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ARTICLE

## Hindered Rotational Physisorption States of H<sub>2</sub> on Ag(111) Surfaces

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We have investigated the physisorption states of H<sub>2</sub> on Ag(111) surfaces. To clarify the accurate adsorption properties of H<sub>2</sub> on Ag(111), we performed first-principles calculations based on spin-polarized density functional theory (DFT) with the semiempirical DFT-D2 method and the newly-developed exchange functional with the non-local correlation functional vdW-DF2 (rev-vdW-DF2). We constructed exhaustive potential energy surfaces, and revealed that non-negligible out-of-plane potential anisotropy with a perpendicular orientation preference exists even for H<sub>2</sub> physisorption on planar Ag(111), as predicted by previous results of resonance-enhanced multiphoton ionization spectroscopy and temperature-programmed desorption experiments. Therefore, the molecular rotational ground states of ortho-H<sub>2</sub> split into two energy levels in the anisotropic potential. The obtained adsorption energy and the number of bound states, including the zero-point energies and rotational energy shift, agree with diffractive and rotationally mediated selective adsorption scattering resonance measurements. The origin of the potential anisotropy on Ag(111) is a combination of the London dispersion interaction and the virtual transition of the metal electron to the unoccupied molecular state.

### 1. Introduction

One of the most important topics in surface science is to understand the behavior of hydrogen molecules on various surfaces. Hydrogen molecules appear in various catalytic reactions. Many experimental studies using high-resolution electron-energy-loss spectroscopy (HREELS),<sup>1,2</sup> molecular beam scattering,<sup>3-8</sup> and temperature-programmed desorption (TPD)<sup>9,10</sup> have attempted to clarify the nature of physisorption states on various surfaces. However, there is little detailed information regarding hydrogen molecule behavior on various surfaces, including charge transfer, diffusion, hindered rotation, and physical bonding. This is because hydrogen molecules are difficult to directly observe because they are relatively inert and have weak molecule-surface interactions, which necessitates quite high energy resolution for unambiguous detection. Even with theoretical studies, it has been difficult to describe the physisorption states accurately. However, recent developments in theoretical techniques<sup>11-14</sup> and computational power allow accurate description of these physisorption systems. In addition, resonant ionization experiments can achieve rotational-state-selective observation of hydrogen molecules on various surfaces.<sup>15,16</sup> Thanks to these developments in theoretical and experimental techniques, we can approach a fuller understanding of hydrogen molecule physisorption states with both theoretical and experimental methods.

Hydrogen also receives attention because of its minimal mass. Hydrogen systems have been investigated as they represent the most distinctive examples which show significant quantum effects. In fact, the quantum effects of hydrogen have been reported in various phenomena, such as tunneling effects in H<sub>2</sub> dissociative adsorption and hydrogen recombination reactions.<sup>17</sup> Furthermore, recent nuclear reaction analyses have directly observed zero-point vibration of hydrogen adsorbed on Si and Pt surfaces.<sup>18</sup> With its importance in catalysis and quantum mechanics, understanding the behavior of hydrogen on the surface is one of the most interesting topics in the condensed matter and physical chemistry fields.

In addition, understanding the rotational states of hydrogen molecules are important for the adsorption properties. Hydrogen molecules on surfaces have hindered rotational states in the anisotropic potential, while free rotational states appear in gas phase. The adsorption energy in hindered rotational states changes from those in free rotational states because of the rotational energy difference between the gas phase and adsorption states. Despite its importance, the potential anisotropy and its molecular axis orientation preference are still controversial for physisorption systems. The conventional theory of the physisorption interaction, which consists of the attractive van der Waals interaction and Pauli repulsion, leads to almost no potential anisotropy or a slight parallel preference toward the surface in the case of inert diatomic molecules on noble surfaces. In contrast, recent theoretical studies with multi-reference configuration interaction have reported that a non-negligible perpendicular preference exists in cases of H<sub>2</sub> on Cu(100)<sup>19</sup> and Ag(100)<sup>20</sup> surfaces. Such a non-negligible perpendicular preference of H<sub>2</sub> on Ag(111) has also been experimentally observed in resonant ionization experiments.<sup>21</sup> Therefore, further studies are required to clarify the orientational

