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# Superalkali nature of the $\text{Si}_9\text{M}_5$ ( $\text{M} = \text{Li}, \text{Na}, \text{and K}$ ) Zintl clusters: a theoretical study on electronic structure and dynamic nonlinear optical properties†

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Zintl clusters have attracted widespread attention because of their intriguing bonding and unusual physical properties. We explore the  $\text{Si}_9$  and  $\text{Si}_9\text{M}_5$  (where  $\text{M} = \text{Li}, \text{Na}, \text{and K}$ ) Zintl clusters using the density functional theory combined with other methods. The exothermic nature of the  $\text{Si}_9\text{M}_5$  cluster formation is disclosed, and the interactions of alkali metals with pristine  $\text{Si}_9$  are shown to be noncovalent. The reduced density gradient analysis is performed, in which increased van der Waals interactions are observed with the enlargement of the size of alkali metals. The influence of the implicit solvent model is considered, where the hyperpolarizability ( $\beta_0$ ) in the solvent is found to be about 83 times larger than that in the gas phase for  $\text{Si}_9\text{K}_5$ . The frequency-dependent nonlinear optical (NLO) response for the dc-Kerr effect is observed up to  $1.3 \times 10^{11}$  au, indicating an excellent change in refractive index by an externally applied electric field. In addition, natural bonding orbitals obtained from the second-order perturbation analysis show the charge transfer with the donor–acceptor orbitals. Electron localization function and localized orbital locator analyses are also performed to better understand the bonding electrons in designed clusters. The studied Zintl clusters demonstrate the superalkali character in addition to their remarkable optical and nonlinear optical properties.

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## 1 Introduction

Designing novel materials with excellent nonlinear optical (NLO) properties has gained significant interest in the last three decades because of their potential applications in various optical and electrical devices.<sup>1–4</sup> As a prerequisite for nonlinear media, materials must be in noncentrosymmetric structures in order to generate effective non-equilibrium spontaneous electron polarization.<sup>5</sup> Literature reveals that not only the hyperpolarizability but also third-rank NLO responses are equally contributing to achieving modern-day optical technologies such

as optical data storage, optical communication, biological imaging, and signal processing.<sup>6–8</sup> For obtaining exceptional NLO features in molecule systems, numerous techniques have been proposed in the literature, such as utilizing the push–pull mechanism,<sup>9</sup> creating the metal–organic framework,<sup>10</sup> introducing diradical character in the conjugated system,<sup>11</sup> designing multidecker sandwich complexes,<sup>12</sup> and induction of excess electrons in molecules.<sup>13</sup>

Since Dye *et al.* carried out an innovative study of excess electron compounds based on cryptand and crown ether,<sup>14</sup> the significant impact of excess electrons on the hyperpolarizability of molecules and clusters gives rise to new prospects for designing and exploring high-performance NLO materials.<sup>15</sup> Almost two decades ago, Li *et al.* first reported the NLO properties of systems with excess electrons and uncovered the pivotal role of loosely bound electrons in amplifying the first hyperpolarizability ( $\beta_0$ ).<sup>16</sup> Up until now, several molecular systems that exhibited the nature of excess electrons have been designed for optical and optoelectronic applications.<sup>17–19</sup> The role of excess electrons in triggering the hyperpolarizability response has been revealed, and these electrons remarkably reduce excitation energies (transition energies), which would result in rapid excitation of electrons to virtual orbitals.<sup>13</sup> The theory is evident that excitation energy ( $\Delta E$ ) has an inverse

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relation with  $\beta_0$  of molecules from the conventional two-level model.<sup>20</sup>

In the development of excess electron molecules, alkali-like superatom clusters are frontline and emerging as building blocks for constructing the three-dimensional periodic table.<sup>21,22</sup> As an intriguing subset of the superatom family, superalkalis has characteristics similar to the alkali metals.<sup>23</sup> Generally, the superalkali nature of clusters is usually described by their reduced ionization potential (IPs) as compared to alkali metals (3.9–5.4 eV).<sup>24</sup> A series of experiments on molecular species as superalkali clusters were reported such as  $\text{XLi}_2$  ( $\text{X} = \text{F}, \text{Cl}, \text{Br}, \text{and I}$ ),<sup>25</sup>  $\text{OM}_3$  ( $\text{M} = \text{Li}, \text{Na}, \text{and K}$ ),<sup>26</sup>  $\text{NLi}_4$ ,<sup>27</sup>  $\text{BLi}_n$  ( $n = 1-7$ )<sup>28</sup> and a variety of superalkali cluster were designed theoretically, such as bimetallic, uninuclear, and polynuclear ones.<sup>29-31</sup> Very recently, Ayub *et al.* reported the superalkali ( $\text{Li}_3\text{O}$ ) and alkali metals doped crown ether complexes  $\text{Li}_3\text{O}[12\text{-crown-4}]$  for optoelectronic properties,<sup>32</sup> where dynamic third-order Kerr effect increased up to  $2.75 \times 10^{12}$  au. The alkali anion (superalkalide nature) and reduced excitation energy were observed for these complexes. Likewise, a class of bimetallic superalkali clusters was investigated for dynamic NLO properties, where a substantial hyperpolarizability value was assigned to the presence of excess electrons. Likewise,  $\text{M}_2\text{OCN}$  and oxacarbon ( $\text{C}_3\text{X}_3\text{Y}_3$ ) superalkali clusters show tremendously enhanced NLO properties owing to the nature of excess electrons.<sup>33-35</sup> The exceptional charge transfer from superalkali clusters to complexant and their superior reducing properties make them ideal candidates for constructing high-performance molecular NLO materials. The prospective applications can be seen in the synthesis of unusual charge-transfer salts (supersalts), cluster-assembled nanomaterial in the reduction of carbon dioxide as storage materials, and noble-gas-trapping hosts.<sup>23,36</sup>

Since the discovery by Eduard Zintl in 1930, groups 14, 15, and Zintl superatom clusters have drawn much curiosity and have been considered as potential antecedents for material design.<sup>37</sup> It is also suggested that Zintl clusters can be connected *via* transition metal, alkali metal, non-metal atoms, or organic linkers to construct nanonetworks or materials with novel and tunable electronic properties. As far as we know, the study of the Zintl clusters based on Si-atom is very limited. Very recently, Zintl clusters  $[\text{Si}_9\text{R}_2]^{2-}$  and  $[\text{Si}_9\text{R}_3]^-$  [ $\text{R} = \text{SiH}(\text{tBu})_2, \text{SnCy}_3, \text{Si}(\text{TMS})_3$ ] have been synthesized experimentally.<sup>38</sup> Later, Sinha *et al.*<sup>39</sup> investigated the superhalogens nature of  $\text{Si}_9\text{R}_3$  clusters theoretically, in which Zintl anion ( $\text{Si}_9^{2-}$ ) is functionalized with electronegative ligands such as  $-\text{CF}_3$ ,  $-\text{CN}$ ,  $-\text{BO}$ , and  $-\text{NO}_2$ .

