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Defects and dopant properties of $\text{Li}_3\text{V}_2(\text{PO}_4)_3$

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Polyanion phosphate based $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ material has attracted considerable attention as a novel cathode material for potential use in rechargeable lithium ion batteries. The defect chemistry and dopant properties of this material are studied using well-established atomistic scale simulation techniques. The most favourable intrinsic defect process is the Li Frenkel (0.45 eV/defect) ensuring the formation of Li vacancies required for Li diffusion via the vacancy mechanism. Long range lithium paths via the vacancy mechanism were constructed and it is confirmed that the lowest activation energy of migration (0.60 eV) path is three dimensional with curved trajectory. The second most stable defect energy process is calculated to be the anti-site defect, in which Li and V ions exchange their positions (0.91 eV/defect). Tetravalent dopants were considered on both V and P sites in order to form Li vacancies needed for Li diffusion and the Li interstitials to increase the capacity respectively. Doping by Zr on the V site and Si on the P site are calculated to be energetically favourable.

The increased need for electrical energy storage for static and mobile applications in conjunction with the demand for higher capacity, better safety, increased cycle performance, and durability made the solid-state lithium batteries technologically important^{1,2}. The research is focusing mainly on the electrolyte and cathode trying to identify more efficient materials^{3–17}. In particular, electrode materials require should satisfy safety requirements, be low cost, and critically have a higher energy density (i.e. large density of Li^+ ions).

State of the art cathodes for solid-state lithium batteries include polyanion-type oxides, layered lithiated transition metal oxides and Mn-based spinels¹⁸. Monoclinic $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ has gained the interest of the community as a cathode material for solid-state lithium batteries due to its low cost, safety, low environmental impact, appropriate cycling stability, and high theoretical capacity (197 mAhg^{-1})^{18–25}. Fu *et al.*²⁶ synthesized this material using mixed lithium precursors with particles high surface area leading to good electrochemical performance. Solid state⁷ Li NMR together with two-dimensional exchange study of Lithium was used to determine the temperature dependent Li hopping process to understand the Li dynamics on the microscopic scale suggesting that their methodology can be applied to the cycled materials and other lithium metal phosphates²⁷. Lee and Park²² employed molecular dynamics simulation to calculate the vacancy migration energy of Li at different temperatures and confirmed the mobility of Li^+ ions is anisotropic. Though these separate studies show different properties in this material, fundamental understating of this material is needed to optimize its performance.

Electrochemical behaviour of an electrode material is important to assess its applicability in batteries. This behaviour can be studied theoretically by performing defect calculations and we note that such studies are absent in the literature. Atomistic modelling based on the classical pair potentials is a powerful method and can provide useful information about the defect processes, cation doping behavior and ion migration mechanism. This methodology has been applied to a variety of oxides including Li containing materials and excellent agreement in trends and energetics of defect processes was observed between calculation and the experiment^{7,28,29}. Here, we extend our recent modelling of electrode materials^{30–34} where we examined the defects, ion diffusion and dopants. In the present study, we employ established atomistic modeling techniques to investigate the intrinsic defect chemistry, the impact of doping on the formation of lithium interstitials and lithium ion diffusion pathways in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$. We consider the solution of a range of oxides in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$, including aliovalent dopants (e.g. Si, Ge and Ti) and isovalent dopants (e.g. Al, Ga and Sc).