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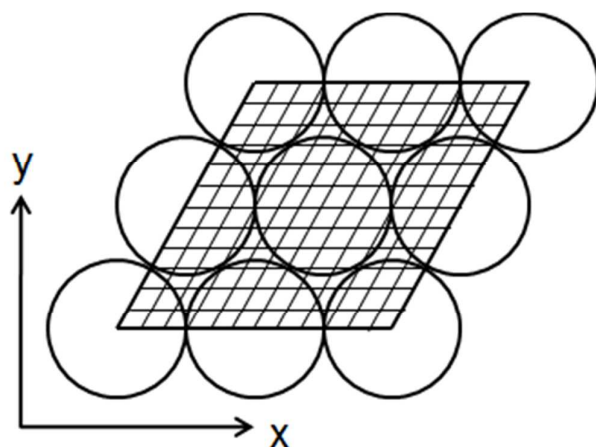


Fig.1 Adsorption sites for potential energy calculations of  $H_2$  on Ag(111) surfaces.

preference and origin of potential anisotropy of hydrogen molecules on noble surfaces.

In this study, we performed a first-principles investigation of  $H_2$  molecular adsorption on Ag(111) surfaces by calculating the relevant potential energy surface (PES). We focused on  $H_2/Ag(111)$  systems to compare our theoretical studies with previous experimental results.<sup>4,21</sup> Although results have been reported for  $H_2$  on high symmetry adsorption sites,<sup>22,23</sup> we performed exhaustive studies with a finer grid of adsorption sites. We also performed quantum mechanical computations of hydrogen nuclei with these PES results to take into account quantum effects and hindered rotation. From the computational results, we obtained accurate physisorption states of  $H_2$  on Ag(111) surfaces.

## 2. Computational Methods

We performed total energy calculations based on spin-polarized DFT, using the generalized gradient approximation with the revised Perdew–Burke–Ernzerhof functional for the exchange–correlation energy,<sup>24</sup> which is implemented in the plane-wave and projector-augmented wave method code, the Vienna Ab-initio Simulation Package (VASP 5.3.3).<sup>25–30</sup> To include the van der Waals interaction, we adopted the semiempirical DFT- D2 method by Grimme.<sup>11</sup> In

addition, we also adopted the second version of van der Waals density functional (vdW-DF2)<sup>31</sup> as the nonlocal correlation functional. We used the newly developed exchange functional by Hamada<sup>14</sup> with vdW-DF2 (rev-vdW-DF2). We applied a 600 eV cutoff to limit the plane-wave basis set without compromising computational accuracy. A  $7 \times 7 \times 1$  Monkhorst–Pack special k-point grid<sup>32</sup> for the first Brillouin zone sampling and a Gaussian smearing model of  $\sigma=0.05$  eV was used. The computed equilibrium gas phase  $H_2$  bond lengths with DFT-D2 and rev-vdW-DF2 are 0.747 and 0.750 Å, respectively. The Ag substrate was simulated as a slab of four fcc  $2 \times 2$  Ag(111) layers. The supercell was constructed with a 15.5 Å vacuum separation between slabs to reduce the interaction between slabs. Our model with a single  $H_2$  molecule on a  $2 \times 2$  Ag(111) surface corresponds to a surface coverage of 0.25 monolayers. The adsorption energy difference between results from simulations using  $2 \times 2$  and  $3 \times 3$  Ag(111) surfaces is 1 meV. Lattice constants for this system were initially set based on the theoretically predicted equilibrium lattice constant of 4.24 Å with DFT-D2 and 4.10 Å with rev-vdW-DF2, obtained using a  $15 \times 15 \times 15$   $k$ -mesh on the primitive one-atom fcc unit cell for bulk Ag. The corresponding lateral and interlayer Ag–Ag distances for DFT-D2 and rev-vdW-DF2 are 3.00 and 2.90 Å, respectively. For reference, the bulk Ag lattice constant obtained with powder diffraction experiments (JCPDS Card No. 04-783) is 4.0862 Å. To determine the optimized Ag(111) surface structure, we performed preliminary calculations in which the top two layers were relaxed until the forces on each atom were smaller than 0.02 eV/Å. The supercell lattice vectors are held fixed during the relaxation. Because the  $H_2$  mass is much less than Ag, we expect a large difference in the time scales associated with surface relaxation and  $H_2$  adsorption dynamics. Thus, as a first step, we neglected surface relaxation.