The present study mainly focuses on exploring superalkali and excess electron nature through noncovalent interactions of 1st group metals with pure  $\text{Si}_9$  cluster. In the designed clusters  $\text{Si}_9\text{M}_5$  ( $\text{M} = \text{Li}, \text{Na}, \text{and K}$ ), loosely bound alkali electrons are actively transferring charge and are crucial for activating the NLO of responses. In addition, van der Waals (vdW) interaction is very important in numerous chemical processes,<sup>40-44</sup> and its role in the formation and properties of clusters is of great interest. The present work also uncovers the nature and magnitude of vdW forces in tuning the optoelectronic properties in the designed clusters. This paper is organized as follows. The computational details are given in Section 2. The results are

presented and discussed in Section 3. Finally, a brief conclusion is given in Section 4.

## 2 Methods and computational details

For the designed  $\text{Si}_9\text{M}_5$  ( $\text{M} = \text{Li}, \text{Na}, \text{and K}$ ) clusters, *ab initio* molecular dynamics (AIMD) simulations were performed using the ORCA 5.0 package,<sup>45</sup> and other quantum chemical simulations were performed by Gaussian 16.<sup>46</sup> To make the results reliable, the method and basis set should be chosen carefully.<sup>47-51</sup> The initial-guess structure for the pure  $\text{Si}_9$  cluster is obtained from literature, and the present geometry of  $\text{Si}_9$  is in good consistent with those reported in literature,<sup>52</sup> which justifies that it is a global minimum. As for  $\text{Si}_9\text{M}_5$ , considering that the geometry of  $\text{Si}_9$  is not altered or distorted greatly during the adsorption of alkali metals by vdW interactions, we performed initial optimization in dozens of designed initial-guess structures, and then find the structure that has lowest potential energy. Our AIMD calculations justify that the present structures are the global minima, and it should be noted that a global optimization procedure<sup>53-56</sup> would have better efficiency in searching global minimum on a potential energy surface (PES). Initial optimization is carried out using the B3LYP/6-31G level of theory. The stable molecular geometries were reoptimized, and the final optimization and the following entire electronic and NLO properties were computed using the  $\omega\text{b97xd/def2-qzvp}$  level. Infrared and Raman frequencies are also computed using the same method. The thermodynamic stability of studied clusters was validated *via* binding energy (cohesive energy) per atom, which can be expressed as:

$$E_B = [E_{\text{Si}_9\text{M}_5} - E(X)]/n \quad (1)$$

where  $E_{\text{Si}_9\text{M}_5}$  is the total electronic energy of the cluster,  $E(X)$  is the sum of the energy of isolated atoms (silicon and alkali metals) in a cluster, and  $n$  is the total number of atoms. To investigate geometry fluctuation and thermal stability of the pristine  $\text{Si}_9$  and  $\text{Si}_9\text{M}_5$ , AIMD simulations at the B3LYP-D3/def2-SVP were performed, with 3500 geometries calculated at 300 K with a time step of 1.0 femtoseconds.<sup>57</sup>

Superalkali nature and reactivity were identified and illustrated through global reactivity parameters. Frontier molecular orbital (FMO) and natural population analysis (NPA) were chosen to get the orbital energies and charge transfer in  $\text{Si}_9\text{M}_5$ . A second-order Fock matrix study using the NBO tool was considered for the donor-acceptor atoms and type of electronic transition. The reactivity and topological properties were further examined using molecular electrostatic potential (MESP). The bonding nature of alkali metals to Si-atoms and vdW interactions were outlined through the quantum theory of atom in molecules (QTAIM) and noncovalent interaction (NCI) study. Additionally, the electron localization function (ELF) and localized orbital locator (LOL) analyses were performed to determine the nature of bonding (localized) and delocalized (lone pair) electrons within clusters. The chemical potential ( $\mu$ ) and electronegativity can be calculated using the equation:



$$\mu = -(\text{IP} + \text{EA})/2 \quad (2)$$

where IP and EA are ionization potential and electron affinity, respectively, which are obtained from Koopman's theorem. The negative of chemical potential is considered as electronegativity of clusters.

For the optical and NLO characteristics, dipole moment ( $\mu_o$ ), polarizability ( $\alpha_o$ ), first-order hyperpolarizability ( $\beta_o$ ), and static second hyperpolarizability ( $\gamma_o$ ) were calculated with the help of the following equations:

$$\mu_o = (\mu_x^2 + \mu_y^2 + \mu_z^2)^{1/2} \quad (3)$$

$$\alpha_o = 1/3(\alpha_{xx} + \alpha_{yy} + \alpha_{zz}) \quad (4)$$

$$\beta_o = \sqrt{\beta_x^2 + \beta_y^2 + \beta_z^2} \quad (5)$$

where

$$\beta_x = \beta_{xxx} + \beta_{xyy} + \beta_{xzz}, \beta_y = \beta_{yyy} + \beta_{yzz} + \beta_{yxx} \text{ and } \beta_z = \beta_{zzz} + \beta_{zxx} + \beta_{zyy}, \quad (6)$$

$$\langle \gamma \rangle = 1/5(\gamma_{xxxx} + \gamma_{yyyy} + \gamma_{zzzz} + \gamma_{xxyy} + \gamma_{xxzz} + \gamma_{yyxx} + \gamma_{yyzz} + \gamma_{zzxx}) \quad (7)$$

here,  $\beta_{ijk}$  ( $i, j, k = \{x, y, z\}$ ) is the tensor component of  $\beta_o$ ,  $\gamma_{ijkl}$  ( $i, j, k, l = \{x, y, z\}$ ) is the tensor component of second hyperpolarizability ( $\gamma_o$ ). The second hyperpolarizability ( $\gamma$ ) is fourth rank tensor of  $3 \times 3 \times 3 \times 3$  form which exhibit both static and dynamic nature.

Furthermore, the density of states (DOS) spectral study was carried out to get a comprehensible picture of orbital energies and HOMO-LUMO gaps for clusters using the GaussSum software.<sup>58</sup> TD-DFT study was also carried out by considering forty excited states for singlet and triplet. In this analysis, we calculated various excited state parameters and absorbance of clusters. Scattering hyperpolarizability ( $\beta_{\text{HRS}}$ ) was calculated by using the following relation:

$$\beta_{\text{HRS}}(-2\omega; \omega, \omega) = \sqrt{\langle \beta_{zzz}^2 \rangle + \langle \beta_{zxx}^2 \rangle} \quad (8)$$

where  $\langle \beta_{zzz}^2 \rangle$  and  $\langle \beta_{zxx}^2 \rangle$  are the average of orientational ( $\beta$ ) tensor. While the related depolarization ratio for these superalkali clusters (DR) ratio is also given by:

$$\text{DR} = \langle \beta_{zzz}^2 \rangle / \langle \beta_{zxx}^2 \rangle \quad (9)$$

Moreover, the frequency-dependent (dynamic) nonlinear optical parameters were calculated at the 532 and 1064 nm wavelength. The frequency-dependent  $\beta(-\omega; \omega, 0)$  electro-optic Pockel's effect (EOPE) and  $\beta(-2\omega; \omega, \omega)$  electric field-induced second harmonic generation (ESHG) were calculated. The second hyperpolarizability  $\gamma(\omega)$ , dc-Kerr  $\gamma_{\text{dc-Kerr}}(\omega) = \gamma(-\omega; \omega, 0, 0)$  and second harmonic generation  $\gamma_{\text{ESHG}}(\omega) = \gamma(-2\omega; \omega, \omega, 0)$  were also obtained.