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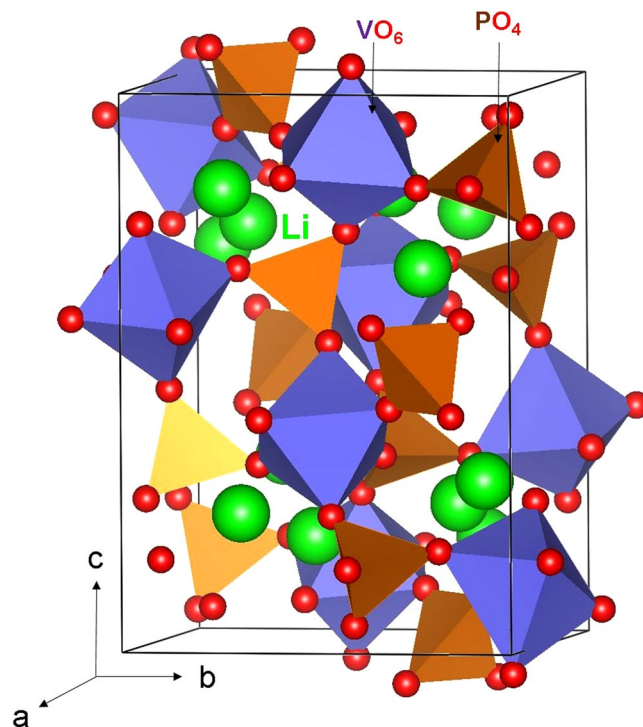


Figure 1. Crystal structure of $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ (space group $P2_1/n$).

Parameter	Calc	Expt ¹³	$ \Delta (\%)$
a (Å)	8.431424	8.597800	1.94
b (Å)	8.548920	8.593300	0.52
c (Å)	12.076179	12.032700	0.36
α (°)	90.0000	90.0000	0.00
β (°)	90.070	90.496	0.47
γ (°)	90.0000	90.0000	0.00

Table 1. Calculated and Experimental Structural Parameters for Monoclinic ($P2_1/n$) $\text{Li}_3\text{V}_2(\text{PO}_4)_3$.

Results and Discussion

$\text{Li}_3\text{V}_2(\text{PO}_4)_3$ structure. The crystal structure of $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ exhibits a monoclinic crystallographic structure with space group $P2_1/n$ (lattice parameters $a = 8.5978 \text{ \AA}$, $b = 8.5933 \text{ \AA}$, $c = 12.0327 \text{ \AA}$, $\alpha = 90.0^\circ$, $\beta = 90.496^\circ$ and $\gamma = 90.0^\circ$) as reported by Fu *et al.*²⁶ Fig. 1 shows this structure and the chemical environment of P (forming tetrahedral unit with four O atoms) and V (forming octahedral unit with six O atoms). The starting point for the present study was to reproduce the experimentally observed monoclinic crystal structure to enable an assessment of the quality and efficacy of the classical pair potentials (refer to Table S1 in the supplementary information for the potentials parameters used and method section for the detailed description of the methodology) used here. The calculated equilibrium lattice constants (refer to Table 1) are in excellent agreement with experiment.

Intrinsic defect processes. To understand the electrochemical behavior of an electrode material, intrinsic defect processes are crucial. A series of isolated point defect (vacancy and interstitial) energies were calculated, which were combined to determine the formation energies for Frenkel and Schottky-type defects in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$. The following equations represent the reactions involving these defects as written using Kröger-Vink notation³⁵.