We investigated the PES for  $H_2$  adsorption and diffusion by calculating the total energy of  $H_2/Ag(111)$  systems as a function of the  $H_2$  center-of-mass positions. In Fig. 1, we show the  $H_2$  adsorption configurations on the  $2 \times 2$  Ag(111) surface. To obtain an accurate PES, we adopted a  $12 \times 12 \times 23$  grid for  $H_2$  adsorption configurations. We considered  $H_2$  adsorbed from 2.6 to 7.0 Å from the surface. The step size for parallel and perpendicular direction to the surface are 0.5 and 0.2 Å, respectively. These step sizes are sufficiently small so that the accuracy of the calculated PES is ensured. All energies are potential energies with respect to the infinitely separated slab and  $H_2$ .

Table 1 Calculated adiabatic potential energies and the most stable  $H_2$  center-of-mass height from the surface  $z$  for  $H_2$  at high-symmetry sites on Ag(111) surfaces. Results of DFT-D2, rev-vdW-DF2, and PBE computations are shown.  $\perp$  and  $\parallel$  means molecular axis perpendicular and parallel to the surfaces, respectively.

		Potential Energy (meV)				$z$ (Å)
		top	bridge	fcc-hollow	hcp-hollow	
DFT-D2	$\perp$	-36.8	-37.7	-38.1	-38.1	3.8
	$\parallel$	-30.9	-30.1	-30.3	-30.3	3.8
rev-vdW-DF2	$\perp$	-39.8	-39.7	-39.7	-39.7	3.6
	$\parallel$	-35.3	-33.8	-33.4	-33.3	3.6
PBE	$\perp$	-10.1	-10.7	-10.8	-10.8	3.8
	$\parallel$	-5.9	-4.9	-5.1	-5.0	3.8

$$E_0 = E_{\text{Ag}(111)} + E_{\text{H}_2}. \quad (1)$$

In these calculations, we set the electric dipole correction layer in the vacuum area to compensate for the electric dipole interactions between repeated slabs.<sup>33</sup> Electron transfer is obtained by taking the difference of the electron density distribution between two configurations – isolated and adsorbed on substrate – using Bader charge analysis.<sup>34</sup>

### 3. Results and Discussion

First, we investigated the potential energy and potential anisotropy of H<sub>2</sub> on four high-symmetry adsorption sites with the H-H axis oriented parallel and perpendicular to the surface. The computed DFT-D2 and rev-vdW-DF2 results are contained in Table 1. For reference, we also show the results with the conventional PBE functional. The four high-symmetry adsorption sites considered are the top site, bridge site, fcc-hollow site, and hcp-hollow site. At first, we point that the most stable H<sub>2</sub> center-of-mass height from the surface  $z$  over all adsorption configurations considered herein is 3.6 and 3.8 Å with DFT-D2 and rev-vdW-DF2, respectively. We found that the most stable H<sub>2</sub> adsorption configuration with DFT-D2 is 3.8 Å above the surface at the fcc-hollow sites with the H<sub>2</sub> bond oriented normal to the surface. Conversely, the most stable H<sub>2</sub> adsorption configuration with rev-vdW-DF2 is 3.6 Å above the surface at the top site normal to the surface. From Table 1, we can also see the corresponding potential energy with DFT-D2 and rev-vdW-DF2 are 38.1 and 39.8 meV, respectively. In comparison with the results with the conventional PBE which does not include the van der Waals interaction accurately, both DFT-D2 and rev-vdW-DF2 can improve the potential energies of molecularly adsorbed H<sub>2</sub> on Ag(111) surfaces. Though DFT-D2 corrected the potential energies by simple semiempirical dispersion terms, DFT-D2 gives similar results with rev-vdW-DF2 which includes the nonlocal correlation functional. The electron transfer from Ag(111) surfaces to H<sub>2</sub> is only 0.01  $e$ , which indicates that H<sub>2</sub> physisorbs on Ag(111) surfaces. The H<sub>2</sub> bond length  $r$  in the most stable H<sub>2</sub> adsorption configuration becomes 0.747 and 0.752 Å with DFT-D2 and rev-vdW-DF2, respectively. In subsequent calculations used to construct the corresponding PES, we fixed the H<sub>2</sub> bond length to these values. From the calculated exhaustive PES, we find that the potential energy difference between each adsorption site on Ag(111) surfaces is smaller than 1.3 meV with DFT-D2 and 0.1 meV with rev-vdW-DF2, which corresponds with the diffusion barrier height for in-plane diffusion on Ag(111). These values are negligibly small, so we conclude that H<sub>2</sub> can diffuse with no barrier on Ag(111) surfaces under finite temperature conditions. In addition, as we mentioned, the adsorption height from the surface  $z$  over all adsorption configurations does not change. From these data, we can say that the adsorption properties do not change during diffusion processes.