In the NBO analysis, donor ( $i$ )-acceptor ( $j$ ) interactions between filled Lewis orbitals and empty non-Lewis orbitals are explored to further enrich the structural-reactivity relationship. For this purpose, a second-order Fock matrix is considered,

where only high stabilization energy ( $E_{(2)}$ ) interactions are considered:<sup>59</sup>

$$E_{(2)} = \Delta E_{ij} = q_i \frac{(F(i, j))^2}{\epsilon_j - \epsilon_i} \quad (10)$$

where  $F(i, j)$  is the NBO Fock matrix element for non-diagonal orbitals,  $q_i$  denotes the donor orbit occupancy rate,  $i$  denotes the diagonal element, and  $j$  represents the non-diagonal element of the matrix.

## 3 Results and discussion

### 3.1 Electronic structure and thermodynamic stability

We begin the neutral Zintl cluster ( $\text{Si}_9$ ) geometry as core, which is decorated with alkali metals ( $M = \text{Li}, \text{Na}, \text{ and } \text{K}$ ) for creating Zintl-superatom clusters with superalkali nature. The pure  $\text{Si}_9$  cluster shown in Fig. 1 has a bicapped pentagonal pyramid geometry, whereas the  $\text{Si}_9^{2-}$  and  $\text{Si}_9^{4-}$  clusters have different geometries (see Fig. S1†). The geometries of  $\text{Si}_9\text{M}_5$  are consistent with previously reported clusters<sup>60</sup> which are also trigonal prismatic, and the obtained bond distances are given in Fig. 1 and Table S2 of the ESI.† In  $\text{Si}_9\text{Li}_5$ , the interaction distance between Si and alkali metals ranged from 2.77 to 2.92 Å, while for  $\text{Si}_9\text{Na}_5$  increased up to 3.02 Å. The highest interaction distance (3.79 Å) is observed between the Si-K bonds in the  $\text{Si}_9\text{K}_5$  cluster. The calculated results at the  $\omega\text{b97xd/def2-qzvp}$  level are given in Table 1. As seen, the binding energy per atom ( $E_B$ ) is higher for pure  $\text{Si}_9$  cluster as compared to  $\text{Si}_9\text{M}_5$ . A monotonic reduction  $E_B$  for  $\text{Si}_9\text{M}_5$  with the increased alkali metal size and interaction distance ( $d_{\text{Si-M}}$ ) are observed. The binding energies at the  $\omega\text{b97xd/def2-qzvp}$  level are -4.42, -3.66, -4.25, and -3.53 eV for  $\text{Si}_9$ ,  $\text{Si}_9\text{Li}_5$ ,  $\text{Si}_9\text{Na}_5$ , and  $\text{Si}_9\text{K}_5$ , respectively. These values are higher than those reported for the  $\text{Ge}_9\text{AM}_5$  and  $\text{P}_7\text{M}_2$  ( $M = \text{Li}, \text{Na}, \text{ and } \text{K}$ ) clusters,<sup>60,61</sup> indicating that the present Si-based Zintl clusters have better thermodynamic stabilities. The computed mean dipole moment ( $\mu_o$ )

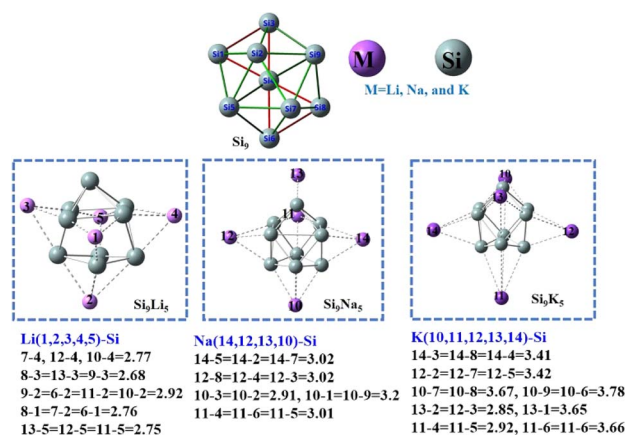


Fig. 1 The optimized structure of the  $\text{Si}_9$  and  $\text{Si}_9\text{M}_5$  clusters at the  $\omega\text{b97xd/def2-qzvp}$  level of theory. The Si atom is in green and the alkali metal atoms are in pink. The important interaction distances (in Å) of alkali metals with silicon are given below the geometries. The corresponding Cartesian coordinates are given in Table S1.†



**Table 1** The calculated global reactivity descriptors of the Si<sub>9</sub> and Si<sub>9</sub>M<sub>5</sub> (M = Li, Na, and K) clusters

Properties	Si <sub>9</sub>	Si <sub>9</sub> Li <sub>5</sub>	Si <sub>9</sub> Na <sub>5</sub>	Si <sub>9</sub> K <sub>5</sub>
μ <sub>o</sub> (D)	0.73	2.61	4.46	20.42
NBO on Si (e)	−0.17/0.11	−0.60	−0.52	−0.48
NBO charges (e)	—	0.87	0.89	0.95
Ionization potential (eV)	7.58	4.35	4.10	2.41
Electron affinity (eV)	1.75	0.18	0.06	0.03
E <sub>HOMO</sub> (eV)	−7.58	−4.35	−4.10	−2.41
E <sub>LUMO</sub> (eV)	−1.75	−0.18	−0.06	−0.03
E <sub>g</sub> (eV)	5.83	4.17	4.06	2.37
Chemical potential (eV)	−4.66	−2.27	−2.08	−1.22
Hardness (eV)	2.92	2.09	2.02	1.19
Softness (eV)	0.34	0.48	0.49	0.84
Electronegativity (χ)	4.66	2.27	2.08	1.22
Electrophilicity index (eV)	3.73	1.23	1.07	0.63
E <sub>b</sub> (eV)	−4.42	−3.66	4.25	−3.54

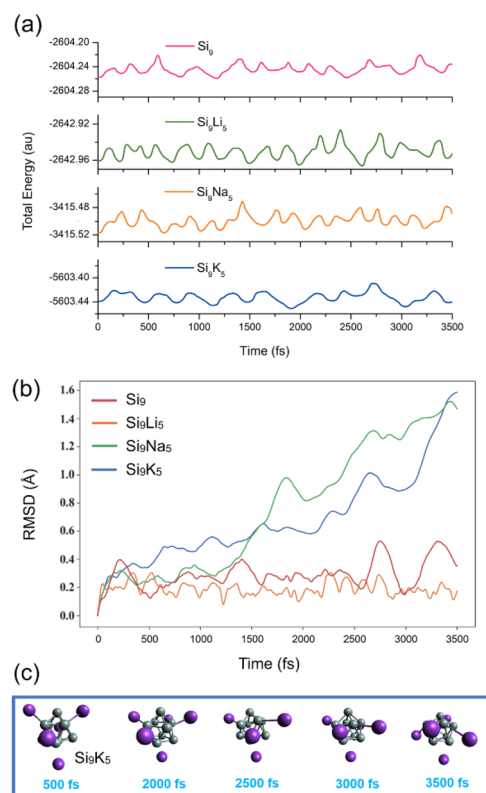
increase with the enlargement of the size of alkali metals. The μ<sub>o</sub> value of Si<sub>9</sub>K<sub>5</sub> is 20.42 D, which is 27 times higher than that of the pristine Si<sub>9</sub> cluster (0.73 D). In addition, we can also see from Table 1 that, the chemical hardness of Si<sub>9</sub> is 2.92 eV, higher than those of the Si<sub>9</sub>M<sub>5</sub> clusters, and the chemical softness of Si<sub>9</sub>M<sub>5</sub> increases with the increased metal size.