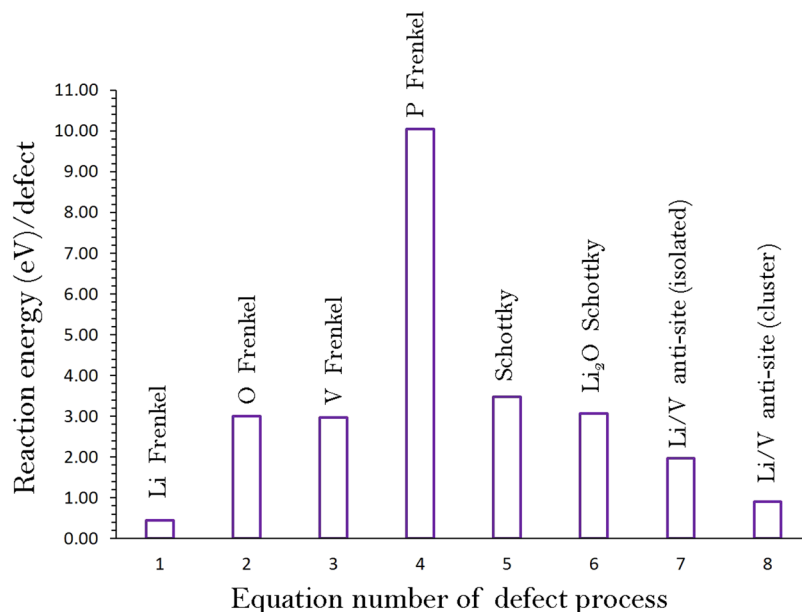
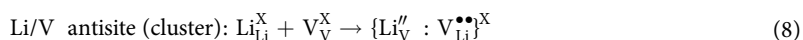
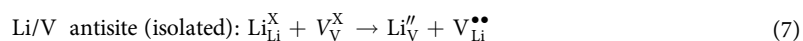
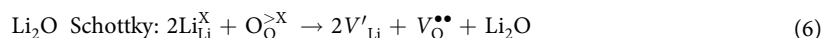
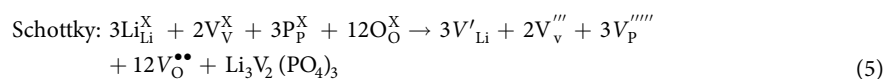


Figure 2. Energetics of intrinsic defect process in monoclinic $\text{Li}_3\text{V}_2(\text{PO}_4)_3$.



The reaction energies for these intrinsic defect processes are reported in Fig. 2 and Table S2. The most favourable intrinsic disorder is Li Frenkel and the formation of other Frenkel and Schottky defects is less energetically favourable. The second most favourable defect process is calculated to be Li-V anti-site. This indicates that there will be a small percentage of Li on V sites (Li''_{V}) and P on Li sites (V'_{Li}) particularly at higher temperatures. In the relaxed configuration, there is insignificant changes observed in the cation-oxygen bond distances. Antisite defects have been observed experimentally and theoretically in a variety of Li ion cathode battery materials^{30–33,36–41}. In the experimental study of as-prepared $\text{Li}_2\text{MnSiO}_4$, a small amount of Li-Mn anti-site defect was observed⁴¹. During cycling of $\text{Li}_2\text{FeSiO}_4$, Nyten *et al.*³⁶ observed structural rearrangement in the crystal structure responsible for the Li-Fe anti-site. The difference between the isolated and cluster defect energies is calculated to be -1.06 eV suggesting that the anti-site cluster is stable compared to its isolated form. The formation enthalpy of Li_2O via the Li_2O Schottky-like reaction (relation 6) is a process that requires an energy of 3.07 eV per defect (refer to Table S2, supplementary information). This is a process that can lead to further V'_{Li} and $\text{V}_{\text{O}}^{\bullet\bullet}$, however, at elevated temperatures. The trend calculated for Li and V Frenkel and Li-V antisite defects is in agreement with the theoretical calculations performed by Lee *et al.*²², though there is a difference in defect energetics. Such difference is dependent on the choice of classical pair potentials used.

Lithium ion-diffusion. As the intrinsic lithium ion diffusion of $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ material is of crucial importance when assessing its use as a possible high-rate cathode material in lithium batteries, we used the present static atomistic simulation to examine various possible diffusion paths responsible for Li ion conduction, which are often difficult to explore on the atomic scale by experiment alone. For the Li vacancy migration, we identified four lower activation energy local hops (A, B, C and D) and constructed long range paths connecting local Li hops (refer to Fig. 3). There are many long range three dimensional paths present. The lowest overall migration energy (0.60 eV) was calculated for the $\text{D} \rightarrow \text{A} \rightarrow \text{B} \rightarrow \text{A}$ path. Other possible long range paths were considered. However, the overall activation energy was calculated to be 0.87 eV due to the local hop C involved in the long range path. Here the activation energy of migration is defined as the position of the highest potential energy along the migration path. Migration energies are reported in Table 2 together with the Li-Li separation, whereas energy profile diagrams are shown in Fig. 4. Lee *et al.*²² calculated the one dimensional lithium ion diffusion mechanism in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ and their values deviates with our study. This is because in the present study we calculated three dimensional Li migration paths, which are the lowest energy migration paths (refer to Fig. 3 for detailed migration

