High Performing CO₂ Capture by Smart Strategies in Functionalized Ionic Liquids

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Functionalized ionic liquids (ILs) are the most promising approaches to achieve high performing CO₂ capture. This mini-review outlines some important progress for functionalized ILs in CO₂ capture. Amino-functionalized ILs exhibit high reactivity with CO₂, and their careful structural design is able to produce high absorption capacity of CO₂. The introduction of intra-molecular hydrogen bonding/proton transfer in amino-functionalized ILs is an attractive approach to avoid the formation of intermolecular hydrogen bonded networks generally occurred in traditional amino-functionalized ILs, thus resulting in enhanced absorption capacity of CO₂ and improved uptake rate. Non-amino anion-functionalized ILs such as substituted azolide or phenolate ILs show great potential for rapid and reversible uptake of CO₂ due to their lack of hydrogen bonding, controllable absorption enthalpy and excellent stability. However, there is still a long way to go to construct high performing systems based on functionalized ILs including high capacity of CO₂, rapid absorption kinetics and excellent cycling life. Smart strategies such as dual-tuning methods, multi-site cooperative interactions, and intra-molecular hydrogen bonding/proton transfer would promote the development of CO₂ capture in functionalized ILs significantly.

Keywords: functionalized ionic liquids, smart strategies, high CO₂ capacity, rapid uptake kinetics, long cycling life

Introduction
Developing advanced materials or technologies for efficient, fast and reversible capture of post-combustion CO₂ is one of the most important research activities for a sustainable environment. Among various approaches, ionic liquids (ILs), a class of low-temperature molten salts with melting point usually below 100 °C, have gained in popularity for the mitigation of CO₂ crisis by taking advantage of their unique properties including negligible vapour pressure, wide liquid temperature range, high stability, non-flammability, virtually unlimited tunability and excellent CO₂ affinity.[1-3] The first report on physical solubility of CO₂ in the IL 1-butyl-3-methylimidazolium hexafluorophosphate [BMIM][PF₆] demonstrated that the high pressure would result in high solubility of CO₂, for example, CO₂ uptake reached a molar ratio of 0.6 at 8 MPa.[4] Much attention from academia then was paid to understanding and improving physical solubility of CO₂ in conventional ILs. However, to our best knowledge, the pure physical dissolution of CO₂ in conventional ILs at atmosphere pressure and room temperature is particularly low, only up to a molar fraction of 0.035 (gravimetric uptake capacity around 0.4%), which is almost impractical for industrialization.[5]

Thus, smart design on the structure of ILs is highly desired for significant improvement of CO₂ uptake. Thanks to the first chemisorption of CO₂ in a task-specific IL,[6] the progress on CO₂ capture technologies is being pushed to a large extent. This task-specific IL, 1-propylamine-3-butyl imidazolium tetrafluoroborate ([apbim][BF₄]), also called as functionalized IL, is prepared through attaching an amine group to the imidazolium cation, where absorption capacity of CO₂ could reach a molar fraction of up to 0.5 under ambient conditions (Scheme 1). However, one significant disadvantage of this approach is its low absorption rate, associated with the relatively high viscosity of the IL after CO₂ absorption and formation of carbamate.[5] Nevertheless, this pioneering work encouraged researchers to design smart strategies in functionalized ILs for high performing CO₂ capture.

Scheme 1 Proposed reaction between the first TSIL [apbim][BF₄] and CO₂.[6]
taking advantage of the dual-tuning roles of large n-conjugated anions. Cui and co-workers[13] demonstrated a novel strategy based on cooperative interactions between CO2 and multiple active sites in the pre-organized anion for highly efficient and reversible capture of low-concentration CO2. Recently, Pan et al.[13,14] established a series of amino-functionalized ILs for efficient CO2 absorption as well as controllable viscosity change during the uptake process by creating intra-molecular hydrogen bonding or intra-molecular proton transfer. Therefore, the aim of this mini-review is to outline some typical advances in functionalized ILs for highly efficient, fast, and reversible capture of CO2 in recent years.

**High capacity of CO2**

Since the limit capacity of CO2 in [apbim][BF4] is only 0.5 mol per mol IL, much attention is paid on increasing the molar absorption capacity of CO2 in amino-functionalized ILs towards equivalent molar ratio or beyond.[15-20] One popular approach is to tether the amino group to the anion of IL such as trihexyl(tetradecyl)phosphonium methionine ([P66614][Met]) and trihexyl(tetradecyl)phosphonium proline ([P66614][Pro]), and make the anion charge centre and amino group in close proximity (Scheme 2).[15,16] As a result, a 1 : 1 stoichiometry of CO2 uptake was obtained through formation of relatively stable carboxamic acid. The introduction of more amino groups into the IL is a general method to further increase the molar absorption capacity. The naturally-occurring amino-acid anions containing an additional amine group (e.g., lysine, asparaginate, glutamate) and trihexyl(tetradecyl)phosphonium cation ([P66614]) were used for the fabrication of functionalized ILs for beyond one molar absorption of CO2.[17-19] The cation effect was also studied by replacement of [P66614] with trihexyl(tetradecyl)-ammonium [N66614] when the anion was fixed as lysinate ([Lys]) anion.[20] Surprisingly, the absorption capacity in [N66614][Lys] increased to 2.1 mol CO2 per mol IL, exceeding 0.7 mol CO2 per mol IL in comparison with [P66614][Lys]. This increase should relate to the difference in anion structures of corresponding IL-CO2 adducts. However, the use of [P66614] cation would significantly decrease the gravimetric capacity of CO2 due to its high molar mass.

