



Ion Transport in the Structures of Conducting Mineral-like Crystals [†]

Dmitry Pushcharovsky ^{1,*} and Alexey Ivanov-Schitz ²

¹ Geological Faculty, Lomonosov Moscow State University, Leninskie Gory 1, Moscow 119991, Russia

² Kurchatov Complex of Crystallography and Photonics (KCCF), National Research Center “Kurchatov Institute”, Leninsky pr., 59, Moscow 117333, Russia; alexey.k.ivanov@gmail.com

* Correspondence: dmitp@geol.msu.ru

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Abstract

The paper gives an overview of new ideas related to the characterization of the structural features of minerals and their synthetic analogs with high ion mobility. The main conditions for fast ionic transport are related to the disorder in the positions occupied by the mobile ions and the presence of conduction channels running inside the structure. Special attention is paid to the principle distinction between solid electrolytes and cathode materials. It is noted that the growing industry of modern electronic devices implies an increase in lithium production. The main mineral sources of this technologically important element are described.

Keywords: ionic conductivity; solid electrolytes; cathode electrodes; sources of Li

1. Introduction

In recent decades, the importance of crystals in our daily lives has become more evident. With the ever-increasing demands on their properties, there has been a need for improved techniques in crystal production. To achieve this goal, it is essential to understand the relationship between the chemical composition, atomic structure, and physical properties of crystals.

Crystalline materials with ionic conductivity are technologically important and form the basis of miniature power sources [1,2]. The movement of ions through the crystal is dependent largely on structural features: (1) the number of energetically favorable crystallographic sites available for ion positions must exceed the number of actual ions; (2) the energy required to disorder the ions and the energy needed for their movement across the crystal lattice must be minimal; (3) a continuous “channel network” must exist within the crystal structure to allow for the efficient movement of ions. If this network is discontinuous, the rapid movement of charged particles would only be possible within a limited number of unit cells [1,2].

There are two main groups of crystals that exhibit this physical property.

The first category includes superionic conductors, also known as solid electrolytes, which have conductivities ranging from 10^{-3} S·cm⁻¹ to 10 S/cm, significantly higher compared to ordinary solids, in which the specific conductivity does not exceed 10^{-10} – 10^{-12} S/cm. These values are exceptionally high for ionic crystals, yet still lower than those of many electronic conductors, such as metals, which typically have conductivities in the range of 10 to 10^5 S/cm [3]. In many solid electrolytes, ionic conductivity is attributed



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to the elevated concentration of impurity ions, which contribute to the presence of structural disorder.

The specific structural features of mineral-like solid electrolytes, including natisite $\text{Na}_2\text{TiSiO}_5$, pearceite-polybasite group with general formula $(\text{Ag,Cu})_{16}\text{M}_2\text{S}_{11}$, where $\text{M} = \text{Sb}$ and As , polymorphs of brizzite NaSbO_3 , lithiophosphate Li_3PO_4 , Na,REE silicates with 12-membered tetrahedral rings, lithium-ion conductors $\text{Li}_3\text{M}_2(\text{PO}_4)_3$, where $\text{M} = \text{Fe, Sc, Cr, In, etc.}$, were considered in detail in a recent publication [4].

In ionic conductors of the second group, both ions and electrons move between two electrodes connected to an external electrical circuit and immersed in an electrolyte. This type of material has been found to exhibit ionic conductivity, and is found in a large group of minerals [5,6]. These materials are currently widely used in metal-ion power supplies for military, medical, household, and industrial electronic devices. Ions of metals, including lithium, sodium, and aluminum, are involved in the process of electrical charge transfer between the cathode and anode in these batteries. Currently, the most commonly used materials in industry are those with lithium, hydrogen, and oxygen conductivity. In the design of metal-ion batteries, lithium is selected due to its unique characteristics. Firstly, lithium is the lightest metal, with only half the weight of water. Its density of 0.534 g/cm^3 is approximately the density of wood. The Li^+ ion has a small radius of $0.59 \text{ \AA}$, allowing it to easily move through the voids of a large number of crystalline structures.

This article is an extended version of a report presented by the authors at IOCMS 2026, an international online conference on mineral science, which took place in March 2026. It is challenging to draw conclusions about the features and structural conditionality of ion transport in crystals due to the vast amount of research conducted on this subject. Along with the analysis of the results from the first studies on mineral-like compounds with halite, spinel, and olivine structural types, the authors have attempted to address key issues in mineralogical crystallography related to lithium sources and its reserves.