The superalkali nature of examined clusters can be monitored by their minimized ionization potential (IP) and electron affinity (EA) values. Pristine Si<sub>9</sub> has an IP value of 7.58 eV, higher than the designed Si<sub>9</sub>M<sub>5</sub>, while its EA value is 1.75 eV. Table 1 shows that the interaction of alkali metals with the Si<sub>9</sub> cluster has significantly lowered the IP and EA values. For instance, the obtained IP values are 4.35, 4.10, and 2.41 eV for Si<sub>9</sub>Li<sub>5</sub>, Si<sub>9</sub>Na<sub>5</sub>, and Si<sub>9</sub>K<sub>5</sub>, respectively. A similar trend of decreasing IP by doping alkali metals can also be found in the literature.<sup>62</sup> EA value also decreased to 0.03 eV, which is much smaller than previously reported P<sub>7</sub>M<sub>2</sub> clusters. The smaller EA values declare the electropositive nature and excellent reducing properties of the Si<sub>9</sub>M<sub>5</sub> clusters. Furthermore, the superalkali character of these clusters can be observed by their reduced IP values compared to alkali metals. The IPs of Si<sub>9</sub>Li<sub>5</sub> and Si<sub>9</sub>Na<sub>5</sub> are lower than that of the Li atom, and the IP of Si<sub>9</sub>K<sub>5</sub> has even lower than that of the Cs atom (3.89 eV), demonstrating that these clusters manifest superalkali characteristics.<sup>27</sup> Due electropositive nature, alkali metals become electron deficient after sharing their valence electrons ns<sup>1</sup> to np of Si-atoms within clusters. On the other hand, the Si<sub>9</sub> cluster acquires electronic charge from alkali due to its comparatively higher electronegativity. The electronic stability of Si<sub>9</sub>M<sub>5</sub> can also be correlated to the famous Jellium model. The core Zintl cluster Si<sub>9</sub> contains 36 electrons, and after interactions with alkali metals, there are 41 electrons in total. Hence, after losing one electron, these clusters may become stable by attaining the electronic shell closure configuration of 40 electrons. The presence of loosely bound (excitable) electrons in these clusters mimics the chemistry of the first group metals.

To investigate the kinetic and thermodynamic stability of the studied clusters, a total of 3500 different geometries for each cluster are obtained during the AIMD simulations at the B3LYP-

D3/def2-SVP level of theory. The snapshots are taken at every 500 fs to ensure their structural integrity. Fig. 2a displays the fluctuation curves of total energy, indicating that the designed clusters are kinetically stable with steady fluctuations in energy. In addition, the changes in root-mean-square deviation (RMSD) of the geometries within the simulations are shown in Fig. 2b. As seen, the fluctuations are more pronounced for the Si<sub>9</sub>K<sub>5</sub> cluster than the other three clusters, and the RMSD value for Si<sub>9</sub>K<sub>5</sub> increases up to 1.5 Å near the 3500 fs. Although RMSD curves for both Na and K-based clusters are increasing, no isomerization or dissociation is observed in the geometries of clusters (see Fig. 2c and S2†). The larger deviations in the RMSD of Si<sub>9</sub>Na<sub>5</sub> and Si<sub>9</sub>K<sub>5</sub> may be due to their big size of metals and interaction distances. Hence, the present designed Zintl clusters are kinetically stable at room temperature, and can be further probed for optoelectronic applications.

Manipulating the FMO analysis, it is attainable to uncover complex interactions between two components in a system based on the HOMO–LUMO band gap (E<sub>g</sub>). For the pure Zintl Si<sub>9</sub>, the E<sub>g</sub> value is 5.83 eV, according to our FMO analysis. The orbital energies are presented in Table 1. As can be seen, due to the doping/interactions of alkali metals on Si<sub>9</sub>, the energy gaps (between HOMO and LUMO orbitals) of the present Si<sub>9</sub>M<sub>5</sub> clusters are reduced. This is reasonable since the delocalized electrons of alkali (loosely held) would influence the valence electrons in the Si<sub>9</sub> Zintl cluster, and then a diffuse excess



**Fig. 2** Time evolution of the (a) total energy, (b) root-mean-square deviation (RMSD), and (c) snapshots of the Si<sub>9</sub>K<sub>5</sub> geometries during *ab initio* molecular dynamics simulations at 300 K using the B3LYP-D3/def2-SVP method.





electron system is generated, resulting in a reduced  $E_g$  gap. The HOMO–LUMO gaps of  $\text{Si}_9\text{Li}_5$ ,  $\text{Si}_9\text{Na}_5$ , and  $\text{Si}_9\text{K}_5$  are 4.17, 4.06 and 2.37 eV, respectively. The decreasing values have a periodic trend with the enlargement of the size of metals. In addition, the doping of alkali metals led to an increase in the energy of HOMO orbitals because of the residing excess electrons which lead to the generation of new HOMOs. The HOMO–LUMO gaps of  $\text{Si}_9\text{M}_5$  are slightly higher than those of  $\text{Ge}_9\text{AM}_5$  (ref. 60) and much lower than those of the  $\text{P}_7\text{M}_2$  Zintl clusters.<sup>61</sup> Fig. 3 shows the FMOs of the present clusters. As seen, the shape of LUMO of  $\text{Si}_9\text{Na}_5$  and  $\text{Si}_9\text{K}_5$  is spherical (similar to s-orbital) in shape. In the case of  $\text{Si}_9\text{Li}_5$ , the shape is more diffused, and the electronic density of the orbital is still higher around alkali metals than other places.

To visualize intra- and intermolecular charge transfer, we simulated the natural bonding orbital (NBO) charges on  $\text{Si}_9\text{M}_5$ , and the values are also given in Table 1. NBO charges on Si-atoms ( $Q_{\text{Si}}$ ) have both positive and negative in magnitude. After alkali metals interaction, the Si-atoms get significant negative NBO charges, whereas partial charges on alkali metal ( $Q_{\text{M}}$ ) atoms become positive as compared to silicon atoms. The highest magnitude (0.95 |e|) of NBO charge (positive) is displayed by the K-atom in the  $\text{Si}_9\text{K}_5$  cluster, indicating excellent charge transfer. Such charge transfer from alkali metals to Si-atoms would result in asymmetric charge distribution within designed clusters.

