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Materials design principles of amorphous cathode coatings for lithium-ion battery applications†

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Cathode surface coatings present one of the most popular and effective solutions to suppress cathode degradation and improve cycling performance of lithium-ion batteries (LIBs). In this work, we carry out an extensive high-throughput computational study to develop materials design principles governing amorphous cathode coating selections for LIBs. Our high-throughput screening includes descriptors to evaluate the thermodynamic stability, electrochemical stability, chemical reactivity with electrolytes and cathodes, and ionic diffusion of the cathode coatings. In the ionic diffusion analysis, we mainly focus on Li-containing compounds. From the 20 selected materials, we highlight the formidable challenge of mitigating oxygen diffusion when selecting an ideal cathode coating, and suggest 7 promising coating candidates: $\text{Li}_3\text{B}_{11}\text{O}_{18}$, $\text{LiZr}_2(\text{PO}_4)_3$, LiB_3O_5 , LiPO_3 , LiSb_3O_8 , LiAlSiO_4 and LiTaSiO_5 . Combining the screening results and detailed ionic diffusion analysis of the selected cathode coatings, we summarize the general selection guidelines of amorphous cathode coatings for LIBs.

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Introduction

Lithium-ion batteries (LIBs) are ubiquitous in portable electronic devices and have enabled the development of cleaner energy storage and electric vehicles (EVs). For the past decade, LIB-powered EVs have gradually penetrated the automotive market. With an increasing demand of reducing greenhouse gas emissions, the global fleet of EVs will continue to rise for the coming decade.¹ Future improvements in LIBs include high energy density cathode materials to enable longer driving range; however these materials frequently operate at high potential and experience surface degradation with associated performance degradation under extended cycling. The current commercialized cathode materials of LIBs are classified as layered ($\text{LiNi}_x\text{Co}_y\text{Mn}_z\text{O}_2$, NMC), spinel (LiMn_2O_4) and olivine (LiFePO_4). Regardless of their crystal structure, these cathode materials all exhibit surface degradation and detrimental surface phase transformations, which compromise the cycle life and thermal stability of LIBs. For example, upon a higher voltage operation (>4.3 V), surface oxygen evolution triggers an irreversible transformation in NMC cathodes from layered phase into a mixture of spinel and rock salt phases that deteriorates capacity retention.² Similarly, in LiMn_2O_4 , surface

oxygen loss causes considerable compressive lattice strain, which densifies the cathode surface and blocks the Li-migration pathways.³ The LiFePO_4 cathode exhibits an excellent capacity retention, however, its eventual failure is associated with the surface amorphization and oxygen loss after the prolonged cycling.⁴ In addition, side reactions between the electrolyte and cathode lead to transition metals dissolution and surface impedance build-up, which further accelerate the capacity/voltage fade.⁵ Therefore, it is of high interest to engineer the cathode surface to achieve high energy density LIBs with a stable, safe, and long-term cycling performance.⁵⁶

A common strategy to stabilize the cathode surface is to apply a multifunctional protective layer to mitigate surface degradation and simultaneously maintain facile Li^+ transport.⁶ Such cathode coatings typically exhibit an amorphous character, with a thickness between 1 to 10 nm.^{7,8} A variety of coating materials have been explored and shown varying degrees of effectiveness in enhancing the cyclability of LIBs, such as metal oxides (e.g., Al_2O_3 (ref. 9)), nonmetal oxides (e.g., B_2O_3 (ref. 10)), polyanionic oxides (e.g., $\text{Li}_3\text{B}_{11}\text{O}_{18}$ (ref. 11)), and fluorides (e.g., AlF_3 (ref. 12)), etc. However, several reported cathode coatings have been found to exhibit chemical and/or electrochemical instability and large overpotential during cycling. For example, Al_2O_3 and ZnO effectively mitigate the side reactions of the cathode surface with the electrolyte,^{9,13} however, the metal oxide coating layer forms a metal oxyfluoride or a metal fluoride layer by scavenging F^- from HF in the electrolyte.^{13,14} Furthermore, because of its inherent low Li^+ ion diffusivity, Al_2O_3 coatings can lead to large overpotentials and reduced capacity, even at a thickness as low as 2 nm.^{15,16} On the other hand, Li-containing compounds have been found to exhibit better capacity retention than their non-

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lithiated counterparts, due to their improved ability to transport Li^+ .¹⁷ However, a recent study found that an NMC cathode surface still transforms from a layered structure into an oxygen loss-induced rock-salt structure after cycling, even when conformally coated with a $\text{Li}_3\text{B}_{11}\text{O}_{18}$ layer.¹¹ Similar surface reconstruction phenomenon has been observed in Al_2O_3 - and AlF_3 -coated cathodes,^{12,18} regardless of liquid-electrolyte or solid-electrolyte battery implementations. As different coating materials may enhance one aspect of performance while hindering or falling short of another, ultimately, the question is what are the optimal coating design choices given the battery application, and can we provide a systematic guidance to identify them?

Given the complex reactions between the cathode, coating and electrolyte and the difficulty in deconvoluting experimentally measured solid state ionic diffusion, first-principles modeling provides robust guidelines for new cathode coatings. Aykol *et al.* reported a high-throughput screening of crystalline oxides materials that can stabilize the cathodes in a liquid-electrolyte battery system.¹⁹ However, ionic diffusivity in the coatings was not considered. Liu *et al.* screened Li-containing crystalline fluoride materials and identified 10 promising coating materials along with their calculated Li^+ migration barriers.²⁰ Xiao *et al.* screened crystalline Li-containing cathode coatings for solid-state batteries and proposed three polyanionic compounds as the most appealing candidates.²¹ We note that the ionic diffusion analyses in all previous computational screening work have addressed exclusively the crystalline coating materials, whereas cathode coatings are often amorphous or polycrystalline. In addition, due to their isotropic non-periodic structures, amorphous films tend to be more conformal than polycrystalline films, with reduced grain boundaries, dislocations, or other defect regions.²² Therefore, amorphous coatings provide a better cathode surface protection against surface oxygen loss and side reactions with electrolytes than polycrystalline coatings. Their unique processability also enables high degrees of interfacial contact with electrodes.²² Moreover, many amorphous solids, such as Li_3PO_4 and Al_2O_3 , have been found to exhibit higher Li^+ conductivity than their crystalline phases.^{23,24} However, to our best knowledge, no study has considered O^{2-} diffusion in amorphous films, which is directly related to the oxygen-loss-induced cathode surface densification. In addition, Li^+ and O^{2-} diffusion corresponds to the kinetics of the coatings but has never been applied broadly or systematically enough to derive design rules. In this work, we carry out an extensive high-throughput computational study to develop materials design principles governing amorphous cathode coating selections for LIBs. We evaluate the thermodynamic stability, electrochemical stability, chemical reactivity with electrolytes and cathodes, as well as the Li^+ and O^{2-} diffusion in amorphous cathode coatings. Based on the trends in the screening results and ionic transport, we summarize general guidelines for selecting amorphous cathode coatings.