Among the numerous compounds being investigated as potential electrode materials, the structural analogs of minerals stand out. This is because natural phases may not be ideal for research due to the presence of impurities that are often unstable. However, their crystal structures can serve as valuable reference points for the development of new materials. Therefore, the primary objective of this paper is to provide an overview of mineral-like crystals with ion conductivity, focusing on their structural characteristics and applications in metal-ion batteries.

2. The Different Functions of Solid Electrolytes and Electrode Materials in Metal-Ion Batteries

First of all, we will consider the operating principle of metal-ion batteries. As noted above, two types of substances are distinguished based on the nature of their conductivity. The first group includes solid electrolytes, which exhibit exclusively ionic conductivity; the second includes electrode materials, whose electrical conductivity involves both electrons and ions. These characteristics determine the different functions of these substances in rechargeable batteries. Their basic operating diagram is shown in Figure 1.

Solid electrolytes conduct ions (usually Li^+ ions) but block electrons, preventing short circuits in batteries. They act as an ion-conducting membrane separating the electrodes, ensuring ion transport between the cathode and anode, and increasing battery capacity. Electrode materials accumulate and release lithium ions during the charge/discharge cycle. During charging, the external electrical voltage must be used to ensure that electrons flow in the external circuit and create a negative pole on the graphite.

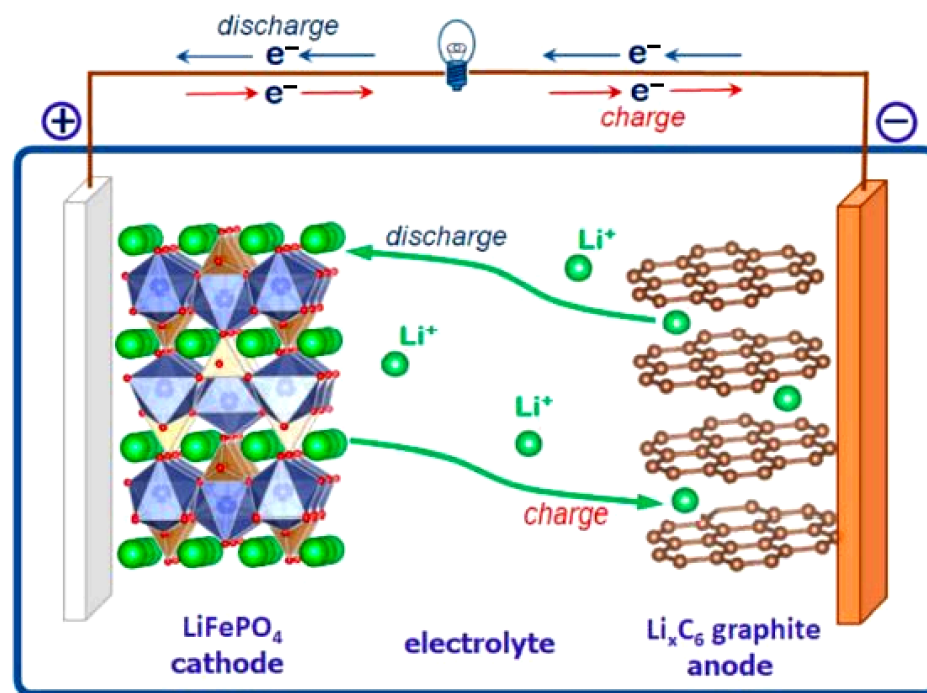


Figure 1. Schematic diagram of a Li-ion battery based on triphylite $\text{Li}(\text{Fe},\text{Mn})\text{PO}_4$ (s.t. olivine). On the left is the cathode electrode, on the right is the graphite electrode. Between them is a solid electrolyte. Electron movement is determined by the potential difference in the external electrical circuit, adapted from [5].