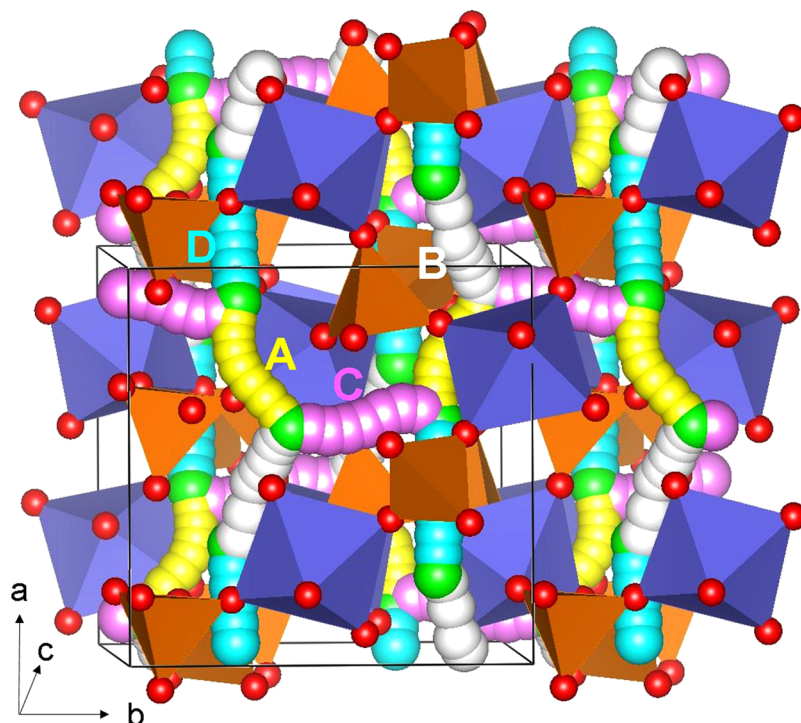


Figure 3. Possible long range sodium vacancy migration paths considered. Local Li migration paths are shown in blue, yellow, white and light purple atoms. PO₄ and VO₆ units are shown brown and violet colors respectively.

Migration path	Li-Li separation (Å)	Activation energy (eV)
A	2.9561	0.53
B	3.2091	0.46
C	3.2676	0.87
D	3.3501	0.60

Table 2. Calculated Li-Li separations and activation energies for the sodium ion migration between two adjacent Li sites refer to Fig. 3.

path). Migration paths calculated in this study exhibit curved trajectories while in other studies, the paths are linear. Cahill *et al.*²⁷ performed Li NMR measurements to estimate the activation energy for Li ion migration. The reported range of activation energies (0.73–0.83 eV) agrees reasonably with our calculated values of 0.46–0.87 eV.

Tetravalent doping. The Li Frenkel is calculated to be only 0.45 eV/defect; however, an increase in the concentration of Li will further increase the applicability of Li₃V₂(PO₄)₃ as a cathode material for rechargeable lithium batteries. A way to increase the content of intrinsic defects in oxides is by the solution of aliovalent dopants as it was previously demonstrated in CeO₂ (for example ref.⁴² and references therein). Here we considered the solution of RO₂ (R = Ce, Zr, Ti, Si and Ge) via the following process (in Kröger-Vink notation):



Figure 5 reports the solution energies of RO₂ and it can be observed that ZrO₂ has the lowest solution energy of 2.18 eV. Solution energies of CeO₂ and GeO₂ are 2.31 eV and 2.35 eV respectively meaning that Ce and Ge are also promising candidate dopants. As these solution energies are higher compared to the Li Frenkel process, the solution of ZrO₂, GeO₂ and CeO₂ during synthesis should be examined experimentally as they can increase the Li vacancy concentration (via relation (9)).