We also focused on the hindered rotational states of H<sub>2</sub> on Ag(111) surfaces. From Table 1, we see that the corresponding potential anisotropy at the most stable adsorption heights vary

from 6.7 to 9.2 meV with DFT-D2 and from 4.6 to 6.4 meV with rev-vdW-DF2.

Here, we calculated the molecular rotational wave function in the anisotropic potential. We defined the angle  $\theta$  as the angle between the molecular axis and the surface normal. The  $\varphi$  rotation is not hindered in H<sub>2</sub>/Ag(111) systems, thus, we could define the  $\varphi$  angle as the angle between the molecular axis and an arbitrary reference axis parallel to the surface. In the case of H<sub>2</sub> hindered rotation with out-of-plane potential anisotropy on Ag(111) surfaces, we calculated the wave functions of the hindered rotational states using the following Hamiltonian  $H_R$ .<sup>35</sup>

$$H_R = -\frac{\hbar^2}{2I} \left( \frac{1}{\sin\theta} \frac{\partial}{\partial\theta} \left( \sin\theta \frac{\partial}{\partial\theta} \right) + \frac{1}{\sin^2\theta} \frac{\partial^2}{\partial\varphi^2} \right) + V_a(z) \cos^2\theta, \quad (2)$$

$$V_a(z) = V_{\perp}(z) - V_{\parallel}(z), \quad (3)$$

where  $\hbar$ ,  $I$ , and  $V_a(z)$  are the reduced Planck constant, the reduced mass of H<sub>2</sub>, and the value of the out-of-plane potential anisotropy obtained from our DFT calculations, respectively. We adopted the potential anisotropy at the most stable adsorption configurations. The corresponding potential anisotropy with DFT-D2 and rev-vdW-DF2 are -7.8 and -4.5 meV, respectively. As mentioned, such non-negligible orientation preference of H<sub>2</sub> normal to the surface has also been reported in other non-corrugated surface systems, for example, H<sub>2</sub>/Cu(100),<sup>19</sup> H<sub>2</sub>/Ag(100),<sup>20</sup> and H<sub>2</sub>/Ag(110)<sup>36</sup> systems. We used a spherical harmonics basis to solve the Schrödinger equation with the Hamiltonian for the hindered rotational states  $H_R$ . We considered azimuthal quantum numbers of 0 to 20. From the obtained wave functions, we found that the hybridization of the spherical harmonics basis between different rotational states is less than 0.1%. The H<sub>2</sub> rotational constant,  $\hbar^2/2I$ , which corresponds to 7.3 meV, is large owing to the small mass. Therefore, the rotational energy levels are well discretized, which leads to less hybridization of the rotational motion wave functions. In addition, according to the symmetry requirement for exchange of nuclei, the molecular rotational states of H<sub>2</sub> are strongly coupled with the nuclear spin states. Thus, the molecular rotational states can hybridize only in odd or even azimuthal rotational quantum numbers. From these points, we can assume that the molecular rotational motion wave function can be still treated as spherical harmonics even in the anisotropic adsorption potential on Ag(111) surfaces.

To compare our theoretical results with the previously reported experimental results, we expressed the potential energy with the isotropic and anisotropic terms using a Legendre polynomial. We define the potential energy as follows:

$$V(z, \theta) = V_0(z) + V_2(z) P_2(\cos\theta), \quad (4)$$

$$V_0(z) = V_{\parallel}(z) + \frac{1}{3} V_a(z), \quad (5)$$

$$V_2(z) = \frac{2}{3} V_a(z), \quad (6)$$

Table 2 Calculated adsorption energies of H<sub>2</sub> and D<sub>2</sub> on Ag(111) surfaces. Isotropic terms  $\tilde{V}_0(n)$  and anisotropic terms  $\tilde{V}_2(n)$  are shown. Experimental results of REMPI-TPD<sup>21</sup> and DSA-RMSA<sup>4</sup> are also included for comparison.