Furthermore, charge transfer and delocalization can be explained using the interactions between bonds and different properties (such as stability, reactivity, and the relationship between donor and acceptor), as well as the relationship between donors ( $i$ ) and acceptors ( $j$ ). Table S3† lists the values from our NBO analysis, from which a number of electronic transitions are observed and the most significant transition with a major stabilization ( $E_{(2)}$ ) contribution is reported. Evidently, molecular interactions between the investigated system are mainly by  $\sigma$ – $\sigma^*$  and  $\pi$ – $\pi^*$  electronic transitions

between Si–Si atoms. In Table S3,† we can also observe that, some bonds are very strong in  $\text{Si}_9$  due to strong interaction between Si–Si atoms. The most important maximum energy associated with the present clusters is to donate electrons from  $\sigma$  (Si4–Si6) to  $\sigma$  (Si4–Si9) in  $\text{Si}_9$ , from  $\sigma^*$  (Si9–Si11) to  $\sigma^*$  (Si9–Si13) in  $\text{Si}_9\text{Li}_5$ , from  $\pi$  (Si7–Si9) to  $\pi^*$  (Si1–Si2) in  $\text{Si}_9\text{Na}_5$  and from  $\sigma^*$  (Si4–Si8) to  $\sigma^*$  (Si3–Si8) in  $\text{Si}_9\text{K}_5$ , with stable energies being 80.41, 44.86, 45.66 and 50.04 kcal mol<sup>−1</sup>, respectively.

### 3.2 Noncovalent interactions

The noncovalent interaction plays a very important role in many chemical processes.<sup>63–65</sup> To investigate the nature of interactions between  $\text{Si}_9$  and alkali metals, we carried out a reduced density gradient (RDG) analysis based on the noncovalent interaction (NCI) method. Fig. 4 displays the RDG scatter graph, where the  $\lambda_2$  sign is exploited to differentiate between the bonded ( $\lambda_2 < 0$ ) and non-bonded ( $\lambda_2 > 0$ ) interactions. As seen in Fig. 4, for the present clusters,  $\lambda_2$  sign  $\rho$  function ranges from  $-0.05$  to  $0.05$  au. The red peaks in the range of  $\lambda_2 > 0$  correspond to the effect of steric repulsion, green spikes appearing in the region of  $\lambda_2 = 0$  represent the dipole–dipole or London dispersion forces,<sup>13</sup> blue-colored spikes in the regions  $\rho > 0$  and  $\lambda_2 < 0$  represent the electrostatic interactions. In addition, Fig. 4 shows a significant increase in weak vdW attractions after the doping of alkali metals to the pure  $\text{Si}_9$  cluster. The strong, attractive interaction appears between  $-0.035$  and  $-0.025$  au. Hence, the isosurface plot indicates the presence of vdW interactions between the alkali metals and the pristine  $\text{Si}_9$  cluster, in which the dispersion interaction may play an important role. A significant increase in the magnitude of noncovalent can be seen with the increased atomic number of alkali metals, which may cause a strong impact on the NLO properties of the designed  $\text{Si}_9\text{M}_5$  Zintl cluster.

We also performed the QTAIM analysis to identify the nature of bonding within the present clusters, and values are given in Table 2. The generated bond critical points (BCP) at (3,  $-1$ ) appear in Fig. S3.† The interaction energies between alkali and silicon atoms (M–Si) are relatively weaker than the interaction between Si–Si in pure  $\text{Si}_9$ , which demonstrates the presence of non-bonding interactions in present clusters. The Laplacian of electronic density ( $\nabla^2\rho(r)$ ) and total energy density ( $H(r)$ ) values

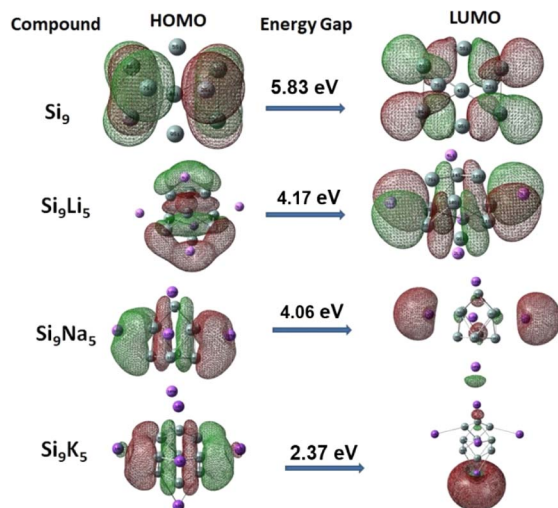


Fig. 3 Representation of frontier molecular orbitals (FMOs) at the  $\omega\text{b97xd/def2-qzvp}$  level (isovalue = 0.025).

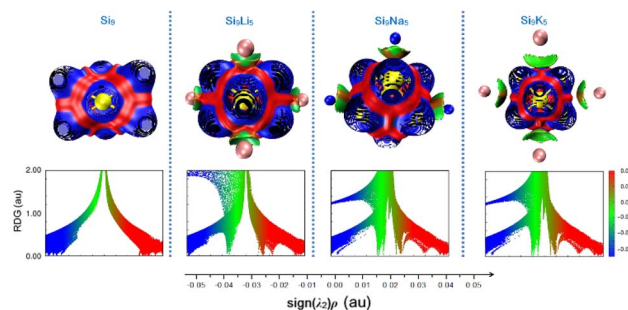


Fig. 4 Representation of reduced density gradient (RDG) spectra and three-dimensional surfaces for non-covalent interactions analysis (NCI) at the  $\omega\text{b97xd/def2-qzvp}$  level.



Table 2 Calculated QTAIM parameters for bond critical points (BCPs) at (3, -1) electron density. The values are in au

Cluster	Interaction	$\rho(r)$	$\Delta^2\rho(r)$	$G(r)$	$V(r)$	$G(r)/ V(r) $	$H(r)$
Si <sub>9</sub>	Si1-Si4	0.047	0.0040	0.0144	-0.0280	0.5124	-0.0136
	Si4-Si5	0.051	-0.0041	0.0155	-0.0323	0.4798	-0.0168
	Si4-Si9	0.047	0.0042	0.0143	-0.0279	0.5125	-0.0136
	Si5-Si8	0.062	-0.0292	0.0168	-0.0417	0.4028	-0.0248
Si <sub>9</sub> Li <sub>5</sub>	Li1-Si8	0.016	0.0723	0.0153	-0.0126	1.2142	0.0027
	Li2-Si12	0.016	0.0745	0.0159	-0.0131	1.2137	0.0024
	Li3-Si8	-0.016	0.0725	0.0154	-0.0127	0.4494	0.0027
	Li4-Si2	0.055	-0.0121	0.0160	-0.0356	1.2126	0.0027
	Li5-Si13	0.016	0.0729	0.0154	-0.0127	0.8717	0.0027
Si <sub>9</sub> Na <sub>5</sub>	Na10-Si3	0.012	0.0489	0.0034	-0.0039	0.0903	-0.0004
	Na11-Si5	0.011	0.0419	0.0027	-0.0299	0.8571	-0.0003
	Na12-Si4	0.012	0.0400	0.0030	-0.0035	0.9285	-0.0004
	Na13-Si6	0.010	0.0407	0.0026	-0.0028	0.8571	-0.0001
Si <sub>9</sub> K <sub>5</sub>	Na14-Si2	0.012	0.0418	0.0030	-0.0035	1.2258	-0.0005
	K10-Si7	0.006	0.0179	0.0038	-0.0031	1.2258	0.0007
	K11-Si4	0.061	-0.0282	0.0169	-0.0418	0.4043	0.0007
	K12-Si7	0.011	0.0332	0.0076	-0.0069	1.1014	0.0006
	K13-Si2	0.011	0.0345	0.0079	-0.0071	1.1126	0.0007
K14-Si8	0.011	0.0332	0.0076	-0.0069	1.1014	0.0006	

at BCP (3, -1) between Si-Si bond are negative, while positive for Si-M (where M = Li, Na, and K), which further suggests the non-covalent nature of bonds. Alkali metal interactions with silicon (M-Si) have a smaller value of total electronic density ( $\rho(r) < 0.1$ ) and a positive magnitude of  $\nabla^2\rho(r)$ , indicating the weak interactions are operational in the present Si<sub>9</sub>M<sub>5</sub> clusters. Similarly,  $G(r)/|V(r)|$  ratios are close to or larger than unity for M-Si interactions, which also demonstrates the presence of vdW forces between Si and alkali metals in the present clusters.