Computational details

First-principles calculation

All density functional theory (DFT) calculations are performed using the Vienna *Ab initio* Simulation Package (VASP),^{25,26} with

Projector Augmented Wave (PAW) potentials.²⁷ The generalized gradient approximation (GGA) as parameterized by the Perdew–Burke–Ernzerhof (PBE)²⁸ is used for the exchange–correlation functional. For AIMD simulations, we employ Γ -point only Brillouin zone integration at a plane-wave cutoff energy of 400 eV and a time step of 2 fs.

We utilize a “liquid-quench” process to generate the amorphous structures, in which heating, equilibration, and quenching are performed through an AIMD workflow, which can be found as part of the open-source mpmorph package at <https://github.com/materialsproject/mpmorph>. We use the Packmol package²⁹ to generate all initial amorphous structures. To generate the “liquid” phase of the amorphous structures, we equilibrate the structures at 3000 K using a sequence of 4 ps AIMD simulations in the NVT ensemble until the external pressure and energy are converged. Next, the structures are simulated for an additional 10 ps, from which three independent configurations are selected and quenched to 0 K to obtain the ground-state amorphous structures. To perform ion diffusion analysis, we equilibrate the ground-state structure at $T = 1800, 2000, 2200, 2400, 2600,$ and 2800 K, and then simulate an 80 ps diffusion trajectory at each corresponding temperature. The equilibration procedure follows the same steps used to equilibrate the “liquid” amorphous structure. In the end, there are three independent diffusion trajectories at each temperature. Further details about the entire AIMD and DFT workflows can be found in ref. 30.

Self-diffusion coefficients and overpotentials

From the obtained diffusion trajectories, we calculate the self-diffusion coefficients (D) of Li^+ and O^{2-} ions in amorphous structures using the Einstein relation: $D = \frac{1}{6} \frac{d\langle \Delta r^2 \rangle}{dt}$, where t is the time, r is the ion position and $\langle \Delta r^2 \rangle$ is the mean square displacement (MSD). Within the temperature window 1800–2800 K, there are three D values calculated from three independent diffusion trajectories at each temperature. The D values at room temperature are extrapolated from those at high temperatures using the Arrhenius relation of D as a function of T : $D = D_0 \exp(-E_a/k_B T)$, where k_B is the Boltzmann constant, D_0 is the pre-exponential factor and E_a is the activation energy of ion diffusion. In addition, the trajectories at lower temperatures (*e.g.* 1800 K) frequently exhibit fewer ionic hops, which incurs higher statistical uncertainties of fitted D values than those at higher temperatures (*e.g.* 2800 K). Therefore, we consider the uncertainty of the D values at each temperature when linearly fitting $\log D$ vs. $1/T$ by assigning the standard deviation of $\log D$ as the uncertainty for each averaged D .

From the calculated room temperature Li^+ diffusivity $D_{\text{Li}}^{\text{Li}}$, we estimate the overpotential, ΔV , across a cathode coating layer using a theoretical model which assumes a constant potential gradient, a uniform Li^+ concentration and the Einstein relation to relate Li^+ mobility and diffusion coefficient in the coating.^{31,32} The model calculates ΔV as a function of current density, coating thickness, Li^+ concentration, Li^+ diffusivity and temperature, providing a qualitative evaluation on coating's



ability to transport Li⁺ ions. The relation between ΔV and $D_{\text{rt}}^{\text{Li}}$ follows the methodology used in the earlier work,^{24,33} namely:

$$\Delta V = \frac{J l_c k_B T}{D_{\text{rt}}^{\text{Li}} c^{\text{Li}} q^2} \quad (1)$$

where l_c is the coating thickness, k_B is the Boltzmann constant, T is the temperature, c^{Li} is the Li⁺ concentration in the coating, q is the electron charge, *i.e.*, $q = |e| = 1.602 \times 10^{-19}$ C, and J is the current density through the cathode coating, which results from a flux of Li⁺ ions and can be approximated as:²⁴

$$J = \frac{\rho V_P C}{S_P t} = \frac{\rho r C}{3t} \quad (2)$$

where ρ is cathode density, V_P is the particle volume, S_P is the particle surface area, r is the particle radius, C is the cathode capacity, and t is the charging/discharging time. Combining eqn (1) and (2), ΔV can be expressed as:

$$\Delta V = \frac{\rho r C}{3t} \frac{l_c k_B T}{D_{\text{rt}}^{\text{Li}} c^{\text{Li}} q^2} \quad (3)$$

In the ESI† we provide the full derivation and assumptions for eqn (1). According to eqn (2), the current density J is normalized by the cathode surface area, while experimentally, J is more commonly normalized by geometric area of the cathode disk. In addition, we assume that the entire spherical cathode particle surface area is available for Li⁺ intercalation.