vibrational state <i>n</i>	Adsorption Energy (meV)							
	DFT-D2		rev-vdW-DF2		REMPI-TPD <sup>21</sup>		DSA-RMSA <sup>4</sup>	
	$\tilde{V}_0(n)$	$\tilde{V}_2(n)$	$\tilde{V}_0(n)$	$\tilde{V}_2(n)$	$\tilde{V}_0(n)$	$\tilde{V}_2(n)$	$\tilde{V}_0(n)$	
H <sub>2</sub>	0	-28.0	-5.2	-31.0	-3.1	-26	-5	-25.74
	1	-19.7	-4.9	-20.9	-2.7			-16.87
	2	-12.9	-4.4	-12.7	-2.1			-10.11
	3	-7.6	-3.9	-6.6	-1.7			-5.47
	4	-3.6	-3.4	-2.5	-1.3			-2.61
5	-1.1	-2.7	-0.3	-0.8			-1.21	
D <sub>2</sub>	0	-29.2	-5.0	-32.6	-3.1			
	1	-23.2	-4.8	-25.1	-2.8			-20.97
	2	-17.8	-4.5	-18.5	-2.4			-15.25
	3	-13.1	-4.2	-12.9	-2.1			-10.09
	4	-9.1	-3.9	-8.3	-1.8			-6.57
	5	-5.9	-3.5	-4.8	-1.5			-3.97
	6	-3.3	-3.1	-2.2	-1.1			-2.39
7	-1.5	-2.6	-0.6	-0.7			-1.13	

where  $V_0(z)$  and  $V_2(z)$  are the isotropic and anisotropic potential terms, respectively.  $P_2(\cos\theta)$  is the second-order Legendre polynomial. From eq. (4), we can see that one-third of the anisotropic potential contributes to the isotropic potential energy. Thus, the isotropic potential energy, which corresponds to the potential energy of the molecular rotational ground states, includes the adsorption energy shift caused by the potential anisotropy. In addition, because H<sub>2</sub> is the lightest molecule, we take into account the zero-point energy. We assumed that H<sub>2</sub> is bounded only for the perpendicular direction to the surfaces. Therefore, we calculated only the corresponding zero-point energy of the H<sub>2</sub>-Ag(111) vibration along the surface-normal direction. We calculated the adsorption energy  $\tilde{V}_0(n)$ , which includes the zero-point energy and H<sub>2</sub>-Ag(111) vibrational energy, from the Hamiltonian  $H_v$  as follows:

$$\tilde{V}_0(n) = \langle n | H_v | n \rangle, \quad (7)$$

$$H_v = -\frac{\hbar^2}{2m} \nabla^2 + V_0(z), \quad (8)$$

where  $|n\rangle$  and  $m$  are the wave function of  $n$ -th H<sub>2</sub>-Ag(111) vibrational state in the isotropic potential  $V_0(z)$  and total mass of H<sub>2</sub>, respectively. In this paper, we adopted the Morse potential function for the potential energy curve fitting. Thus, we could obtain  $|n\rangle$  and  $\tilde{V}_0(n)$  analytically. We show  $\tilde{V}_0(n)$  with various vibrational states  $n$  in Table 2. We also show results for D<sub>2</sub> to illustrate the isotope effect. Bound states of H<sub>2</sub> and D<sub>2</sub> exist up to  $n=5$  and 7, respectively. The isotropic adsorption energy is equivalent to the adsorption energy of para-H<sub>2</sub> and ortho-D<sub>2</sub> in the rotational ground states. DFT-D2 and rev-vdW-DF2 predict zero-point energies of 4.6 and 5.8 meV, respectively. These values correspond to about 15 % of the isotropic potential energy depth. Thus, we conclude that the zero-point energies cannot be neglected. Focusing on the isotope effect, the zero-point energy of D<sub>2</sub> is 3.3 and 4.2 meV