This point needs an important clarification. Unlike in electrical engineering, the anode in electrochemistry is the electrode where oxidation occurs, with the loss of electrons, and the cathode is the electrode where reduction occurs, with the gain of electrons. Thus, as shown in Figure 1, during charging, having lost electrons, the left electrode (anode) becomes positively charged, while the right electrode (cathode) becomes negatively charged. This initiates the movement of positively charged Li^+ ions toward the cathode. The right electrode then becomes intercalated graphite (anode) and acquires a positive charge. Graphite deposited on copper foil is a traditional electrode material used in Li-ion batteries. Accordingly, during discharging, the opposite process occurs: cations move from right to left, while electrons, when disconnected from the external circuit, move in the same direction, restoring the left electrode, which thus becomes the cathode. The name “cathode materials” for such electrodes is related to this discharge process. The intermediate position of the solid electrolyte between the two electrodes prevents the battery from short-circuiting. The transfer of electrons in the external circuit during the charge/discharge process is carried out by metal conductors. The movement of cations and electrons during discharge continues until the resulting electric field between the two electrodes equalizes their electrochemical potentials μ_A and μ_C . During this process, the voltage decreases between the cathode and anode due to the movement of ions across the electrode/electrolyte interface within the electrolyte.

The effective energy density stored in the cell is equal to QV/W , where V is an open circuit voltage: $V = (\mu_A - \mu_C)/e$ (e is the magnitude of the electronic charge), Q/W is the specific capacity, the amount of electronic charge Q transferred from the anode to the cathode during complete discharge, i.e., upon completion of the chemical reaction, and W is the weight of the cell [7].

3. Cathode Materials in Li-Ionic Rechargeable Battery

“They created a rechargeable world”. That is how the Swedish Royal Academy of Sciences headed in 2019 the announcement of the Nobel Prize for Chemistry [8].

Key parameters used to characterize rechargeable batteries include:

1. Operating voltage, defined as the potential difference between the cathode and anode materials (V);
2. Specific energy capacity, calculated as the battery capacity (battery’s ability to store or deliver electrical energy, expressed in W·h) stored per unit mass (g or kg); this value (W·h/kg) indicates the power that a given 1 kg battery can deliver over 1 h;
3. Number of operating cycles—the number of charge–discharge cycles during which at least 80% of the battery’s capacity is retained.

3.1. Oxide Cathode Materials with Halite and Spinel Structural Types

Layered oxides of LiMO_2 ($M = \text{Mn, Fe, Co, Ni}$) with a rock salt structure type play a special role in the study of cathode materials. They are widely used in lithium-ion batteries (Figure 2). Their discovery dates back to 1980 [9]. Beginning in 1976, this publication was preceded by a series of studies aimed at obtaining and characterizing Li-containing compounds with extremely dense anionic packing, including the sulfides MoS_2 and NiPS_3 . J. Goodenough’s group set two goals: first, to demonstrate the feasibility of low-temperature synthesis of transition metal oxides in their high-valence states; second, to demonstrate that the mobility of the Li^+ ion in oxides Li_xCoO_2 ($0 < x < 1$) with layered structures would be sufficient to generate a stable and high electrical potential difference. Thus, the focus was on LiMO_2 crystals, where M is a transition metal. In their NaCl-like structure, M^{3+} octahedra form alternating layers (111), similar to CdCl_2 , with the spaces between them filled by Li^+ ions (Figure 2). They found that, even with a decrease in Li content down to $x = 0.067$, this compound retains its stability at room temperature and can then regain its composition.

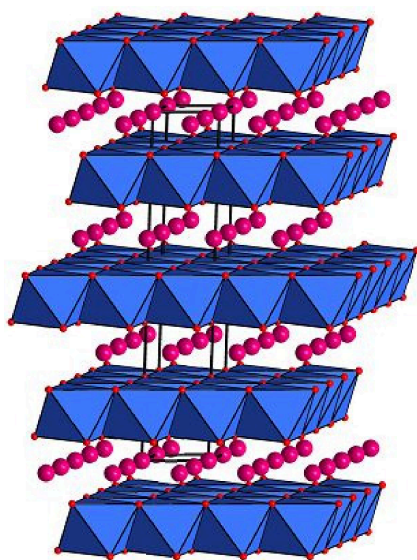


Figure 2. Halite-like crystal structure of LiCoO_2 with Li^+ cations (represented by pink balls) located between layers formed by CoO_6 octahedra (in blue).