Oxygen flux and transport time

We use the Onsager transport equations to estimate the O²⁻ flux J^{O} under the driving force of the oxygen chemical potential gradient $\nabla \mu^{\text{O}}$ across the coating layer, which can be expressed as:

$$J^{\text{O}} = -L^{\text{OO}} \nabla \mu^{\text{O}} \quad (4)$$

where L^{OO} is the Onsager transport coefficient for oxygen transport. It should be noted that in this study we ignore the contributions from cross-correlations between oxygen and other species, such as L^{OLi} , and between distinct oxygen sites, *i.e.* $L_{\text{distinct}}^{\text{OO}}$, to J^{O} . We approximate the $\nabla \mu^{\text{O}}$ to be a constant across the thickness of the coating under steady-state conditions. Therefore, eqn (4) can be expressed as:

$$J^{\text{O}} = L^{\text{OO}} \frac{\mu_c^{\text{O}} - \mu_e^{\text{O}}}{l_c} \quad (5)$$

where μ_c^{O} and μ_e^{O} are the oxygen chemical potential at the cathode and electrolyte sides, respectively. Ignoring the $L_{\text{distinct}}^{\text{OO}}$ term, L^{OO} can be directly related to the self-diffusion coefficient D^{O} :³⁴

$$L^{\text{OO}} \approx L_{\text{self}}^{\text{OO}} = \frac{D^{\text{O}} c^{\text{O}}}{k_B T} = \frac{D_0^{\text{O}} e^{-\frac{E_a}{k_B T}} c^{\text{O}}}{k_B T} \quad (6)$$

where c^{O} is the O²⁻ concentration in the coating. The room-temperature $L_{\text{rt}}^{\text{OO}}$ is extrapolated from L^{OO} values at high temperatures by fitting eqn (6). It should be noted that previous experiments have reported several active oxygen intermediates

during oxygen evolution reactions at cathode surface, such as covalent peroxide bonds, oxygen radicals and singlet oxygen (¹O₂).^{35–37} Because of their high reactivity, we assume these oxygen intermediates will react with the coating materials and become O²⁻. Therefore, we use O²⁻ diffusion to represent oxygen diffusion in the coatings.

Materials database and descriptors

The entire database used in this study contains 146 323 crystalline compounds, which are queried from the Materials Project (v2021.11.10).³⁸ The materials properties include DFT calculated total energies, formation energies, energies above convex hull (E_{hull}), band gaps (E_g), *etc.* It should be noted that at zero temperature, the Gibbs free energy of a crystalline polymorph is always lower than that of its amorphous state.³⁹ However, there is no universal description for the energetics of the amorphous materials, therefore we use the energies of the crystalline phases to approximate the stability of the amorphous phases. Indeed, the distribution of synthesizable crystalline polymorph energies tends to follow the trend of the amorphous energies.³⁹

Phase stability. A compound's E_{hull} value is calculated by constructing the convex hull that includes the formation energies of all known crystalline phases in the same chemical space. The compounds that constitute the convex hull, *i.e.* have $E_{\text{hull}} = 0$, are deemed stable phases (at low temperature) or ground states for the system studied. The E_{hull} value for metastable phases therefore provides a measure of the driving force for decomposition and a descriptor for the phase stability of each compound.

Electrochemical stability. The calculations of the electrochemical stability window follow the methodology proposed by Aykol *et al.*,¹⁹ which combines DFT formation energies in the Materials Project, experimental thermochemical data for gaseous species and experimental electrochemical data for solvated ions. First, we calculate the standard Gibbs free energy of a reaction (ΔG^0), which is obtained as:

$$\Delta G^0 = G_{\text{products}} - G_{\text{reactants}} \quad (7)$$

At room temperature, we assume the entropy contributions of solid phases are negligible while the entropy contributions of gaseous species (O₂, F₂, Cl₂, H₂ and N₂) are much higher than that of solid phases. For the gaseous species, their entropy values S at room temperature are taken from the JANAF tables.⁴⁰ Thus, ΔG^0 can be approximated as:

$$\Delta G^0 \approx H_{\text{products}} - H_{\text{reactants}} - T(S_{\text{gaseous products}} - S_{\text{gaseous reactants}}) \quad (8)$$

where H represents enthalpy. For solid phases, we assume $P\Delta V$ contributions are negligible and H can be approximated with the DFT calculated internal energy E at 0 K. For gaseous species, we add the anion corrections, which also includes the $P\Delta V$ contribution to their enthalpy.⁴¹ For a reaction involved with solvated ions, we assume a one-step single ion dissolution: $A = A^{n+} + ne^-$ and we add the standard free energy of formation of



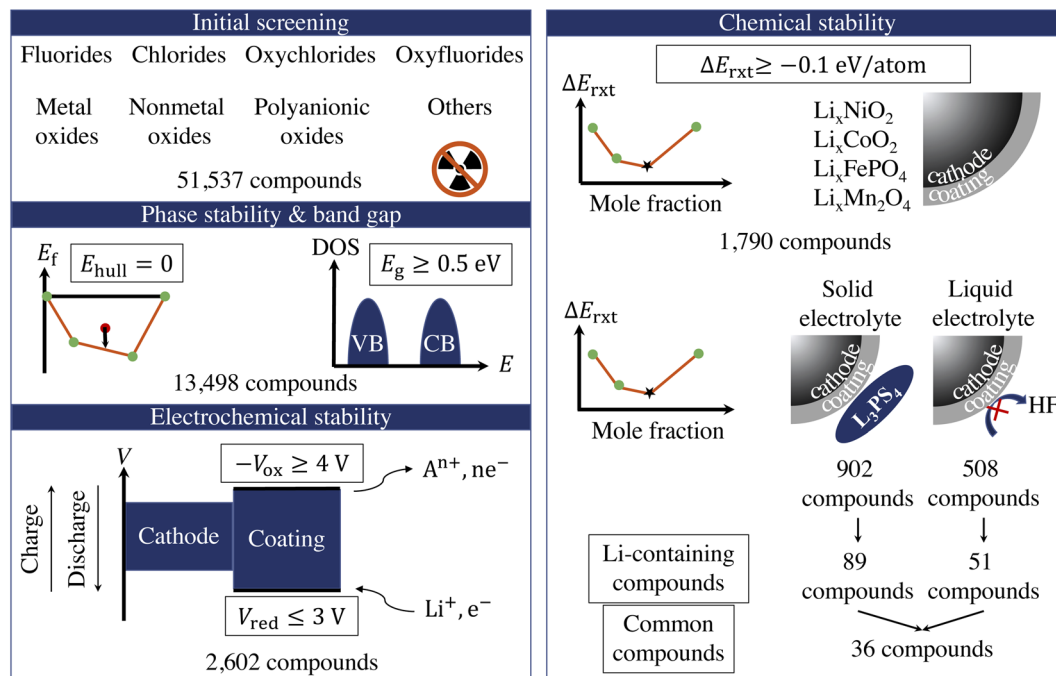


Fig. 1 The flowchart of the high-throughput computational screening of cathode coating materials. Compounds with radioactivity or energy above convex hull (E_{hull}) greater than 0 are excluded. Compounds with band gap (E_{g}) smaller than 0.5 eV are excluded. Compounds with reduction limit (V_{red}) above 3 V or oxidation limit ($-V_{\text{ox}}$) below 4 V are excluded. Compounds with reaction energy (ΔE_{rxt}) with cathode or electrolyte smaller than -0.1 eV per atom are excluded.

