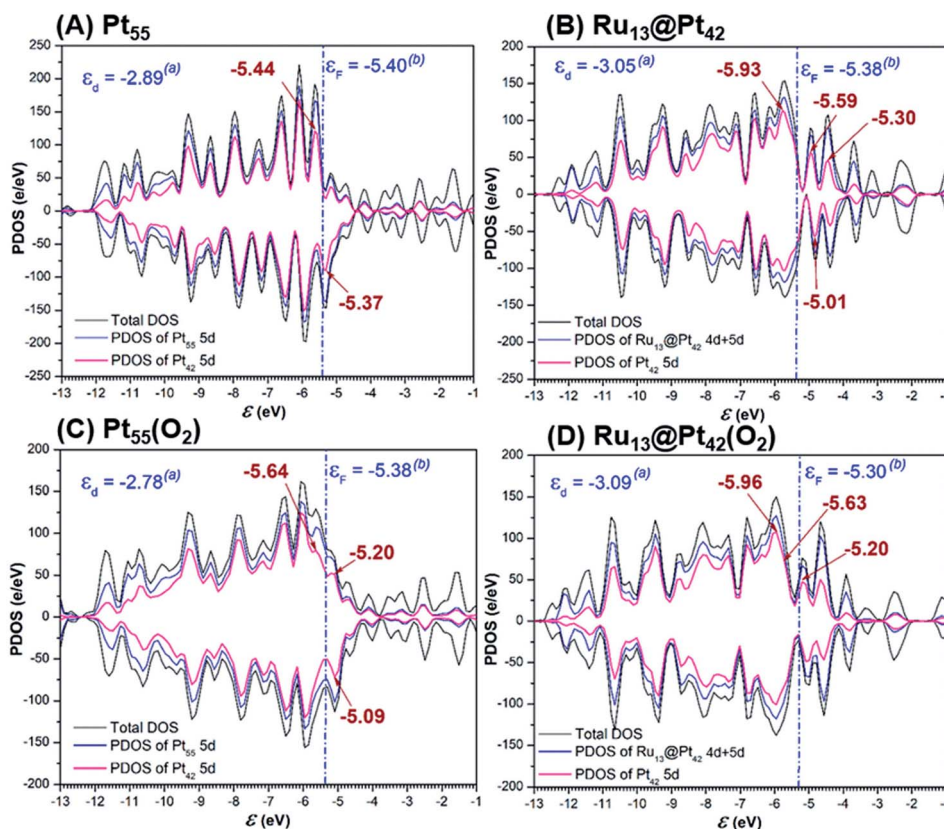


Fig. 5 Density of states (DOS), partial density of states (PDOS) of total d of whole particle and 5d of the  $\text{Pt}_{42}$  shell in (A)  $\text{Pt}_{55}$ , (B)  $\text{Ru}_{13}@Pt_{42}$ , (C)  $\text{Pt}_{55}(\text{O}_2)$ , and (D)  $\text{Ru}_{13}@Pt_{42}(\text{O}_2)$ .



influences little the Fermi level after the correction, as shown in Table S4 in the ESI (page S10<sup>†</sup>), and also we wish to note the 5d-valence band-top energy differs moderately from that of our previous work,<sup>47</sup> because of the different computation method, as explained in the ESI (pages S11 to S12<sup>†</sup>). The O<sub>2</sub> adsorption decreases the density of the d-valence band-top and that of the d-conduction band-bottom in both Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub>, as shown by Fig. 5A, B and C, D, indicating that the d-valence band-top mainly participates in the CT from the Pt<sub>42</sub> shell to the O<sub>2</sub>, and the d-conduction band-bottom mainly participates in the reverse CT from the O<sub>2</sub> to the Pt<sub>42</sub> shell. The higher energy d-valence band-top and the lower energy d-conduction band-bottom induce stronger CT from Pt<sub>55</sub> to O<sub>2</sub> than that from Ru<sub>13</sub>@Pt<sub>42</sub> to O<sub>2</sub> and, also, stronger CT from O<sub>2</sub> to Pt<sub>55</sub> than that from O<sub>2</sub> to Ru<sub>13</sub>@Pt<sub>42</sub>, respectively. Consequently, the binding energy of O<sub>2</sub> molecule with Pt<sub>55</sub> is larger than that with Ru<sub>13</sub>@Pt<sub>42</sub>, as discussed above, but the O<sub>2</sub> moiety is less negatively charged in Pt<sub>55</sub>(O<sub>2</sub>) than in Ru<sub>13</sub>@Pt<sub>42</sub>(O<sub>2</sub>); see Table 1. As shown in Fig. 5C and D, the d-valence band-top and d-band center exist at higher energy in Pt<sub>55</sub>(O<sub>2</sub>) than in Ru<sub>13</sub>@Pt<sub>42</sub>(O<sub>2</sub>). The higher energy d-valence band-top and d-band center in Pt<sub>55</sub>(O<sub>2</sub>) than in Ru<sub>13</sub>@Pt<sub>42</sub>(O<sub>2</sub>) are the origin of the smaller E<sub>a</sub> value of the O–O bond cleavage on Pt<sub>55</sub> than on Ru<sub>13</sub>@Pt<sub>42</sub>. Considering these results, we mainly employ the d-valence band-top and the conduction band-bottom for discussion; these DOSs correspond to HOMO and LUMO in the frontier orbital theory in molecular theory. Also, we used the d-band center for discussion because it is an important property representing the electronic structure of metal particles.