The idea behind the work of J. Goodenough’s group was to create a battery containing two electrodes: graphite and LiCoO_2 . A liquid or gel electrolyte composed of LiPF_6 , LiBF_4 , LiClO_4 , LiAsF_6 , or other Li salts is placed between them. Solid electrolytes (for example, garnet-like $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$, NASICON-like $\text{Li}_{1.3}\text{Al}_{0.3}\text{Ti}_{1.7}(\text{PO}_4)_3$, and perovskite-

like $\text{Li}_{0.33}\text{La}_{0.55}\text{TiO}_3$ et al.) are also used in batteries as an alternative to traditional liquid or gel electrolytes. They serve as both ion conductors and separators, offering excellent ion conductivity and ensuring high ion flow rates in solid-state batteries.

During charging, Li^+ moves from the LiCoO_2 (anode) to the graphite cathode, creating intercalated graphite Li_xC_6 . When the power is turned off, discharging begins. Thus, the graphite enriched with Li^+ becomes the anode, and $\text{Li}_{1-x}\text{CoO}_2$ (with partially oxidized Co^{4+}) serves as the cathode. Accordingly, Li^+ moves from intercalated graphite to $\text{Li}_{1-x}\text{CoO}_2$ until LiCoO_2 is formed again. Since Sony first used this compound in the production of ion batteries in 1991, LiCoO_2 crystals remain the most common cathode material. Thanks to this type of lithium-ion battery, a number of mineral-like compounds with spinel, olivine, and other structures created the basis for the development of modern portable electronics, such as smartphones, laptops, and notebooks.

Beyond the conventional rock salt-like oxides, recent progress in materials for energy storage applications is related to new compounds comprising multiple elements with a similar structural type. This class of high-entropy substances contains five or more principal elements, in roughly equal proportions and with disordered distribution in their sites. Their complex, chemically disordered atomic structures, with atomic-sized differences, create varying electrostatic fields, which facilitate rapid ion diffusion. Namely, a novel highly promising compound $(\text{Mg}_{0.2}\text{Co}_{0.2}\text{Mn}_{0.2}\text{Ni}_{0.2}\text{Zn}_{0.2})\text{O}$ demonstrates an exceptional reversible specific capacity of $773.4 \text{ mA}\cdot\text{h/g}$ even after 200 cycles at 0.1 A/g [10].

During the last decade, lithium cobalt oxide found a new application in fiber-based electronic devices with one-dimensional structures. They have attracted increasing attention due to their high flexibility and ability to withstand deformation. In particular, these devices can be woven into breathable and comfortable fabrics for wearable applications. It is worth noting that mass-produced fiber batteries have an energy density of $85.69 \text{ W}\cdot\text{h/kg}$, while typical values are below $1 \text{ W}\cdot\text{h/kg}$ [11]. In the first fiber lithium-ion battery (FLB), lithium cobalt oxide is coated around a commercial aluminum wire to form the positive electrode, and graphite is coated around a copper wire to create the negative electrode. The negative fiber electrode is wrapped with a commercial separator film to prevent a short circuit.

Recently, to avoid poor interfacial stability in fiber lithium-ion batteries, a generalized channel structures strategy with optimized in situ polymerization technology has been proposed [12]. As a result, FLBs can be woven into power-generating textiles of various sizes, providing a high energy density output of $128 \text{ W}\cdot\text{h/kg}$. Obviously, this promising approach expands the possibilities for the development of FLBs with specific polymer gel electrolytes.

Materials with spinel-like structures—cubic magnetite Fe_3O_4 and tetragonal hausmannite Mn_3O_4 with Li^+ cations located in the channels—were proposed as matrices for cathode electrodes in 1982–1983 [13,14]. Although both compounds contain a three-layer cubic close-packed O^{2-} anion structure and retain structural similarity, there is an important difference between them. As is known, magnetite crystallizes in the inverse spinel structure $\text{Fe}^{3+}[\text{Fe}^{2+}\text{Fe}^{3+}]\text{O}_4$, while hausmannite has a normal spinel $\text{Mn}^{2+}[\text{Mn}^{3+}]_2\text{O}_4$ structure (Figure 3). This difference is due to the different positions of the Li^+ ions intercalated in these structures. In the magnetite structure, Li^+ intercalation leads to the formation of the compound $\text{Li}_x\text{Fe}_3\text{O}_4$ with values of x in the range $0 < x < 2$. For values of x in this range, the octahedral framework of Fe_2O_4 remains unchanged, and the Fe^{3+} ions occupying tetrahedral voids are displaced into unoccupied octahedral voids. Interstitial Li^+ ions are also present in this structure. This leads to the formation of a defected halite-like structure, $(\text{Li},\text{Fe}^{3+})\text{Fe}_2\text{O}_4$, with empty tetrahedral voids and completely filled octahedral voids, with two regular cation site systems.