Incorporation of additional lithium into the as-prepared material will enhance the capacity and further increase the applicability of Li₃V₂(PO₄)₃ as a viable cathode material for rechargeable sodium batteries. A defect engineering way to increase the amount of lithium is by doping tetravalent cations on P site through creating Li interstitials. The efficacy of the approach has been previously demonstrated experimentally and theoretically in Li battery cathode materials¹⁸. In a theoretical study of polymorphs of Li₂MnSiO₄, it was suggested that Al doping on the Si site is a possible way of introducing additional Li interstitial in Li₂MnSiO₄⁴⁰. Here we considered the solution of RO₂ (R = Si, Ge, Ti, Zr and Ce) via the following process (in Kröger-Vink notation):

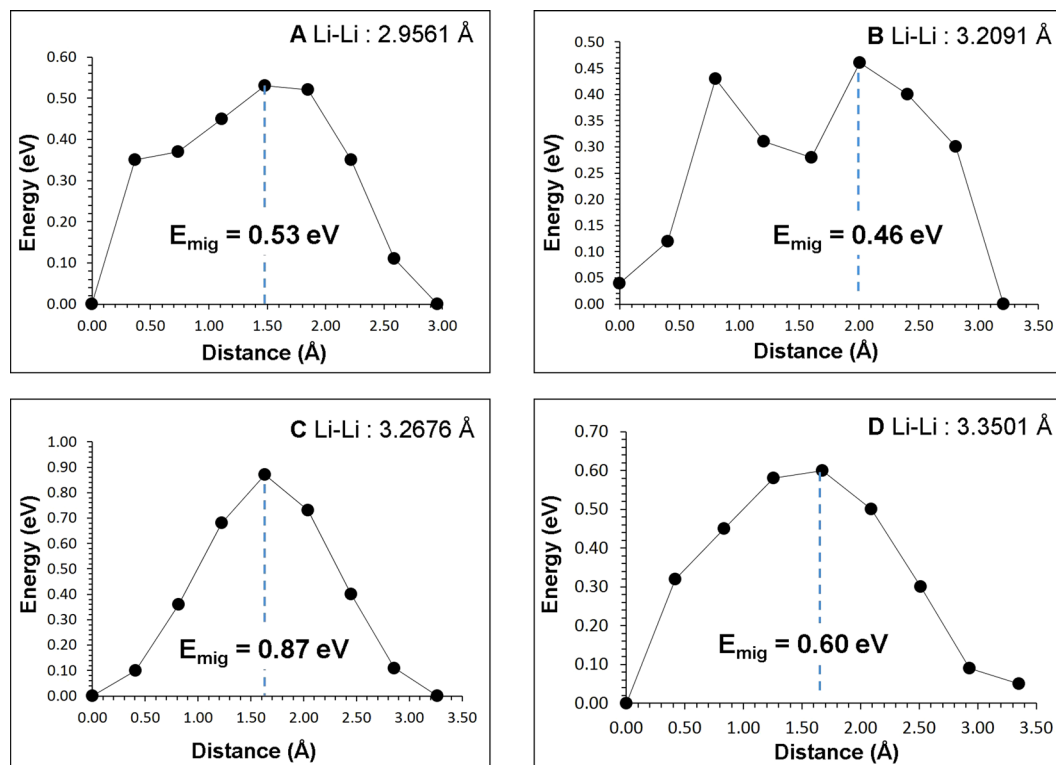


Figure 4. Four different energy profiles (as shown in Fig. 3) of Li vacancy hopping between two adjacent Li sites in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$.