with DFT-D2 and rev-vdW-DF2, respectively. The zero-point energy ratios between H<sub>2</sub> and D<sub>2</sub> with both methods are slightly smaller than  $\sqrt{2}$ , which is generally considered as the conventional isotope effect. This originates from anharmonicity of the adsorption potential. The activation barriers for in-plane diffusion with the zero-point energy exist at the bridge site with both methods. The corresponding diffusion barrier heights are 0.2 meV with DFT-D2 and 1.1 meV with rev-vdW-DF2. These values are still negligibly small. Therefore, we posit that H<sub>2</sub> can diffuse freely on Ag(111) surfaces under finite temperature conditions. In Table 2, we also show experimental results from resonance enhanced multiphoton ionization spectroscopy with temperature-programmed desorption (REMPI-TPD)<sup>21</sup> and diffractive selective adsorption and rotationally mediated selective adsorption (DSA-RMSA) scattering resonance measurements.<sup>4</sup> The value of  $\tilde{V}_0(n)$  obtained from REMPI-TPD is -26 meV. In addition, we can also compare our DFT results of the H<sub>2</sub>-Ag(111) vibrational excited states with the results of selective adsorption experiments. As we mentioned, the H<sub>2</sub>-Ag(111) vibrational states of H<sub>2</sub> and D<sub>2</sub>, which mean the bound states of H<sub>2</sub>/Ag(111) systems, exist up to  $n=5$  and 7 with both DFT methods, respectively. These values are consistent with the DSA-RMSA results. Each H<sub>2</sub>-Ag(111) vibrational energy is also in good agreement with the corresponding experimental results. From these data, we assess that both DFT-D2 and rev-vdW-DF2 reproduce well the accurate physisorption states.

In anisotropic adsorption potential, the adsorption energy has rotational azimuthal and magnetic quantum number dependence. As we mentioned, the H<sub>2</sub> rotational wave functions on Ag (111) surfaces still remain as spherical harmonics type functions. Thus, we treated the anisotropic term  $V_2(z)P_2(\cos\theta)$  as a perturbation to a free rotor. The contribution of the

Table 3 Calculated adsorption energies of H<sub>2</sub> and D<sub>2</sub> on Ag(111) surfaces with vibrational and rotational ground states.  $J$  and  $m$  are the rotational azimuthal and magnetic quantum numbers, respectively.

	$J$	$m$	Adsorption Energy (meV)	
			DFT-D2	rev-vdW-DF2
H <sub>2</sub>	0	0	-28.0	-31.0
	1	0	-15.5	-17.6
		±1	-12.4	-15.8
D <sub>2</sub>	0	0	-29.2	-32.6
	1	0	-23.9	-26.5
		±1	-20.9	-24.7

anisotropic term to the adsorption energy within first-order perturbation can be calculated as follows:<sup>37</sup>

$$\langle n, J, M | V_2(z) P_2(\cos \theta) | n, J, M \rangle = \frac{3\tilde{V}_2(n)}{2J+3} \left( \frac{J^2 - M^2}{2J-1} - \frac{J}{3} \right), \quad (9)$$

$$\tilde{V}_2(n) = \langle n | V_2(z) | n \rangle, \quad (10)$$

where  $J$  and  $M$  are the rotational azimuthal and magnetic quantum numbers, respectively. The calculated  $\tilde{V}_2(n)$  with DFT-D2 and rev-vdW-DF2 are -5.2 and -3.1 meV, respectively. These values correspond well with the experimental value of -5 meV obtained from REMPI-TPD measurements. For the molecular rotational ground states of para-H<sub>2</sub> ( $J=0$ ,  $m=0$ ), there is no energy shift due to the anisotropic term. Conversely, the molecular rotational ground states of ortho-H<sub>2</sub> ( $J=1$ ,  $m=0$ ,  $\pm 1$ ), which are originally degenerate in the isotropic potential, split into two energy levels. From eq. (9), we can see that the molecular rotational energy shifts with  $J=1$  and  $m=0$  with DFT-D2 and rev-vdW-DF2 are -2.1 and -1.2 meV, and with  $J=1$  and  $m=\pm 1$  are 1.0 and 0.6 meV, respectively. We show the adsorption energies of H<sub>2</sub> and D<sub>2</sub> on Ag(111) surfaces with vibrational and rotational ground states in Table 3. We also show the results with ortho-D<sub>2</sub> ( $J=0$ ,  $m=0$ ) and para-D<sub>2</sub> ( $J=1$ ,  $m=0$ ,  $\pm 1$ ), where corresponding rotational constant  $\hbar^2/2I$  is 3.7 meV. From Table 3, We found that the molecular rotational states with  $J=1$  and  $m=0$ , which are p<sub>z</sub> orbital type wave functions, are the molecular rotational ground states of ortho-H<sub>2</sub> and para-D<sub>2</sub> on Ag(111) surfaces. This is because the H<sub>2</sub> and D<sub>2</sub> prefers to have its molecular axis normal to the surface.