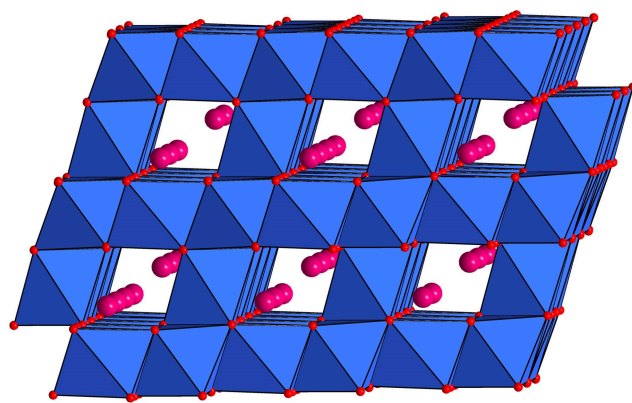


Figure 3. The crystal structure of spinel-like LiMn_2O_4 : octahedral Mn_2O_4 framework (blue color) remains unperturbed. Li^+ cations are shown as pink balls.

The penetration of Li^+ ions into the structures of two spinel-like manganese oxide compounds, the tetragonal hausmannite LiMn_3O_4 and the cubic LiMn_2O_4 , indicated significant differences between them. LiMn_3O_4 maintains the octahedral $[\text{Mn}_2\text{O}_4]$ framework. Unlike hausmannite, $\text{Mn}^{2+}[\text{Mn}^{3+}]_2\text{O}_4$, in this compound, the Mn^{2+} cations leave the tetrahedral positions and, together with the Li^+ cations, occupy the octahedral positions of another regular system of points. In LiMn_2O_4 crystals, the Mn octahedra also form the $[\text{Mn}_2\text{O}_4]$ framework, but the monovalent Li^+ cations occupy the tetrahedral voids, leading to a partial reduction of Mn^{4+} to Mn^{3+} . In this sense, LiMn_2O_4 retains some similarities to hausmannite [14,15].

It is noteworthy that lithium manganese oxide, LiMn_2O_4 , is an attractive cathode material for lithium ion rechargeable batteries owing to its cost and environmental performance. In contrast to layered structures, in which lithium is observed to move in two dimensions lying in one plane (2D), the diffusion of lithium cations in the LiMn_2O_4 structure occurs through a three-dimensional (3D) network of channels within the cubic closest packing of O^{2-} anions.

The main application of LiMn_2O_4 and its derivatives is in hybrid and electric vehicle batteries. According to the International Energy Agency (IEA), there were 12.9 million electric vehicles in the world in 2020. Under the IEA 2DS scenario, which aims to limit global temperature increase to 2°C above pre-industrial levels by 2100, their number will increase to 150 million by 2030 (growing by an average of 27.7% per year in 2021–2030) and to almost 1000 million by 2050 (growing by 10% per year in 2031–2050) [16]. A central role in the implementation of this program is associated with the active introduction of electric vehicles.

The large-scale transition to clean energy and the construction of a decarbonized economy based on low-carbon, even carbon-free, renewable energy sources suppose the expansion of Li-ion car battery production. The cathode materials most commonly used in these batteries are derivatives of the halite- and spinel-like structural types discussed above. In particular, 60% of the total capacity of batteries currently in use is accounted for by the complex lithium-nickel-manganese-cobalt-oxide ($\text{LiNi}_x\text{Mn}_y\text{Co}_z\text{O}_2$, NMC), with a structure similar to LiCoO_2 , and 20% by the lithium-manganese-oxide LiMn_2O_4 , LMO [16] described above. Different relationships between the transition elements make it possible to modify the properties of the corresponding cathode materials, and for the elements themselves to change their valence when Li^+ ions are removed during charging or added during discharging. In the case of $\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$, the initial oxidation states are Mn^{4+} , Co^{3+} , and Ni^{2+} . Cobalt and nickel are partially oxidized to Co^{4+} and Ni^{4+} during charging, while Mn^{4+} retains its valence state. The growth of the nickel content in this compound

increases its initial capacity but reduces its thermal stability and capacity retention. In addition to these oxide materials, Li-ion cathode materials based on natural phosphate analogs, which are presented in the next Section 3.2, are being increasingly used.