In OOH formation, on the other hand, the charge distribution changes to a lesser extent than in the O–O bond cleavage, as mentioned above, but the E<sub>a</sub> value is considerably different between Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub>. This result suggests that some different factor plays an important role in this reaction. One plausible factor is bond dissociation energy (BDE). In OOH formation, M–O<sub>2</sub> and M–H bonds are broken and M–(OOH) and O–H bonds are formed, where M represents Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub>. Because the O–H bond formation is common in both Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub> cases, we focus here on M–O<sub>2</sub>, M–H, and M–(OOH) bonds. As shown in Scheme 3, the Pt<sub>55</sub>–(O<sub>2</sub>) and Pt<sub>55</sub>–H bonds are stronger than the Ru<sub>13</sub>@Pt<sub>42</sub>–(O<sub>2</sub>) and Ru<sub>13</sub>@Pt<sub>42</sub>–H bonds, respectively, in the reactant side, while the Pt<sub>55</sub>–(OOH) bond is stronger than the Ru<sub>13</sub>@Pt<sub>42</sub>–(OOH) bond in the product side. Therefore, two strong Pt<sub>55</sub>–(O<sub>2</sub>) and Pt<sub>55</sub>–H bonds (the sum of BDEs = 4.48 eV) are converted to one strong Pt<sub>55</sub>–(OOH) bond (BDE = 1.96 eV) in the OOH formation on Pt<sub>55</sub>, where the energy

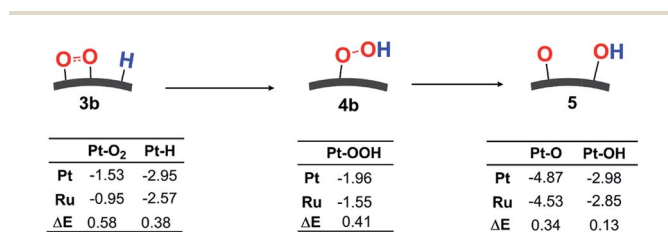
loss is 2.52 eV. In the OOH formation on Ru<sub>13</sub>@Pt<sub>42</sub>, on the other hand, two weaker Ru<sub>13</sub>@Pt<sub>42</sub>–(O<sub>2</sub>) and Ru<sub>13</sub>@Pt<sub>42</sub>–H bonds (the sum of BDEs = 3.52 eV) are converted to one weaker Ru<sub>13</sub>@Pt<sub>42</sub>–(OOH) bond (BDE = 1.55 eV), where the energy loss is 1.71 eV. Apparently, the reaction occurs more easily on Ru<sub>13</sub>@Pt<sub>42</sub> than on Pt<sub>55</sub> because of the smaller energy loss in the reaction by the former than by the latter. These results lead us to the conclusion that the stronger Pt<sub>55</sub>–(O<sub>2</sub>) and Pt<sub>55</sub>–H bonds than Ru<sub>13</sub>@Pt<sub>42</sub>–(O<sub>2</sub>) and Ru<sub>13</sub>@Pt<sub>42</sub>–H bonds, respectively, are reasons why OOH formation from adsorbed O<sub>2</sub> and H needs a larger E<sub>a</sub> on Pt<sub>55</sub> than on Ru<sub>13</sub>@Pt<sub>42</sub>.