We also discuss the origin of the potential anisotropy on Ag(111) surfaces. In the physisorption states, the van der Waals interaction is dominant. The main part of the attractive van der Waals interaction is the London dispersion interaction, which originates the nonlocal electron-electron correlation effect. In the case of H<sub>2</sub>/noble surface systems, the potential anisotropy caused by the London dispersion interaction, which is obtained from the polarizability along and transverse to the molecular axis, prefers the end-on molecular orientation and is 7 % of the isotropic potential term  $V_0(z)$ .<sup>38</sup> We can then assume that the values of the potential anisotropy from the contribution of the London dispersion interaction at the most stable adsorption

configurations are -2.5 and -2.7 meV with DFT-D2 and rev-vdW-DF2, respectively. However, the obtained the potential anisotropy  $V_a(z)$  at the most stable adsorption configurations are -7.8 and -4.5 meV with DFT-D2 and rev-vdW-DF2, respectively. In addition, repulsion caused by electron overlap between H<sub>2</sub> and the surface generally prefers the diatomic to be oriented parallel to the surface. Thus, the origin of the potential anisotropy cannot be understood only through London dispersion interactions. The other important origin of the potential anisotropy is the interaction of metal surface electron states with H<sub>2</sub> anti-bonding resonances.<sup>36</sup> The energy shift from this resonance interaction  $\delta\epsilon_m^u$  can be described in a second-order perturbation expression as follows;

$$\delta\epsilon_m^u = -\frac{|\langle m | v_{\text{mol}} | u \rangle|^2}{\epsilon_u^0 - \epsilon_m^0}, \quad (11)$$

where  $|m\rangle$  and  $|u\rangle$  are wave functions of the metal surface electron states and H<sub>2</sub> anti-bonding states, respectively.  $\epsilon_m^0$ ,  $\epsilon_u^0$ , and  $v_{\text{mol}}$  are one-electron of the metal surface electron states, H<sub>2</sub> antibonding states, and the attractive potential of H<sub>2</sub> nuclei, respectively. This term gives the energy gain from the virtual transition of the metal electron to the unoccupied molecular state. Here, we calculated  $\delta\epsilon_m^u$  with a simple two-level model. We described the wave functions of the Ag(111) surface electron using a nearly-free two-band model.<sup>39</sup> The wave functions of the H<sub>2</sub> anti-bonding orbitals consist of 1s orbitals of two hydrogen atoms that are orthogonal to each other.<sup>40</sup> From this calculation, we clarified that  $\delta\epsilon_m^u$  has the molecular axis orientation dependence. In the case of H<sub>2</sub>/Ag(111) systems, this resonance interaction gives a perpendicular preference to the surface of about -10 meV with  $z=3.6$  Å and  $r=0.75$  Å. This is because the quite small product of the Fermi wave number of the surface electron and the bond length of H<sub>2</sub> in H<sub>2</sub>/Ag(111) systems cancels the contribution of each H atom to the electron transfer in the parallel orientation.<sup>41</sup> In addition, DFT calculations with conventional PBE, which does not include the London dispersion interaction, indicate a preferred orientation perpendicular to the surface. From these points, even in the physisorption states, not only the London dispersion interaction and repulsion term, but also the resonance interaction is important for the potential anisotropy.

#### 4. Conclusions

In this paper, we investigated the physisorption states of H<sub>2</sub> on Ag(111) surfaces using first-principles calculations based on spin-polarized DFT. To include the van der Waals interaction, we adopted the semiempirical DFT-D2 and van der Waals density functional (rev-vdW-DF2) methods. First, we constructed exhaustive potential energy surfaces of H<sub>2</sub> on Ag(111) surfaces. The calculated adsorption energy of H<sub>2</sub> on Ag(111) surfaces, which includes the zero-point energy, is in good agreement with results of DSA-RMSA experiments. The diffusion barrier of H<sub>2</sub> on Ag(111) surfaces is negligible. We also clarified that the non-negligible out-of-plane potential anisotropy, which has a perpendicular preference to the surface, exists even on non-corrugated Ag(111) surfaces, as has been

observed by REMPI-TPD experiments. We clarified that the molecular rotational ground states of ortho-H<sub>2</sub> split into two energy levels in the anisotropic potential. From these points, we conclude that both semiempirical dispersion interaction terms and non-local correlation functionals can improve upon the description of the physisorption states of H<sub>2</sub>/Ag(111) systems. Finally, we revealed that the origin of the potential anisotropy on Ag(111) surfaces is a combination of the London dispersion interaction and the virtual transition of the metal electron to the unoccupied molecular state.

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