oxidation limit of B_2O_3 is estimated using the $-V_{\text{ox}}$ value of $\text{Li}_3\text{B}_{11}\text{O}_{18}$. In the ESI,[†] we illustrate the procedures of calculating $[V_{\text{red}}, -V_{\text{ox}}]$ for LiAl_5O_8 , Al_2O_3 and B_2O_3 coatings. For a cathode coating to be electrochemically stable during charge, its $|V_{\text{ox}}|$ magnitude should be larger than the charge cutoff voltage of the cathode, as shown in Fig. 1. As the oxidation reaction processes are likely to exhibit slow kinetics, an overpotential is expected during the charging cycle. Therefore, we set $|V_{\text{ox}}|$ to be 4 V, even though a typical cathode material can be charged up to as high as 4.5 V. The use of electrochemical stability descriptor returns 2602 compounds for further consideration. Fig. 2a illustrates the reduction and oxidation limits of the compounds that are thermodynamically stable. The electrochemical stability of each category is denoted by two violin plots: the left and right represent oxidation and reduction limits, respectively. We find that in general, fluorides, such as AlF_3 and LiAlF_4 , have the largest electrochemical stability window with high oxidation limits and low reduction limits. On the other hand, metal oxides, such as BaO and Bi_2O_3 , exhibit low oxidation limit, and nonmetal oxides, such as P_2O_5 and SeO_2 , have high reduction limit. The bar graph in Fig. 2a summarizes the numbers of compounds for each category of materials that pass the electrochemical stability screening. After this screening tier, polyanionic oxides have the largest number of candidates, followed by fluorides and chlorides. There are only 12 metal oxides and 1 nonmetal oxide, B_2O_3 , left for further screening.

The fourth attribute we consider is the chemical stability of the cathode coatings. It has been shown that a coating material

can react with cathodes and electrolytes to form new phases at cathode/coating and coating/electrolyte interfaces, respectively.^{7,16} Therefore, we screen for cathode coatings that are inert to chemical reactions with both cathodes and electrolytes. The reaction energy ΔE_{rxt} is calculated using DFT-computed energies of the reactants and products, and a more negative ΔE_{rxt} indicates a more reactive chemical reaction. We set the criterion for chemically stable cathode coatings as: $\Delta E_{\text{rxt}} \geq -0.1 \text{ eV}$ per atom.²¹ We calculate ΔE_{rxt} between cathodes and coating materials using the commonly used cathodes, layered LiNiO_2 and LiCoO_2 , spinel LiMn_2O_4 , and olivine LiFePO_4 . Both lithiated and half-lithiated cathodes are considered corresponding to the discharge and charge cycles, respectively. We select the most negative ΔE_{rxt} , *i.e.*, the most favorable chemical reaction, as the $\Delta E_{\text{rxt}}^{\text{cathodes}}$ for each compound, and we plot $\Delta E_{\text{rxt}}^{\text{cathodes}}$ for each category that pass the electrochemical stability descriptor in Fig. 2b. In Fig. S2,[†] we also plot ΔE_{rxt} of each selected cathode material. We find that compared with other cathodes, LiNiO_2 tends to exhibit a more negative ΔE_{rxt} , therefore reacts more favorably with the coating materials. In addition, oxides coatings are less prone to react with cathodes than fluorides and chlorides. Specifically, all the electrochemically stable metal oxides exhibit low reactivity with common cathodes and pass the chemical stability descriptor. This round of screening returns 1790 compounds for further consideration with polyanionic oxides having the largest number of candidates (714).

Similarly, we calculate ΔE_{rxt} between coating materials and representative electrolyte components. In this study, we consider the commonly used Li_3PS_4 solid electrolyte and LiPF_6



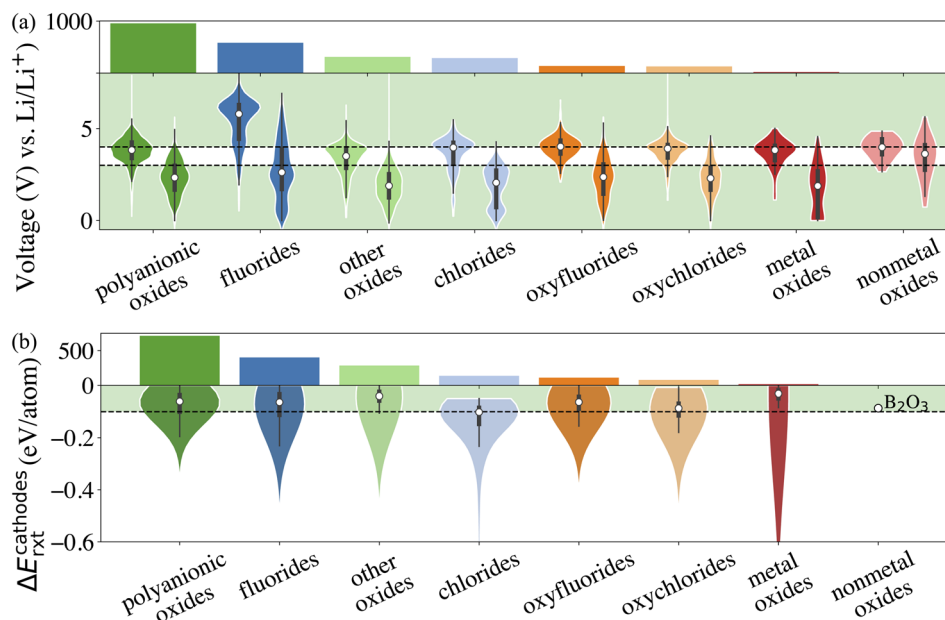


Fig. 2 (a) Distribution of the reduction and oxidation limits for each category that pass thermodynamic stability descriptor. (b) Distribution of the reaction energy ΔE_{rxn} with LiNiO_2 , LiCoO_2 , LiMn_2O_4 and LiFeOP_4 cathodes for each category that pass electrochemical stability descriptor. Both lithiated and half-lithiated cathodes are evaluated and the most negative ΔE_{rxn} is selected as ΔE_{rxn} with cathodes. The horizontal dash lines represent the limits of the descriptors. The histograms in (a) and (b) illustrate the numbers of compounds for each category that pass the descriptors.