Because the O–OH bond cleavage needs CT from the metal particle to the OOH moiety, the higher energy d-valence band-top and d-band center of Pt<sub>55</sub> than those of Ru<sub>13</sub>@Pt<sub>42</sub> are the origin of the smaller E<sub>a</sub> on Pt<sub>55</sub> than on Ru<sub>13</sub>@Pt<sub>42</sub>. In addition, the bond energies relating to this O–OH bond cleavage provide clear understanding of the larger reactivity of Pt<sub>55</sub> than that of Ru<sub>13</sub>@Pt<sub>42</sub>, as follows: the Pt<sub>55</sub>–(OOH) bond is stronger than the Ru<sub>13</sub>@Pt<sub>42</sub>–(OOH) bond, as shown in Scheme 3, and the Pt<sub>55</sub>–O and Pt<sub>55</sub>–(OH) bonds are stronger than the Ru<sub>13</sub>@Pt<sub>42</sub>–O and Ru<sub>13</sub>@Pt<sub>42</sub>–(OH) bonds, respectively. This means that one stronger bond is broken, but two stronger bonds are formed in the O–OH bond cleavage by Pt<sub>55</sub> than by Ru<sub>13</sub>@Pt<sub>42</sub>. Thus, Pt<sub>55</sub> is more reactive for this reaction than Ru<sub>13</sub>@Pt<sub>42</sub>.

As discussed above, the stronger Pt<sub>55</sub>–(O<sub>2</sub>) and Pt<sub>55</sub>–X bonds (X = H, O, OH, and OOH) than the Ru<sub>13</sub>@Pt<sub>42</sub>–(O<sub>2</sub>) and Ru<sub>13</sub>@Pt<sub>42</sub>–X bonds, respectively, are responsible for the reactivity difference in OOH formation and O–OH bond cleavage between Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub>. Also, it has been supposed that the overly strong binding energy of oxygen-containing species with the Pt electrode is unfavorable for ORR activity.<sup>17</sup> Thus, it is of considerable importance to discuss the Pt<sub>55</sub>–X and Ru<sub>13</sub>@Pt<sub>42</sub>–X bond energies and determining factor of these bond energies. Because the Pt<sub>55</sub>–(O<sub>2</sub>) and Ru<sub>13</sub>@Pt<sub>42</sub>–(O<sub>2</sub>) bond energies were discussed above in terms of the d-valence band-top and d-band center energies, we focus here on Pt<sub>55</sub>–X and Ru<sub>13</sub>@Pt<sub>42</sub>–X bond energies. These bonds are neither pure ionic nor pure covalent, but they are understood to be strongly polarized covalent bonds. Polarized covalent bond energy E<sub>cov</sub>(A–B) is approximately represented by eqn (1) on the basis of simple Hückel MO theory,<sup>82</sup>

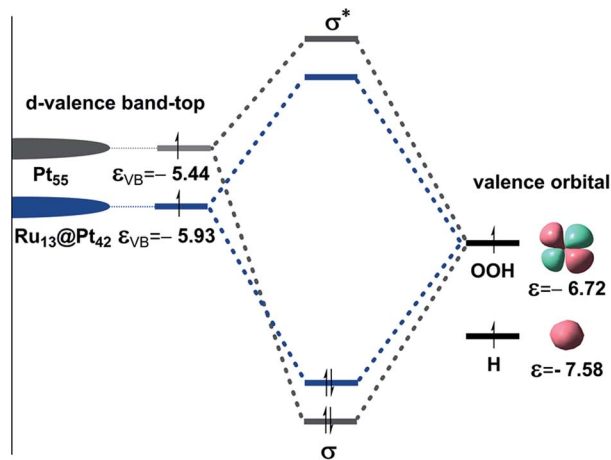
$$E_{\text{cov}}(\text{A} - \text{B}) = \sqrt{(\epsilon_{\text{A}} - \epsilon_{\text{B}})^2 + 4\beta^2}, \quad (1)$$