3.2. Phosphate-Based Mixed-Framework Cathode Materials

Phosphates are promising as cathode electrodes in rechargeable batteries. They are stable, easy to synthesize, provide the required voltage, and are inexpensive. Natural crystals are unsuitable due to irregular morphology and impurities, but their synthetic analogs exhibit good electrochemical properties. This issue is important given the depletion of fossil fuels. The structural diversity of phosphates allows them to be considered as matrices whose conductivity is linked to the transport of Li, K, or Na.

Among more than 425 naturally occurring phosphates (data updated by V.G. Krivovichev in December 2023), approximately 200 are associated with granitic pegmatite, 40 of which are formed directly from pegmatite fluids [5]. They include representatives of the triphylite Li(Fe,Mn)PO_4 –lithiophilite Li(Mn,Fe)PO_4 series.

Their synthetic analogs are used as cathode materials in lithium-ion batteries, which account for 5% of the total energy capacity of these sources [17].

Synthetic phosphates of transition metals and lithium with the general formula LiMPO_4 , where $\text{M} = \text{Mn, Fe, Co, Ni}$, crystallizing in the olivine structure, represent one of the most promising classes of cathode materials for lithium-ion batteries. LiFePO_4 was first proposed as a battery cathode material in 1997. In the well-known structural type of olivine (sp. gr. Pnma), it is common to distinguish the most rigid fragment, formed by columns of edge-linked M-octahedra and associated SiO_4 tetrahedra (Figure 4). In LiFePO_4 , the iron and lithium atoms occupy the octahedral 4a and 4c positions, respectively. Therefore, Li ions are located within the channels in the heteropolyhedral framework consisting of FeO_6 octahedra and PO_4 tetrahedra. The removal of Li leads to the two-phase reaction $\text{LiFePO}_4 = \text{FePO}_4 + \text{Li}^+ + \text{e}^-$, which results in Li_xFePO_4 . Both phases, $\text{LiFe}^{2+}\text{PO}_4$ and $\text{Fe}^{3+}\text{PO}_4$, are members of the olivine structural type. When Li^+ ions are extracted or inserted, corresponding to the transition from $\text{LiFe}^{2+}\text{PO}_4$ to isotypic $\text{Fe}^{3+}\text{PO}_4$ or vice versa, a change in formal mixed valency occurs (e.g., Fe(II)/Fe(III) to Fe(III)/Fe(II) in the oxide host) [7].

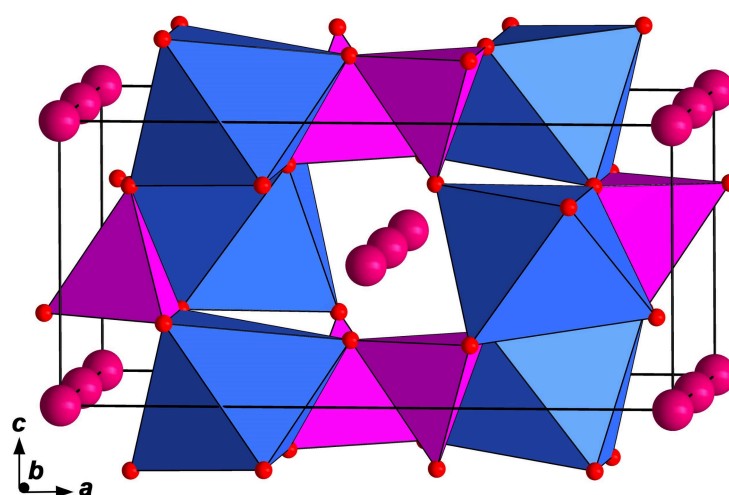


Figure 4. Crystal structure of LiFePO_4 : octahedra with Fe atoms in their centers (blue color) form columns. PO_4 tetrahedra are shown in pink, and the red balls correspond to the sites of Li atoms.

The widespread use of lithium-ion batteries, including those based on synthetic analogs of the triphylite–lithiophilite series of minerals, is determined by their long-term structural stability and a high number of charge/recharge cycles (more than 1000 cycles

with a capacity loss of less than 20%) [18]. Theoretical calculations, confirmed by experimental results of high-temperature neutron diffraction, showed that in compounds with the olivine structure, lithium ion diffusion is possible only in one direction along the [010] axis (Figure 4) [19].