based non-aqueous liquid electrolytes, respectively, and categorize the coating materials based on their reactivity. In the case of LiPF_6 -based electrolytes, we calculate ΔE_{rxn} between coating materials and HF, which is known to react strongly with both cathodes and coating materials. Fig. 3 illustrates the distribution of ΔE_{rxn} with Li_3PS_4 and HF for the compounds that are chemically stable with the cathodes. We find that most fluorides and chlorides have lower chemical reactivity with both Li_3PS_4 and HF than oxides compounds, thus are chemically compatible with both the cathodes and electrolytes. On the other hand, most oxides compounds are not chemically inert in LiPF_6 -based liquid electrolytes due to a high reactivity with HF. It should be noted that these chemical reactions may only happen at the coating/electrolyte interface and render a partially fluorinated oxides coating layer, which could be beneficial for the cycling performance.⁴⁶ Therefore, even though we categorize the coatings based their chemical compatibility with liquid and solid electrolyte, the materials may be effective in both conditions. It should be noted that in LiPF_6 -based liquid electrolyte systems, besides fluorination of the coating layer from an HF attack, other organic species and Li_2CO_3 can also be found on the surface of the coated cathodes. We only consider the HF attack to broadly capture the chemical compatibility between coatings and LiPF_6 -based liquid electrolytes in a high-throughput fashion. This round of screening returns 902 and 508 coating candidates that are chemically compatible with Li_3PS_4 and LiPF_6 based electrolytes, respectively.

In this study, we are mainly interested in the Li-containing compounds, as lithiated compounds tend to exhibit a higher ionic conductivity.³⁰ Adding the Li-containing criterion, the

entire screening procedure returns 89 and 51 Li-containing compounds that pass the proposed criteria for stability with respect to Li_3PS_4 solid state electrolyte and HF, respectively, with 36 compounds that are chemically compatible with both Li_3PS_4 and HF. In Fig. S2,[†] we summarize the numbers of Li-containing compounds for each category that pass the phase stability, electrochemical stability, and chemical stability descriptors. We find that oxides coatings, especially polyanionic oxides, account for the largest number of coatings for Li_3PS_4 -based LIB, followed by fluorides and chlorides. On the other hand, the majority of coatings for LiPF_6 -based LIB are fluorides and chlorides. The common coatings only consist of the fluorides and chlorides. In Table S3,[†] we list the calculated voltage windows, reduction and oxidation reactions, and reaction energies for the 104 Li-containing compounds that pass the screening criteria. In ESI,[†] we list the calculated material attributes of coating candidates.

Ion diffusion analysis

Our computational screening procedure has narrowed down the coatings of interest to 104 Li-containing compounds. Besides providing facile Li^+ diffusion pathways, an optimal cathode coating should block O^{2-} diffusion such that the oxygen-loss-induced cathode surface reconstruction can be mitigated. Therefore, to evaluate Li^+ and O^{2-} transport in the screened amorphous coatings, we calculate ionic diffusivity, flux, and transport time through the coating materials using *ab initio* molecular dynamics (AIMD) simulations and Onsager transport models, as described in Computational details. Due to the high computational cost of investigating the ionic



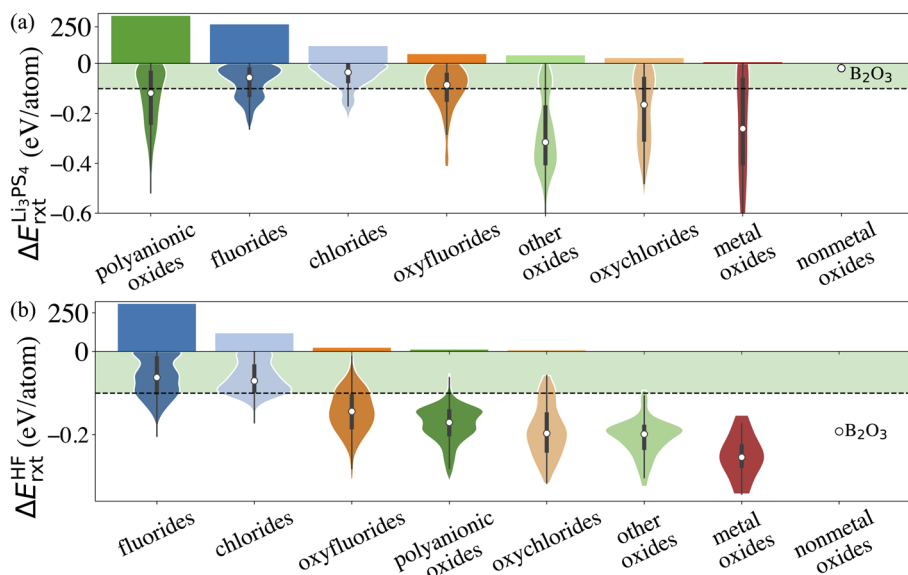


Fig. 3 Distribution of the reaction energy ΔE_{rxt} with Li_3PS_4 (a) and HF (b) for each category that pass chemical stability with the cathodes descriptor. The horizontal dash lines represent the limits of the descriptors. The histograms in (a) and (b) illustrate the numbers of compounds for each category that pass the descriptors.