where  $\epsilon_{\text{A}}$  and  $\epsilon_{\text{B}}$  are the valence orbital energies of A and B, respectively, and  $\beta$  is a resonance integral. This eqn (1) has been employed to discuss the relative bond strengths of various M–R bonds (M = transition metal element and R = alkyl, silyl, etc.).<sup>83–87</sup> Because the M–R bond is understood to be a polarized covalent bond, it is likely that this eqn (1) can be applied to the present discussion. Actually, this equation has recently been applied to the discussion of binding energies of H, O, and OH species with Pd<sub>55</sub> and Rh<sub>55</sub> particles.<sup>66</sup> Eqn (1) indicates that E<sub>cov</sub>(A–B) becomes larger as the energy difference in valence orbital ( $\epsilon_{\text{A}} - \epsilon_{\text{B}}$ ) increases when the  $\beta$  does not differ. Here, the  $\beta$  value is almost the same between Pt<sub>55</sub>–X and Ru<sub>13</sub>@Pt<sub>42</sub>–X because X is bound with the Pt<sub>42</sub> shell in both particles. Thus, the valence



Scheme 3 Bond energy changes (in eV) in OOH formation followed by O–OH bond cleavage on Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub>.





Scheme 4 Schematic representation of orbital interaction between X (X = H or OOH) species and the Pt<sub>42</sub> shell of Pt<sub>55</sub> or Ru<sub>13</sub>@Pt<sub>42</sub> particle.

orbital energies of Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub> play an important role in determining these bond energies. As shown in Scheme 4, the d-valence band-top of the Pt<sub>42</sub> shell is calculated at a higher energy (−5.44 eV) in Pt<sub>55</sub> than in Ru<sub>13</sub>@Pt<sub>42</sub> (−5.93 eV). Because the 2sp valence orbitals of O, OH, and OOH and the 1s valence orbital of H are at lower energy than these d-valence band-tops due to their larger electronegativities, the energy difference between the d-valence band-top of the Pt<sub>42</sub> shell and the valence orbital of X species is larger in Pt<sub>55</sub> than in Ru<sub>13</sub>@Pt<sub>42</sub>, as apparently shown in Scheme 4; for simplicity, O and OH valence orbitals are omitted in this Scheme. Consequently, the Pt<sub>55</sub>–X bond is stronger than the Ru<sub>13</sub>@Pt<sub>42</sub>–X bond.

It should be clearly concluded that the higher energy d valence band-top of Pt<sub>55</sub> than that of Ru<sub>13</sub>@Pt<sub>42</sub> is the origin of the stronger Pt<sub>55</sub>–X bond than the Ru<sub>13</sub>@Pt<sub>42</sub>–X bond. The higher energy d valence band-top of Pt<sub>55</sub> than that of Ru<sub>13</sub>@Pt<sub>42</sub> is also responsible for the larger O<sub>2</sub> adsorption energy to Pt<sub>55</sub> than to Ru<sub>13</sub>@Pt<sub>42</sub> and smaller *E<sub>a</sub>* values of the O–O and O–OH bond cleavages on Pt<sub>55</sub> than on Ru<sub>13</sub>@Pt<sub>42</sub>. Thus, one of the important characteristic features of Ru<sub>13</sub>@Pt<sub>42</sub> is the presence of the d-valence band-top of the Pt<sub>42</sub> shell at lower energy than that of Pt<sub>55</sub>; here we wish to mention that higher energy d-valence band-top relates to higher energy d-band center in many cases, indicating that the d-band center is also useful for discussion.

## 4 Conclusions

O<sub>2</sub> adsorption followed by O–O bond cleavage and OOH formation followed by O–OH bond cleavage on Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub> particles were investigated using DFT computations, and comparisons were made between Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub>. Several important findings are summarized as follows: (i) O<sub>2</sub> is preferentially adsorbed to the vertex Pt and the neighboring edge Pt atoms in a bridging μ<sub>2</sub>-side-on manner. (ii) The O<sub>2</sub> adsorption energy with the Pt<sub>42</sub> shell is larger in Pt<sub>55</sub> than in Ru<sub>13</sub>@Pt<sub>42</sub>. (iii) The O–O bond cleavage occurs with a smaller *E<sub>a</sub>* on Pt<sub>55</sub> than on Ru<sub>13</sub>@Pt<sub>42</sub>. (iv) The OOH formation from the