The relatively high theoretical specific capacity (170 mA·h/g) of LiFePO_4 , combined with environmental safety, thermal stability and low cost, make it attractive for use in power sources of hybrid and electric vehicles [7]. The characteristics of all the above-mentioned types of cathode materials used in lithium-ion batteries are listed in Table 1. It is worth noting that Li and Co, which are widely used in modern batteries, have unstable and relatively high prices. Li-ion batteries can be a potential source of fire and explosion. They can be replaced by Na-containing batteries that are 100 times cheaper, since there are practically no limitations on the scale of production and reserves for Na [16].

Table 1. Electrochemical characteristics of Li-cathode materials, according to [20,21].

Crystals	Operating Voltage (V)	Specific Capacity (A·h/g)	Specific Energy Capacity (W·h/kg)	Number of Operating Cycles
LiCoO_2	3.7	140	518	500–1000
LiMn_2O_4	4.0	148	592	500–3000
LiFePO_4	3.3	150	495	1000–20,000

Therefore, it is understandable why there is a desire to replace Li in these devices with cheaper Na or K, while maintaining the battery design as described above. According to [22], using a $\text{KTi}^{3+}\text{PO}_4\text{F}$ metal-ion electrode with a $\text{KTiO}[\text{PO}_4]$ (KTP) structure, a stable potential difference of 3.6 V was achieved, which is very close to the 4 V associated with a LiCoO_2 -based cell developed by John Goodenough's group. In the last decade, two new minerals, K-arsenate katiarsite (KTiOAsO_4) [23] and jurgesonite $\text{K}_2\text{SnTiO}_2(\text{AsO}_4)$ [24], were discovered in the fumaroles of the Tolbachik volcano in Kamchatka. These compounds are structural and chemical analogs of synthetic $\text{KTi}^{3+}\text{PO}_4\text{F}$.

So far, researchers were unable to obtain a battery with the same properties based on a Na-conducting material. However, recently a new cathode material, NaVPO_4F , also with a KTP structural type (Figure 5), was created, which provides a sodium-ion battery with 10–15% higher energy capacity than previously available materials, and has a discharge voltage of 4 V [25]. Cathodes made from this new material maintain functionality at low temperatures, which is especially important for northern countries.

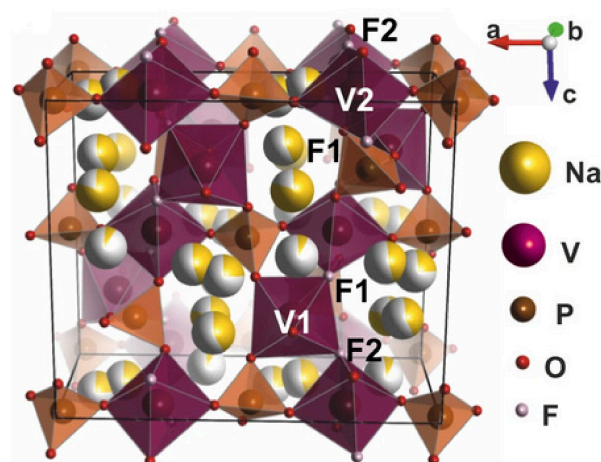


Figure 5. Crystal structure of NaVPO_4F along [010], reprinted with permission from [25].

4. Minerals—Main Sources of Li

The ever-growing production of modern electronic devices, and especially lithium-ion batteries, and especially lithium-ion batteries, which use 56% of the mined Li, requires an increase in the extraction of this element. Modern reserves of Li are estimated at 22,000 thousand tons. In 2020, the production of Li-containing ores amounted to 87 thousand tons. In this regard, the task is set of gradual partial replacement of primary Li-raw materials with secondary ones, the share of which will be 22% by 2030 [16].

Of the more than 130 lithium-containing minerals, only seven are of economic interest. These are amblygonite $(\text{Li,Na})\text{Al}(\text{PO}_4)(\text{OH,F})$; eucryptite LiAlSiO_4 ; hectorite $\text{Na}_{0.3}(\text{Mg,Li})_3(\text{OH})_2\text{Si}_4\text{O}_{10}$; jadarite $\text{LiNaB}_3\text{SiO}_7(\text{OH})$; lepidolite $\text{K}(\text{Li,Al})_3(\text{OH})_2(\text{Si,Al})_4\text{O}_{10}$; petalite $\text{LiAlSi}_4\text{O}_{10}$; spodumene $\text{LiAlSi}_2\text{O}_6$ and zinnwaldite $\text{KLiFe}^{2+}\text{Al}(\text{OH,F})_2\text{AlSi}_3\text{O}_{10}$.