diffusivity of all promising coating candidates, we select 9 representative compounds, consisting of polyanionic oxides $\text{Li}_3\text{B}_{11}\text{O}_{18}$, $\text{LiZr}_2(\text{PO}_4)_3$, Li_3PO_4 , $\text{Li}_2\text{B}_3\text{PO}_8$ and LiB_3O_5 , fluorides Li_3AlF_6 , LiCaAlF_6 , LiYF_4 and chloride Li_2ZnCl_4 , and analyze their ion diffusion. Fig. 4 illustrates the distribution of $D_{\text{rt}}^{\text{Li}}$ and D_{rt}^{O} in the selected compounds, along with 7 Li-containing compounds that are filtered out by electrochemical or chemical stability criterion: LiNbO_3 , Li_2HfO_3 , LiAlO_2 , LiTaSiO_5 , LiPO_3 , LiAlSiO_4 , and LiSb_3O_8 , and 4 binary oxides: Li_2O , ZnO ,

Al_2O_3 , Sb_2O_5 . Our calculations show that in general, Li^+ and O^{2-} diffusion is correlated, *i.e.*, a compound with a higher $D_{\text{rt}}^{\text{Li}}$ also has a higher D_{rt}^{O} . For example, the $D_{\text{rt}}^{\text{Li}}$ and D_{rt}^{O} in Li_3PO_4 are 10^{-9} and $10^{-10} \text{ cm}^2 \text{ s}^{-1}$, respectively, both of which are higher than those in LiAlSiO_4 ($D_{\text{rt}}^{\text{Li}} = 10^{-14} \text{ cm}^2 \text{ s}^{-1}$, $D_{\text{rt}}^{\text{O}} = 10^{-23} \text{ cm}^2 \text{ s}^{-1}$). The correlation between Li^+ and O^{2-} diffusion can be explained by ionic conduction mechanism in amorphous structures. Our previous study³⁰ showed that Li^+ and O^{2-} diffusion consists of discrete vibrational and translational motions. During vibrational motions, Li^+ is bonded to more O^{2-} ions than during translational motions, and its translation to another vibration site is activated by the Li–O bond breaking/formation process, which effectively explains the correlated transport between Li^+ and O^{2-} . In addition, we find that for compounds consisting of the same species, a compound with a higher Li^+ concentration also has a higher Li^+ and O^{2-} diffusion. For example, comparing $\text{Li}_3\text{B}_{11}\text{O}_{18}$ and LiB_3O_5 , we find that LiB_3O_5 , which has a higher Li^+ concentration, exhibits a higher $D_{\text{rt}}^{\text{Li}}$ and D_{rt}^{O} . Similar behavior is found in LiPO_3 and Li_3PO_4 , relating to their $D_{\text{rt}}^{\text{Li}}$ and D_{rt}^{O} . Our results are consistent with Xu *et al.*'s work in which they found that a higher Li^+ solubility will enhance the Li^+ transport across the coating.²⁴ In our work, we further demonstrate that, unfortunately, a higher Li^+ concentration also correlates with increased, detrimental O^{2-} transport.

From the calculated $D_{\text{rt}}^{\text{Li}}$ and D_{rt}^{O} , we evaluate the coating suitability of the selected compounds in terms of their ability to facilitate Li^+ transport while blocking O^{2-} transport. Low Li^+ diffusivity within the cathode coating layer can increase resistance and capacity loss at higher C-rates due to the resulting large overpotential at higher currents.⁴⁷ Thus, for the selected coating compounds, we estimate the overpotential, ΔV , at the cathode surface. We set the criterion for overpotential imposed by the coating as $\Delta V \leq 0.1 \text{ V}$, above which the Li^+ transport

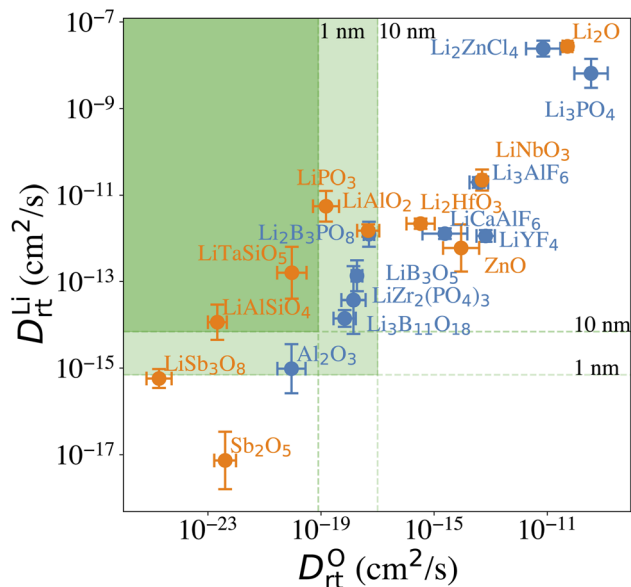


Fig. 4 Calculated room-temperature self-diffusion coefficients of Li^+ ($D_{\text{rt}}^{\text{Li}}$) and O^{2-} (D_{rt}^{O}) in the selected compounds. The dash lines represent the approximated $D_{\text{rt}}^{\text{Li}}$ and D_{rt}^{O} limits based on a coating thickness between 1 to 10 nm.