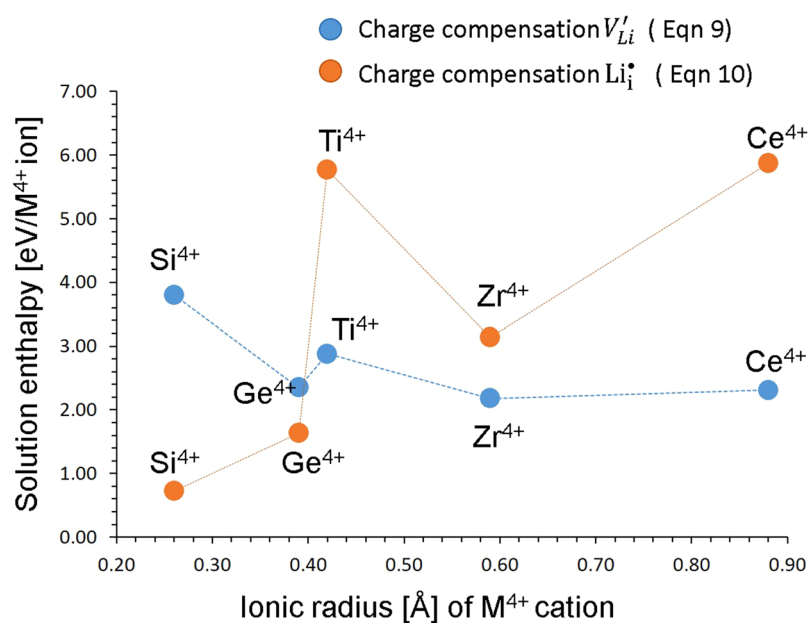


Figure 5. Enthalpy of solution of RO_2 ($R = \text{Si}, \text{Ge}, \text{Ti}, \text{Zr}$ and Ce) with respect to the R^{4+} ionic radius in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$.

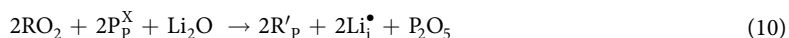


Figure 5 reports the solution energies of RO_2 and it can be observed that the most favorable dopant solution energy is found for Si^{4+} . This suggests that a possible synthesis-doping strategy of introducing additional lithium into $\text{Li}_3\text{V}_2(\text{PO}_4)_3$, although the exact amount of Si incorporation cannot be predicted. The second most favorable dopant is Ge^{4+} . The solution energy increases further with the dopant size.

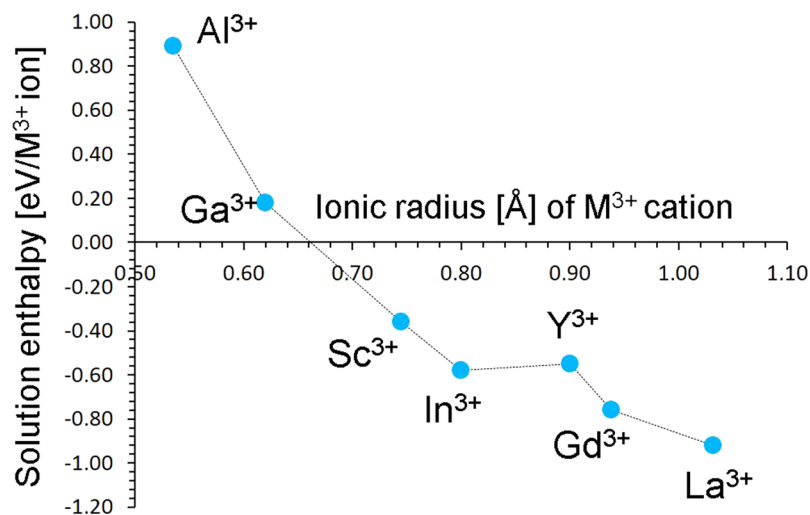


Figure 6. Enthalpy of solution of R_2O_3 ($R = \text{Al, Ga, Sc, In, Y, Gd}$ and La) with respect to the R^{3+} ionic radius in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$.