Spodumene and lepidolite are considered the most important sources of Li. Spodumene belongs to the group of monoclinic pyroxenes [26] (Figure 6a). It is known for its giant, meter-long crystals. A very big spodumene crystal weighing 90 tons found in South Dakota (USA) was 12.8 m long. The reaction of spodumene with sulfuric acid (H_2SO_4) is the basis for lithium production. In Russia, the largest spodumene deposits are confined to the pegmatite veins of the Kola Peninsula. More than 50% of Russia's lithium reserves are concentrated there.

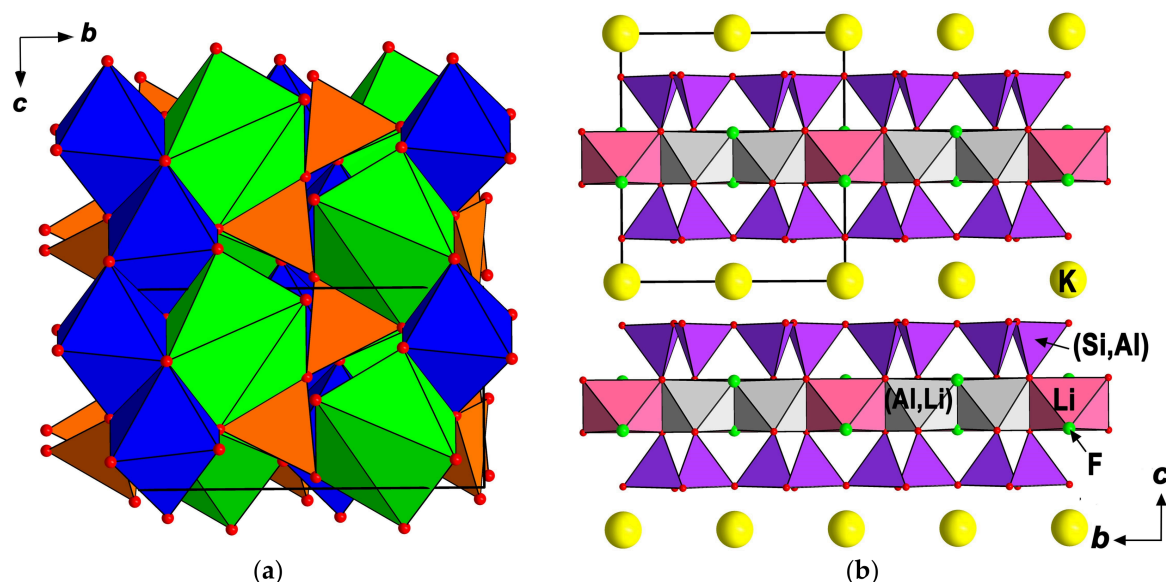


Figure 6. Structure of spodumene (a): Al octahedra—blue; distorted Li six-vertex polyhedra—green; SiO_4 tetrahedra—brown; red spheres—oxygen atoms. Structural data were taken from [26]. Crystal structure of lepidolite (b). Structural data were taken from [27].

Lepidolite is a mineral from the trioctahedral mica group (Figure 6b). The most famous mining locations for this mineral are Brazil, Zimbabwe, the Ural Mountains (Russia), California, Manitoba (Canada), and Madagascar. Furthermore, the world's lithium reserves are largely associated with marine brines, sedimentary rocks, and pegmatites: 66%, 8%, and 26%, respectively.

5. Conclusions

Ever-increasing energy consumption and the depletion of fossil fuel resources necessitates the search for alternative energy sources. Improving the exploration and technology for metal-ion batteries [28] are crucial to this process. The next generation of green and sustainable rechargeable metal-ion battery systems requires an intensive study of materials that have long life spans, abundant resources, low toxicity, and high thermal stability. In

this review, the emphasis was placed on the cathode materials employed in these batteries, which exhibit high ionic conductivity and, as demonstrated above, are structurally similar with various minerals. In the future, some promising materials with improved electrochemical performance and thermal stability are likely to find wider technological applications in various fields of human activity.

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