**Scheme 2** Reaction schematics of CO2 with [P66614][Met] (top) and [P66614][Pro] (bottom).[16]

Protic ILs, formed through proton transfer from a Brønsted acid to a Brønsted base, are able to be designed as flexible molecules with small molar mass and show potential on high uptake of CO2. A mixture of strong organic bases and a wide variety of weak proton donors to attain protic ILs could produce rapid, reversible and equimolar capture of CO2.[27-28] Recently, the MacFarlane’s group[29,30] demonstrated several diamino protic ILs based on azolides as anions absorbed CO2 to more than 20 wt% pointing towards equimolar absorption. The superior absorption capacity makes protic ILs receive considerable attention in CO2 capture. However, the major drawback for protic ILs is the solvent degradation during the adsorption-desorption cycles, resulting in rapid capacity decay of CO2.

Imidazilium ILs are good platforms for high gravimetric capacity of CO2. For example, Li et al.[31] reported a new IL 1-hydroxyethyl-3-methylimidazolium lysine ([C2OIm][Lys]) with an extremely high gravimetric uptake of 0.271 g CO2 per g IL, however, it suffered from sluggish uptake rate of CO2. Amino-functionalized IL-water blends could produce high gravimetric capacity of CO2 as well as fast and reversible uptake of CO2 if the structure of IL was carefully designed to a small scale because the IL can inhibit the evaporation of volatile solvent or solute and in turn, water containing the IL can remarkably decrease the viscosity of the system.[32-36] The dual-functionalized IL, 1-(3-aminopropyl)-3-methylimidazolium glycinate ([APmim]-[Gly]) contains both amine and amino-acidic groups, whose aqueous solution (0.5 M) exhibited high gravimetric capacity of CO2 up to 19 wt%. Similarly, an aqueous solution of 1-(3-aminopropyl)-3-methylimidazolium lysinate ([APmim][Lys]) at the same concentration of 0.5 M achieved an even greater CO2 absorption capacity of 26.7 wt%. Other types of IL-liquid blends such as IL-amine blend also were developed in light of the mature methods and theories for mixed amines.[35,37,38]

The creation of multi-cooperative interactions in functionalized ILs is deemed to be one of the most promising approaches for highly efficient uptake of CO2. The concept of cooperative interaction was firstly proposed by Wang et al.[39] because both the negative oxygen site and adjacent nitrogen atom on the deprotonated hydroxypyridine anion can chemisorb CO2 molecule, producing an ultra-high capacity of up to 1.6 mol CO2 per mol IL. A new strategy for multi-molar absorption of CO2 was reported by the activation of carboxylate groups in amino-acid ILs (Scheme 3).[40] As shown in Figure 1a, the CO2 capacity of [P4424][IDA] is 1.69 mol per mol IL at 40 °C and 1 bar, indicating the presence of multi-site cooperative interactions. The theory calculations reveal the substituted acetate group of [IDA] anion can further interact with a second CO2 very efficiently (ΔH = -52.8 kJ mol⁻¹) after the amino group complexed with the first CO2 (ΔH = -89.0 kJ mol⁻¹) in contrast to that of [Gly] anion (ΔH = -19.6 kJ mol⁻¹) (Figure 1b). The multi-site interactions between [IDA] and CO2 were further verified by FT-IR and 13C NMR spectra (Figures 1c and 1d). In the IR spectra, the peak attributable to N-H stretch disappeared and simultaneously, two new characteristic peaks were observed at 1630 and 1423 cm⁻¹ attributable to NH-CO2 and O-CO2 interactions, respectively. In the 13C NMR spectra, two new resonances at 156.8 ppm and 163.5 ppm were observed, which could be assigned to NH-CO2 and O-CO2 carbon atoms, respectively. Therefore, the introduction of an electron-withdrawing acetate group could reduce the negative inductive effect of the amino group, while the other carboxylate group was simultaneously activated to interact with CO2 efficiently (Figure 1). Thus, an extremely high absorption