Concentration of Li ions will be dominated by tetravalent doping via two processes as shown in equations 9 and 10. The formation Li interstitials will be favored by Si and Ge dopants (eqn 10) on the P site whereas Ti, Zr and Ce on the V site will favor the formation of Li vacancies (eqn 9). Solution of these tetravalent dopants will create the corresponding Li defects.

Trivalent doping. A wide range of isovalent substitutions on V sites were considered. The dopant incorporation mechanism does not require the creation of vacancies or interstitials for charge-compensation. Here we considered the solution of R_2O_3 ($R = \text{Al, Ga, Sc, In, Y, Gd}$ and La) via the following process (in Kröger-Vink notation):



In Fig. 6 the solution energies as a function of the dopant ionic radius are reported. The results reveal that the formation enthalpies for the dopants Sc^{3+} , In^{3+} , Y^{3+} , Gd^{3+} and La^{3+} are exoergic suggesting that they are ideal candidates for substitution at the isovalent V site. The solution enthalpy for La^{3+} is highly negative meaning that it is worth investigating the formation of $\text{Li}_3(\text{V,La})_2(\text{PO}_4)_3$ experimentally and its electrochemical performance.

Summary. In the present study, the atomistic simulation techniques have been used to provide detailed insights into intrinsic defects, lithium ion mobility and trivalent doping, which are relevant to the general electrochemical behavior of $\text{Li}_3\text{V}_2(\text{PO}_4)_3$. The dominant energy defect process is Li Frenkel. The Li-V anti-site defect is calculated to be the second most stable defect process suggesting that there would be small intrinsic concentration of Li on V sites at operating temperatures. The long range Li ion diffusion path with lowest migration energy was calculated to be three dimensional with the migration energy of 0.60 eV. Solution energies of RO_2 ($R = \text{Al, Ga, Sc, In, Y, Gd}$ and La) were calculated to increase Li vacancies and extra Li ions in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$. Zr on V site and Si on P site were found to be the efficient strategies to increase Li vacancies and extra Li ions respectively. Promising candidates for isovalent substitution on V site are Sc, In, Y, Gd and La. The present study aims to inspire further experimental work on doped $\text{Li}_3\text{V}_2(\text{PO}_4)_3$.

Methods

To calculate the energetics for the formation of intrinsic defects and the Li ion diffusion pathways, the classical pair potential method as implemented in the GULP package⁴³ was employed. This method is based on the classical Born model description of the ionic crystal lattice. All systems were treated as crystalline solids with interactions between ions consisting of the long-range attractions and short-range repulsive forces representing electron-electron repulsion and van der Waals interactions. The short-range interactions were modelled using Buckingham potentials (refer to Table S1, supplementary information)^{30,31,44–48}. Simulation boxes and the corresponding atom positions were relaxed using the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm⁴⁹. The Mott-Littleton method⁵⁰ was used to investigate the lattice relaxation about point defects and the migrating ions. It divides the crystal lattice into two concentric spherical regions, where the ions within the inner spherical region (on the order of >700 ions) immediately surrounding the defect relaxed explicitly. Li ion diffusion was calculated considering two adjacent vacancy sites as initial and final configurations. Seven interstitial Li ions were considered in a direct linear route and they were fixed while all other ions were free to relax. The local maximum energy along this diffusion path is calculated and reported as activation energy of migration. As the present model assumes a full charge ionic model with the calculations corresponding to the dilute limit the defect enthalpies will be overestimated, however, relative energies and trends will be consistent.

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Author Contributions

N.K. performed the calculations. A.C. contributed to the writing of the paper.

Additional Information

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