adsorbed O<sub>2</sub> molecule and H atom occurs with a smaller *E<sub>a</sub>* on Ru<sub>13</sub>@Pt<sub>42</sub> than on Pt<sub>55</sub>. The CT occurs much less in this reaction than in the O–O bond cleavage. The stronger Pt<sub>55</sub>–(O<sub>2</sub>) and Pt<sub>55</sub>–H bonds than the Ru<sub>13</sub>@Pt<sub>42</sub>–(O<sub>2</sub>) and Ru<sub>13</sub>@Pt<sub>42</sub>–H bonds, respectively, are the origin of the larger *E<sub>a</sub>* on Pt<sub>55</sub> than on Ru<sub>13</sub>@Pt<sub>42</sub>. (v) The OOH formation *via* H<sup>+</sup>/e<sup>−</sup> addition to the adsorbed O<sub>2</sub> molecule also occurs easily in Pt<sub>55</sub> similarly to the reaction between adsorbed O<sub>2</sub> molecule and H atom, but more easily in Ru<sub>13</sub>@Pt<sub>42</sub>. And, (vi) the O–OH bond cleavage occurs more easily with much smaller *E<sub>a</sub>* than the O–O bond cleavage of the adsorbed O<sub>2</sub> molecule.

The abovementioned differences between Pt<sub>55</sub> and Ru<sub>13</sub>@Pt<sub>42</sub> are understood on the basis of the PDOS of these metal particles. The d-valence band-top and d-band center of the Pt<sub>42</sub> shell are calculated at higher energy in Pt<sub>55</sub> than in Ru<sub>13</sub>@Pt<sub>42</sub>, but the d-conduction band-bottom of the Pt<sub>42</sub> shell is at lower energy in Pt<sub>55</sub> than in Ru<sub>13</sub>@Pt<sub>42</sub>. Accordingly, the O<sub>2</sub> molecule is adsorbed to Pt<sub>55</sub> more strongly than to Ru<sub>13</sub>@Pt<sub>42</sub>, because the CT from the Pt<sub>42</sub> shell to O<sub>2</sub> and the reverse CT from the O<sub>2</sub> to the Pt<sub>42</sub> shell are more strongly formed with Pt<sub>55</sub> than with Ru<sub>13</sub>@Pt<sub>42</sub>. Because the O–O bond cleavage needs CT from the metal particle to the O<sub>2</sub> moiety, the presence of d-valence band-top at high energy is favorable. Consequently, Pt<sub>55</sub> is more reactive than Ru<sub>13</sub>@Pt<sub>42</sub>. On the other hand, the reactivity for OOH formation from adsorbed O<sub>2</sub> and H depends on the M–(O<sub>2</sub>) and M–H bond energies, as follows: because the Pt<sub>55</sub>–(O<sub>2</sub>) and Pt<sub>55</sub>–H bonds are stronger than the Ru<sub>13</sub>@Pt<sub>42</sub>–(O<sub>2</sub>) and Ru<sub>13</sub>@Pt<sub>42</sub>–H bonds, respectively, OOH formation on Pt<sub>55</sub> needs a larger *E<sub>a</sub>* than that on Ru<sub>13</sub>@Pt<sub>42</sub>.

The binding energy of oxygen-containing species with Pt-based electrode has been discussed as an important factor for ORR activity. Also, the above discussion suggests that the bond energy is an important property for understanding reactions on the Pt-based electrode. We explored the Pt<sub>55</sub>–X (X = H, O, OH, and OOH) and Ru<sub>13</sub>@Pt<sub>42</sub>–X bond energies and found that the Ru<sub>13</sub>@Pt<sub>42</sub>–X bond is weaker than the Pt<sub>55</sub>–X, and the lower energy d-valence band-top of Ru<sub>13</sub>@Pt<sub>42</sub> than that of Pt<sub>55</sub> is the origin of the weaker Ru<sub>13</sub>@Pt<sub>42</sub>–X bond than the Pt<sub>55</sub>–X bond. It is clearly concluded that the lower energy of the d-valence band-top of Ru<sub>13</sub>@Pt<sub>42</sub> than that of Pt<sub>55</sub> is one of the important characteristic features of Ru<sub>13</sub>@Pt<sub>42</sub> in comparison to Pt<sub>55</sub>.

## Conflicts of interest

The authors declare no competing financial interest.

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