### 3.3 Static nonlinear optical properties

It is rather beneficial for the NLO response of the superatom clusters that there is adequate electronic communication across their various moieties. As a new addition to the family of loosely bound excess electron compounds, the Si<sub>9</sub>M<sub>5</sub> clusters designed in this work have superalkali characteristics and contain excess electrons, further prompting us to investigate their optoelectronic properties. Literature is also evident for crucial role of excess electrons and vdW interactions in triggering NLO response of molecules and clusters.<sup>66-68</sup> The optical and NLO responses can be characterized through polarizability, hyperpolarizability, and static second hyperpolarizability. The obtained values are given in Table 3. The determined values of polarizability ( $\alpha_0$ ) and  $\mu_0$  are higher as compared to that of the urea, revealing excellent polarizability and charge separation. Overall,  $\mu_0$  and  $\alpha_0$  response decreases in the order of Si<sub>9</sub>K<sub>5</sub> > Si<sub>9</sub>Na<sub>5</sub> > Si<sub>9</sub>Li<sub>5</sub> > Si<sub>9</sub>. The highest value of  $\alpha_0$  can be seen for the Si<sub>9</sub>K<sub>5</sub> cluster, while the lowest is observed for the pristine Si<sub>9</sub> cluster. The substantial value of polarizability indicates the polarizable nature, which may be due to the presence of soft-nature alkali metals.

Hyperpolarizability ( $\beta_0$ ) is an approach for identifying nonlinear optical features of present clusters. The obtained  $\beta_0$  values for Si<sub>9</sub>, Si<sub>9</sub>Li<sub>5</sub>, Si<sub>9</sub>Na<sub>5</sub>, and Si<sub>9</sub>K<sub>5</sub> are  $1.58 \times 10^2$ ,  $2.22 \times 10^3$ ,  $1.41 \times 10^4$ , and  $6.66 \times 10^4$  au, respectively. The  $\beta_0$  value of

the designed Si<sub>9</sub>M<sub>5</sub> clusters is significantly increased compared to that of the pristine Si<sub>9</sub>, indicating the crucial role of excess electrons and non-covalent interactions. For example, the  $\beta_0$  values of Si<sub>9</sub>Li<sub>5</sub> and Si<sub>9</sub>K<sub>5</sub> are 140 and 421 times larger than that of Si<sub>9</sub>, and the highest  $\beta_0$  value of  $6.66 \times 10^4$  au can be found in the Si<sub>9</sub>K<sub>5</sub> cluster. Formulating excess electrons after the interaction of alkali metals might cause a significant reduction in excitation energies ( $\Delta E$ ), and excess electrons have a dominant role in triggering hyperpolarizability values. Fig. 5 displays  $\Delta E$  of the crucial state and obtained  $\beta_0$  of Si<sub>9</sub> and Si<sub>9</sub>M<sub>5</sub> clusters. As seen, there is an inverse relation of  $\Delta E$  and  $\beta_0$ . The calculated values of  $\alpha_0$  and  $\beta_0$  of the present cluster are higher than those of urea and *p*-nitroaniline.<sup>69</sup> The  $\gamma_0$  values range from  $5.94 \times 10^4$  to  $7.67 \times 10^7$  au, and a monotonic increase is observed from Li to K. Noncovalent interactions are also crucial in promoting the optical and NLO properties of designed clusters. The uptrend in values of hyperpolarizabilities is observed with the increased vdW interactions, as revealed by NCI analysis.

Table 3 Static polarizability ( $\alpha_0$ ), hyperpolarizability ( $\beta_0$ ), projection of hyperpolarizability on dipole moment vector ( $\beta_{vec}$ ), static second hyperpolarizability ( $\gamma_0$ ), average dipolar hyperpolarizability ( $\langle\beta_{J=1}\rangle$ ), average octupolar hyperpolarizability ( $\langle\beta_{J=3}\rangle$ ), percentage contribution to dipolar nature ( $\phi(\beta_{J=1})$ ), and depolarization ratio (DR) of studied clusters

Properties	Si <sub>9</sub>	Si <sub>9</sub> Li <sub>5</sub>	Si <sub>9</sub> Na <sub>5</sub>	Si <sub>9</sub> K <sub>5</sub>
$\alpha_0$ (au)	268.82	403.913	578.84	1017.67
$\beta_0$ (au)	$1.58 \times 10^2$	$2.22 \times 10^3$	$1.41 \times 10^4$	$6.66 \times 10^4$
$\beta_{vec}$ (au)	$1.44 \times 10^2$	$1.01 \times 10^3$	$1.19 \times 10^4$	$4.72 \times 10^4$
$\beta_{HRS}$ (au)	$1.44 \times 10^2$	$1.01 \times 10^3$	$1.19 \times 10^4$	$4.72 \times 10^4$
$\gamma_0$ (au)	$5.94 \times 10^4$	$6.01 \times 10^5$	$2.37 \times 10^6$	$7.67 \times 10^7$
$\langle\beta_{J=1}\rangle$	122.92	1721.66	21 246.21	56 345.58
$\langle\beta_{J=3}\rangle$	430.277	1898.84	21 106.19	126 518.78
$\phi(\beta_{J=1})$	22%	47%	50%	30%
DR	1.84	3.93	4.28	0.69



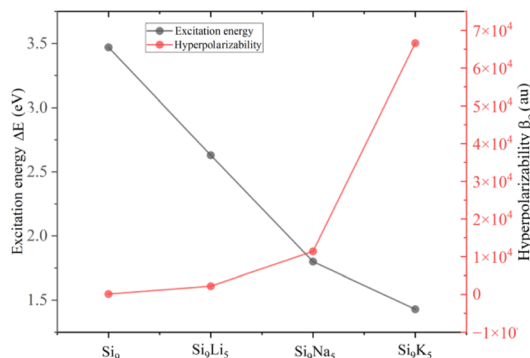


Fig. 5 Plotted excitation energy ( $\Delta E$ ) of crucial state and obtained hyperpolarizability ( $\beta_0$ ) of Si<sub>9</sub> and Si<sub>9</sub>M<sub>5</sub> clusters at the  $\omega b97xd/def2-qzvp$  level.