across the coating will be significantly compromised. In this study, we choose LiNiO_2 as the relevant cathode material, with density $\rho = 4.78 \text{ g cm}^{-3}$ and a theoretical capacity $C = 274 \text{ mA h g}^{-1}$. Eqn (3) shows that a smaller ΔV can be realized by reducing the cathode particle size and coating thickness, and selecting a coating with high Li^+ diffusivity $D_{\text{rt}}^{\text{Li}}$ and concentration c^{Li} . By assuming a radius $r = 1 \mu\text{m}$ LiNiO_2 primary particle and a 1C rate current density through the coating, the current density J is estimated to be 0.044 mA cm^{-2} . Finally, using $D_{\text{rt}}^{\text{Li}}$ and the Li^+ concentration of the compounds, we calculate the ΔV values across a 1 and 10 nm conformal coating, respectively. Fig. 5a shows that for 1 nm surface coatings, all the selected compounds, except Sb_2O_5 (23 V) and LiSb_3O_8 (0.18 V), result in overpotentials below 0.1 V, which indicates a sufficient Li^+ transport in these compounds. The overpotential of the Al_2O_3 coating is found to be 0.07 V. When the coating thickness is increased to 10 nm, the overpotentials of Sb_2O_5 , LiSb_3O_8 and Al_2O_3 coatings increase to 230 V, 1.8 V and 0.7 V, respectively, while the overpotentials of other compounds are still below 0.1 V. Using an $r = 1 \mu\text{m}$ LiNiO_2 primary particle in a 1C rate current density, we estimate the minimum Li^+ diffusivity $D_{\text{rt}}^{\text{Li}}$ to meet the overpotential criterion of $\Delta V \leq 0.1 \text{ V}$. By assuming a Li^+ concentration $c^{\text{Li}} = 10^{22} \text{ cm}^{-3}$, we find that $D_{\text{rt}}^{\text{Li}} = 7 \times 10^{-16} \text{ cm}^2 \text{ s}^{-1}$ and $7 \times 10^{-15} \text{ cm}^2 \text{ s}^{-1}$ for a 1 and 10 nm cathode coating, respectively, which are represented by the horizontal dashed lines in Fig. 4.

To evaluate the effectiveness of these coatings in blocking O^{2-} transport, we estimate the O^{2-} flux J^{O} and the time t required for O^{2-} to diffuse through the coating. We assume the oxygen-loss-induced surface rocksalt layer mainly consists of NiO , which is densified from the layered NiO_2 . As $\text{NiO}_2 \rightarrow \text{NiO} + 1/2\text{O}_2$, we estimate t for surface NiO_2 layer to lose half of its oxygen and transform into an NiO layer. Let $c_{\text{max}}^{\text{O}}$ denote the O^{2-}

concentration in NiO_2 and V_s represent the shell volume of the surface NiO layer. $V_s = \frac{4}{3}\pi[r^3 - (r - l_s)^3]$, where l_s is the thickness of the surface NiO layer. Thus, the upper bound value of the number of O^{2-} ions removed from the cathode surface is $N = 0.5V_s c_{\text{max}}^{\text{O}}$ and the O^{2-} diffusion time t can be expressed as:

$$t = \frac{N}{S_P J^{\text{O}}} = \frac{0.5V_s c_{\text{max}}^{\text{O}}}{S_P J^{\text{O}}} \quad (14)$$

where $S_P = 4\pi r^2$ is the cathode particle surface area. Combining eqn (14) and (15), t can be expressed as:

$$t = \frac{0.5V_s}{S_P} \frac{c_{\text{max}}^{\text{O}} l_c}{L^{\text{OO}}(\mu_c^{\text{O}} - \mu_e^{\text{O}})} = \frac{r^3 - (r - l_s)^3}{6(r + l_c)^2} \frac{c_{\text{max}}^{\text{O}} l_c}{L^{\text{OO}}(\mu_c^{\text{O}} - \mu_e^{\text{O}})} \quad (15)$$

μ_c^{O} can be estimated from the cathode densification reaction consistent with the phase diagram. At a high charge state, layered NiO_2 would densify to rocksalt NiO and spinel Ni_3O_4 with oxygen being released at $\mu_c^{\text{O}} = -4.95 \text{ eV}$, which is equal to the DFT-calculated total energy of an O_2 atom. μ_e^{O} can be estimated from two different conditions: (1) using the condition where the electrolyte reacts with O^{2-} and forms a new compound (Li_3PS_4 reacts with O^{2-} and forms Li_3PO_4 at $\mu_e^{\text{O}} = -8.39 \text{ eV}$) and (2) using the condition where O^{2-} loses electrons to the carbon network and forms O_2 (at room temperature and $P\text{O}_2 = 0.21 \text{ atm}$, $\mu_e^{\text{O}} = -5.24 \text{ eV}$). Thus, we estimate $-8.39 \leq \mu_e^{\text{O}} \leq -5.24 \text{ eV}$. Eqn (15) indicates that for a given cathode coating and a given size of LiNiO_2 primary particle, a longer O^{2-} diffusion time t can be realized by a smaller oxygen chemical potential gradient, *i.e.*, higher l_c and μ_e^{O} . By assuming an $r = 1 \mu\text{m}$ LiNiO_2 primary particle and an $l_s = 2 \text{ nm}$ surface NiO layer, we estimate the time t for O^{2-} ions to diffuse through the selected coatings (see Fig. 5b). We consider a range of conditions by varying l_c and μ_e^{O} , with $l_c = 10 \text{ nm}$, $\mu_e^{\text{O}} = -5.24 \text{ eV}$

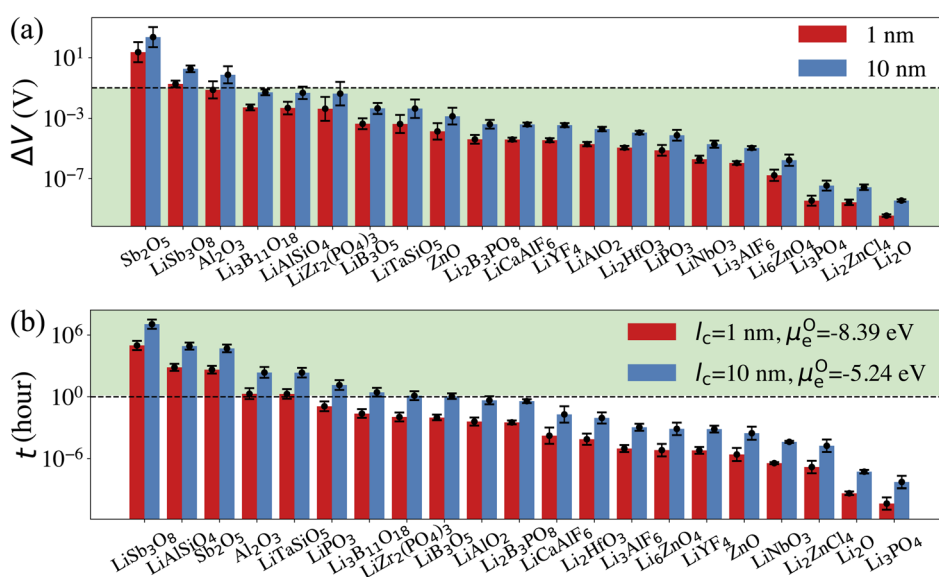


Fig. 5 (a) Calculated overpotentials (ΔV) for a current density of 0.044 mA cm^{-2} across room temperature cathode coatings of $l_c = 1$ and 10 nm . The dashed line represents $\Delta V = 0.1 \text{ V}$. (b) Calculated O^{2-} diffusion time t in the selected compounds assuming a $r = 1 \mu\text{m}$ primary particle and an $l_s = 2 \text{ nm}$ surface rocksalt phase. The dashed line represents $t = 1 \text{ h}$.



prone to oxygen loss and are likely to transform over time into a densified rocksalt phase.

(4) Although non-Li containing, Al_2O_3 can be considered as a promising cathode coating. We estimate that the diffusion time of oxygen in an Al_2O_3 coating varies between 2 to 227 h, depending on l_c and $\nabla\mu^{\text{O}}$ (see Fig. 4). Thus, we predict that an NMC cathode coated with a thin Al_2O_3 coating layer, such as 1 nm, is still prone to surface oxygen loss, especially when cycled at low C-rate. This result could explain why a 3 nm Al_2O_3 surface coating is not sufficient to stabilize NMC cathode surface when cycled at C/7.¹⁸ On the other hand, a thicker Al_2O_3 coating layer can effectively mitigate O^{2-} transport, which results in a better cathode surface protection; David *et al.* showed that an Al_2O_3 ALD coating can effectively prevent surface reconstruction of NMC cathodes even after 760 cycles,⁵⁵ which indicates that a thick and conformal Al_2O_3 coating was applied on the NMC cathodes in their study.

(5) An optimal amorphous cathode coating should not only exhibit sufficient thermodynamic stability, electrochemical stability and chemical stability, but also a low O^{2-} diffusivity and a high Li^+ diffusivity to achieve oxygen-retaining and surface-protective functions while avoiding significant losses in rate capability. However, the correlation between Li^+ and O^{2-} diffusion in amorphous coatings highlights the inherent contradiction in identifying cathode coating materials with optimal Li^+ transport as well as O^{2-} blocking ability. In general, Li^+ diffusion in Li-containing compounds is fast enough to avoid a large overpotential. As a higher Li^+ diffusion may compromise a coating's ability to block O^{2-} diffusion, for compounds with same chemistry, a compound with a lower Li^+ concentration is thus preferred. For example, the Li^+ concentrations in LiPO_3 and Li_3PO_4 are 20% and 37.5%, respectively. Fig. 4 shows that both LiPO_3 and Li_3PO_4 exhibit a facile Li^+ diffusion, but LiPO_3 exhibits an improved oxygen retention as compared to Li_3PO_4 . In addition, the oxidation limit of LiPO_3 (4.9 V) is higher than that of Li_3PO_4 (4.0 V).

Conclusions

In summary, we have carried out an extensive high-throughput computational study to develop materials design principles governing amorphous cathode coating selections for Li-ion battery applications. Our high-throughput screening includes descriptors to evaluate the thermodynamic stability, electrochemical stability, chemical reactivity with electrolytes and cathodes, and ionic diffusion in the cathode coatings. We consider reactivity with the commonly used Li_3PS_4 solid state electrolyte and with HF as a particularly detrimental representative of liquid electrolyte degradation. We find that polyanionic oxides account for the largest number of cathode coatings for Li_3PS_4 -based LIB, followed by fluorides and chlorides. On the other hand, the majority of cathode coatings that are inert to chemical reactions with HF are fluorides and chlorides. Combining the screening results and ionic diffusion analysis of 20 selected compounds, we summarize the promising cathode coatings and general materials design principles:

(1) Li^+ and O^{2-} diffusion are highly correlated, therefore, a higher Li^+ transport promotes higher O^{2-} transport. In Li-containing compounds, the Li^+ diffusion rate is generally fast enough to avoid a large overpotential. When selecting a cathode coating with same chemistry, a compound with a lower Li concentration is preferred, as it exhibits an improved oxygen retention as well as a higher oxidation limit.

(2) Mitigating O^{2-} diffusion is a formidable challenge when selecting an ideal cathode coating as most thin conformal coatings will transport oxygen under prolonged cycling and high voltage. Our results show that in addition to the four experimentally confirmed cathode coatings: $\text{Li}_3\text{B}_{11}\text{O}_{18}$, $\text{LiZr}_2(\text{PO}_4)_3$, LiPO_3 and LiAlSiO_4 , we also identify three new promising cathode coatings: LiB_3O_5 , LiSb_3O_8 and LiTaSiO_5 .

(3) Based on our ionic diffusion analysis, we find that BO_x^{y-} , SiO_x^{y-} , PO_x^{y-} and SbO_x^{y-} anion groups tend to exhibit an improved oxygen retention. Therefore, we expect that compounds such as $\text{LiBa}(\text{B}_3\text{O}_5)_3$, $\text{LiAl}(\text{Si}_2\text{O}_5)_2$, $\text{LiTi}_2(\text{PO}_4)_3$, LiScP_2O_7 , $\text{LiK}(\text{PO}_3)_2$, and $\text{LiCs}(\text{PO}_3)_2$ could also be potentially effective cathode coatings. On the other hand, F^- and Cl^- anion groups tend to exhibit faster Li^+ and O^{2-} diffusion as compared to the oxides. Thus, they are not ideal for high-voltage cathode coatings where the driving force for oxygen loss is high. However, their inherent fast Li^+ diffusivity may render them promising candidates as the solid-state electrolytes or lithium metal coatings.

(4) A non-Li-containing compound generally exhibits slower Li^+ diffusion but better oxygen retention ability as compared to its lithiated counterpart. We mainly consider Li-containing compounds in this study, however, we expect that effective cathode coatings can also be found in non-lithiated compounds, such as Al_2O_3 . Based on our identified anion groups above, we expect that compounds, such as ScBO_3 , HfSiO_4 , ZrP_2O_7 and AlPO_4 , could be potentially effective cathode coatings. A follow-up study on non-Li-containing coatings will be presented in a later report.

Conflicts of interest

There are no conflicts to declare.

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