In addition, the effect of solvent on  $\alpha_0$  and  $\beta_0$  is also considered at the  $\omega b97xd/def2-qzvp$  level, by employing the implicit, namely the universal solvent model based on solute electron density (SMD). Calculated values are presented in Table S4.† Obtained second-order NLO parameters in solvent media are better than those of vacuum-based results. It is worthy of note that computed values of  $\beta_0$  using four different solvents are broadly consistent and in the same tendency. Using water as a solvent leads to slightly larger  $\beta_0$  values. For instance, the calculated  $\beta$  value ( $5.5 \times 10^6$  au) for Si<sub>9</sub>K<sub>5</sub> is found to be 83 times higher as compared to  $\beta$  in the gas phase. The altered electronic density and change in electronic properties due to the presence of solvent may influence the electric field, which would result in increased  $\beta_0$ . The presence of solvent has introduced a strong polarization effect to the applied electric field. Thus, controlling the polarizable environment around studied clusters can be seen as an effective way to adjust the NLO response.

To get deep insight into nonlinear optical features, we disclose the second-order electric susceptibility response of the present clusters theoretically by Hyper-Rayleigh scattering (HRS) simulation, and the results are listed in Table 3. As seen, the obtained  $\beta_{HRS}$  values of Si<sub>9</sub>, Si<sub>9</sub>Li<sub>5</sub>, Si<sub>9</sub>Na<sub>5</sub>, and Si<sub>9</sub>K<sub>5</sub> are  $1.44 \times 10^2$ ,  $1.01 \times 10^3$ ,  $1.19 \times 10^4$ , and  $4.72 \times 10^4$  au, respectively. From Si<sub>9</sub> to Si<sub>9</sub>K<sub>5</sub>,  $\beta_{HRS}$  values have the same trend as  $\beta_0$  values, indicating the excellent NLO characteristics of the present clusters. In particular, the  $\beta_{HRS}$  value of Si<sub>9</sub>K<sub>5</sub> is 328 times larger than that of Si<sub>9</sub>. Furthermore, the average dipolar hyperpolarizability  $\langle\beta_{J=1}\rangle$  and octupolar  $\langle\beta_{J=3}\rangle$  values of the Si<sub>9</sub>M<sub>5</sub> clusters are higher than those of Si<sub>9</sub>. The maximum dipolar contribution is 50% for the Si<sub>9</sub>K<sub>5</sub>, while the remaining clusters exhibit an octupolar-like nature. Compared with the previously reported clusters,<sup>47</sup> the present clusters exhibit greater  $\gamma_0$  values.

### 3.4 Dynamic nonlinear optical properties

We also examined the frequency-dependent hyperpolarizability  $\beta(\omega)$  theoretically considering the externally applied frequency of 532 and 1900 nm, and the obtained results are summarized in Table 4.  $\beta(\omega)$  consists of two parts, *i.e.*, electro-optical

Table 4 Static polarizability frequency-dependent first hyperpolarizability  $\beta(\omega)$  and second hyperpolarizability  $\gamma(\omega)$  using the definition of EOPE  $\beta(-\omega, \omega, 0)$ , ESHG  $\beta(-2\omega, \omega, \omega)$ , dc-Kerr effect  $\gamma(-\omega, \omega, 0, 0)$ , and SHG  $\gamma(-2\omega, \omega, \omega, 0)$  at 532 and 1900 nm

	$\omega = 0.0856$ (532 nm)		$\omega = 0.0240$ (1900 nm)	
	$\beta(-\omega; \omega, 0)$	$\beta(-2\omega; \omega, \omega)$	$\beta(-\omega; \omega, 0)$	$\beta(-2\omega; \omega, \omega)$
Si <sub>9</sub>	$2.79 \times 10^2$	$2.03 \times 10^3$	$1.61 \times 10^2$	$1.25 \times 10^2$
Si <sub>9</sub> Li <sub>5</sub>	$3.39 \times 10^4$	$1.11 \times 10^5$	$2.41 \times 10^3$	$2.80 \times 10^3$
Si <sub>9</sub> Na <sub>5</sub>	$7.62 \times 10^6$	$1.32 \times 10^6$	$3.83 \times 10^4$	$4.45 \times 10^5$
Si <sub>9</sub> K <sub>5</sub>	$2.65 \times 10^6$	$3.05 \times 10^5$	$2.65 \times 10^8$	$1.05 \times 10^8$

	$\gamma(\omega)$			
	$\gamma(-\omega; \omega, 0, 0)$	$\gamma(-2\omega; \omega, \omega, 0)$	$\gamma(-\omega; \omega, 0, 0)$	$\gamma(-2\omega; \omega, \omega, 0)$
Si <sub>9</sub>	$8.53 \times 10^4$	$1.86 \times 10^5$	$6.10 \times 10^4$	$6.42 \times 10^4$
Si <sub>9</sub> Li <sub>5</sub>	$1.10 \times 10^{10}$	$3.30 \times 10^9$	$6.81 \times 10^5$	$1.83 \times 10^6$
Si <sub>9</sub> Na <sub>5</sub>	$3.67 \times 10^9$	$3.90 \times 10^8$	$3.48 \times 10^6$	$2.44 \times 10^8$
Si <sub>9</sub> K <sub>5</sub>	$1.18 \times 10^9$	$1.24 \times 10^9$	$5.86 \times 10^{11}$	$1.30 \times 10^{11}$

Pockel's effect (EOPE) with  $\beta(-\omega, \omega, 0)$  and second harmonic generation phenomena (SHG) with  $\beta(-2\omega, \omega, \omega)$ . The choice of wavelengths also relevant to Nd:YAG laser functioning, which frequently emits invisible light in at longer wavelength and serves in laser-based devices.<sup>70</sup> The electro-optical effect (Pockel's effect) is an essential nonlinear effect used in many applications. As shown in Table 4, for all four clusters, the values of  $\beta(-\omega; \omega, 0)$  and  $\beta(-2\omega, \omega, \omega)$  at  $\omega = 0.0240$  are higher than the corresponding values at  $\omega = 0.0856$ . Hence, the frequency-dependent first hyperpolarizability  $\beta(\omega)$  response dominates at smaller dispersion frequency (at longer wavelength). From Si<sub>9</sub> to Si<sub>9</sub>K<sub>5</sub>, both  $\beta(-\omega; \omega, 0)$  and  $\beta(-2\omega, \omega, \omega)$  show increasing trends. Obviously, the dynamic first hyperpolarizability  $\beta(\omega)$  values of Si<sub>9</sub>M<sub>5</sub> are immensely better than the pristine Si<sub>9</sub> cluster, indicating their excellent dynamic nonlinear optical features.

Table 4 also lists the dynamic second hyperpolarizability  $\gamma(\omega)$  values. As seen, the obtained the dc-Kerr effect  $\gamma(-\omega, \omega, 0, 0)$  and second harmonic generation SHG  $\gamma(-2\omega, \omega, \omega, \omega)$  values are much better than those of static  $\gamma_0$ . The calculated highest response is indicated regarding the Kerr effect with a value up to  $5.86 \times 10^{11}$  au. Additionally, the frequency-dependent SHG and Kerr effect are much more prominent at 1900 nm (small dispersion frequency) than those of at 532 nm. Within the present designed clusters, an uptrend can be seen in both  $\gamma(-2\omega; \omega, \omega, 0)$  and  $\gamma(-\omega, \omega, 0, 0)$  values with increased metal size at 1900 nm, while at 532 nm Si<sub>9</sub>Li<sub>5</sub> has the highest value of  $\gamma(-2\omega; \omega, \omega, 0)$  and  $\gamma(-\omega, \omega, 0, 0)$ . The Kerr effect is caused by the instantaneous change in its refractive index in response to the applied electric field. Also, the change in the refractive index is directly related to the square of electric field strength. Hence, the applied smaller frequency ( $\omega = 0.024$ ) has significantly enhanced values of the Kerr effect as compared to a higher frequency. Fig. S4† reveals the variational trend frequency-





dependent  $\beta(\omega)$  and  $\gamma(\omega)$  at 532 and 1900 nm, respectively, where the SHG and dc-Kerr effects exhibit the same increasing trend from Li to K at 1900 nm.

### 3.5 Spectroscopic study and bonding analysis

Fig. S5† depicts the obtained absorption spectra of the present  $\text{Si}_9\text{M}_5$  clusters by our TD-DFT calculations. As seen, the absorbance maxima are shifted to longer wavelength (bathochromic shift), where the highest absorbance wavelength (866 nm) is seen for the  $\text{Si}_9\text{K}_5$  cluster. The atomic number of alkali metals is the main influencing factor in the absorbance properties where increased-sized metals decrease the excitation energy. The values of excitation energies ( $\Delta E$ ), absorbance maxima ( $\lambda_{\text{max}}$ ), and oscillator strength (O.S.) are given in Table 5. The excitation (transition) energy ( $\Delta E$ ) of the  $\text{Si}_9$  cluster is higher than those with alkali metal decorated, and a gradual decrease in  $\Delta E$  is observed from  $\text{Si}_9\text{Li}_5$  to  $\text{Si}_9\text{K}_5$  for designed clusters. The above results demonstrate that the higher size metals in  $\text{Si}_9$  clusters enable them to harvest light at comparatively longer wavelengths.

In addition, we examined the total density of states (TDOS), and the obtained spectra are given in Fig. S6.† It is known that the different kinds of states inhabited by electrons at a discrete energy level are expressed by electronic states per unit of energy. For the pristine  $\text{Si}_9$ , the wide energy gap can be seen where HOMO is located at  $-8$  eV. After interacting with alkali metals, the HOMO–LUMO gap became narrow, where HOMO has a further increase in energy. Furthermore, the vibrational frequencies of  $\text{Si}_9$  and  $\text{Si}_9\text{M}_5$  are listed in Table S5,† and the spectra of FT-IR and Raman are shown in Fig. S7.† The vibrational and Raman frequencies are simulated at the  $\omega\text{b97Xd/def2-qzvp}$  level. In both  $\text{Si}_9$  and  $\text{Si}_9\text{M}_5$  cases, the Si–Si stretching vibrations agree well with experimental values. The most dominant peaks of stretching vibrations of silicon in  $\text{Si}_9$  are ranging from  $533$  to  $317\text{ cm}^{-1}$  (Table S5†). The increased vibrational frequency of  $\text{Si}_9\text{M}_5$  reveals the structural change after introducing alkali metals.

Fig. 6 displays the results of ELF and LOL analysis, which further justifies the nature of bonding and the presence of loosely bound electrons in present clusters. The color scale of the ELF and LOL maps varies from blue to red in the range of 0 to 1.0, respectively. The area colored in red and blue corresponds to the maximum and minimum Pauli repulsion with the unity and zero values, respectively. However, the highest repulsive interaction (most localized electron state) is shown in red. The strong localization of electrons ( $\text{ELF} > 0.5$ ) corresponds to the

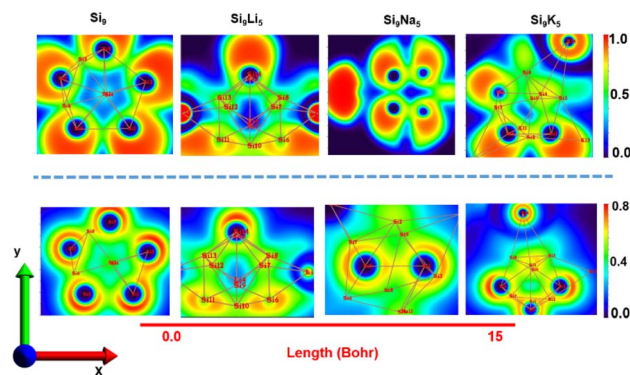


Fig. 6 Electron localization function (ELF) (upper panel) and 2D localized orbital locator (LOL) spectra (lower panel) of the present clusters. The planes that are used to plot the ELF and LOL patterns are shown in Fig. S8.†

covalent bond, lone pair, or inner shells. From the ELF analysis, the  $\text{Si}_9\text{Li}_5$  cluster shows strong electron localization after interactions with alkali metals, where a concentrated red color can be seen with alkali metals. The blue spots ( $\text{ELF} < 0.5$ ) show charge delocalization regions, indicating the existence of non-covalent interactions. The electrons are highly localized when ELF is one and delocalized when ELF is zero. The high level of ELF and LOL values are indicated by the red color near alkali metals. A delocalized electron cloud can be seen as a blue color on the outer surface of the  $\text{Si}_9$  cluster and also in the  $\text{Si}_9\text{M}_5$  cluster. In addition, the green regions on the ELF surface and LOL colour-filled maps point out the presence of vdW interactions.

## 4 Conclusions

In the concluding summary, we investigate the Zintl-based superalkali-excess electron clusters theoretically using various calculations. The designed  $\text{Si}_9\text{M}_5$  ( $\text{M} = \text{Li}, \text{Na}, \text{and K}$ ) clusters are thermodynamically stable, as indicated by the binding energies and AIMD simulations. Also, Si–M interactions are shown to be weak and dominated by vdW interactions, which contribute to optical and NLO properties. Excess electron nature, bonding structures, and partial atomic charges are calculated through FMO and NBO studies. IR and Raman frequencies are calculated to examine the amplitude of vibrations after doping. The HOMO–LUMO gap for  $\text{Si}_9\text{K}_5$  is much reduced as compared to the pristine  $\text{Si}_9$  cluster. Remarkable static polarizability ( $\alpha_0$ ) and hyperpolarizability ( $\beta_0$ ) values are obtained up to  $1.02 \times 10^4$  au and  $6.66 \times 10^4$  au for the  $\text{Si}_9\text{K}_5$  cluster. The influence of the implicit solvent model has been considered, where  $\beta_0$  increased 83 times as compared to the corresponding value in the gas phase for the  $\text{Si}_9\text{K}_5$  cluster. The frequency-dependent NLO response for the dc-Kerr effect is observed up to  $1.3 \times 10^{11}$  au, indicating the excellent change in refractive index by an externally applied electric field. Electron localization (ELF) and localized orbital locator (LOL) further reveal the bonding nature in these clusters.

Table 5 The obtained excitation energies ( $\Delta E$ ), absorption maxima ( $\lambda_{\text{max}}$ ), and oscillator strengths ( $f_{\text{os}}$ ) of the present clusters

Clusters	$\Delta E$ (eV)	$\lambda_{\text{max}}$ (nm)	$f_{\text{os}}$ (au)
$\text{Si}_9$	3.47	356	0.0091
$\text{Si}_9\text{Li}_5$	2.63	469	0.0203
$\text{Si}_9\text{Na}_5$	1.80	685	0.1620
$\text{Si}_9\text{K}_5$	1.43	866	0.4689





## Conflicts of interest

The authors declare no competing financial interest.

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