**Scheme 3** (a) Chemical structures of the anions and cations in amino-poly(carboxylate)-based ILs (AP-CILs) and (b) the proposed mechanism of CO2 absorption by [P4424][IDA] through multiple-site interactions.[11]
capacity of 1.69 mol CO₂ per mol IL was achieved. Furthermore, a new preorganization and cooperation strategy was developed for highly efficient and reversible capture of low-concentration CO₂ by imide-based ILs, giving rise to an extremely high gravimetric capacity of up to 22 wt% (1.65 mol CO₂ per mol IL) and excellent reversibility (16 cycles) from 10 vol% CO₂ in N₂.[12]

Rapid uptake kinetics

Traditional amino-functionalized ILs exhibit high reactivity towards CO₂, however, they often encounter dramatic viscosity increase upon the uptake process due to the formation of a strong and pervasive hydrogen-bonded network.[7] Thus, it is crucial to eliminate intermolecular hydrogen bonding in ILs during the capture process for a fast absorption rate of CO₂. Generally, there are two ways to tackle this issue. Firstly, a series of special means based on amino-functionalized ILs were developed to avoid the formation of an extensive hydrogen-bonded network, such as introducing electrostatic interaction or creating intramolecular hydrogen bonding/intramolecular proton transfer. Secondly, non-amino functionalized ILs such as azolide or phenolate ILs were designed in consideration of the lack of proton donor and acceptor in such systems.[8,13]

Recently, Pan and co-workers[13] designed a series of amino-functionalized ILs that possess equimolar and fast absorption of CO₂ by setting an amino group in the vicinity of negative oxygen atom in the pyridine anion (Scheme 4). Once CO₂ reacts with the amino group to form the carbamic acid, and subsequently the proton on carbamic acid can transfer to the negative oxygen group in the anion, resulting in enhanced CO₂ absorption capacity and improved uptake kinetics. For example, [P₆₆₆₁₄][2-NH₂-3-O-Py] could capture almost equimolar absorption capacity of CO₂ within only 25 min (Figure 2). In contrast to traditional amino-functionalized ILs, the viscosity of [P₆₆₆₁₄]-[2-NH₂-3-O-Py] has a remarkable decrease from original 1567 to 938 cP after the uptake of CO₂.[13] The availability of intramolecular hydrogen bonding prevented the formation of extensive intermolecular hydrogen bonded network and contributed to greater anion asymmetry and disorder for the acceleration of the rotational and translational dynamics of IL, thus resulting in this viscosity decrease of around 40%. This finding endowed amino-functionalized ILs with new vitality toward practical application.

Non-amino anion-functionalized ILs are another important approaches to make the viscosity of system controllable during the CO₂ capture in the absence of hydrogen bonded networks. Substituted azolides or phenolates are the popular options as the functionalized anions of ILs in view of their tunable absorption enthalpy and viscosity change during the CO₂ uptake process, providing an opportunity for high capacity and rapid up-take of CO₂ with low energy demand. Typically, Wang et al.
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reported a class of non-amino anion-functionalized ILs such as azolide-functionalized ILs in order to achieve rapid CO₂ absorption kinetics (Scheme 5 and Figure 3).[5] The absorption was almost complete in the first 10 min and no obvious viscosity change was observed. As example, the viscosities of [P₁₆₆₆₁₄][Pyr] and [P₁₆₆₆₁₄][Im] varied in a small range from 245.4 to 555.1 cP and 810.4 to 648.7 cP after the CO₂ absorption, respectively.[5]

Scheme 5 Structure of anion and cation in azolide or phenolate functionalized ILs for CO₂ capture.[6]

Figure 2 CO₂ absorption by amino-functionalized ILs as a function of time at 30 °C: [P₁₆₆₆₁₄][2-NH₂-3-O-Py] (■), [P₁₆₆₆₁₄][2-NH₂-4-O-Py] (●), [P₁₆₆₆₁₄][2-NH₂-6-O-Py] (▲), [P₁₆₆₆₁₄][3-NH₄-4-O-Py] (▼).[13]

A class of tunable basic ILs such as [P₁₆₆₆₁₄][Triz] was developed for equimolar CO₂ capture as well as excellent reversibility. 25 cycles of CO₂ absorption and desorption demonstrate the CO₂ capture process by [P₁₆₆₆₁₄][Triz] is highly reversible (Figure 5).[6] Moreover, the features of [P₁₆₆₆₁₄][Triz] also include desirable enthalpy of absorption, high absorption capacity, rapid absorption rate, offering an industriously attractive alternative for CO₂ capture. The replacement of [P₁₆₆₆₁₄] by a smaller molar weight cation such as tributyl[(ethyl)phosphonium] [P₂₄₄₂] may benefit for higher gravimetric capacity.[12] Thus, the IL consists of an azolide anion and a phosphonium cation with small molecular mass provides an opportunity to meet the requirements of high performing CO₂ capture.

Long cycling life

The reversibility of IL is an important criterion for evaluating the CO₂ absorption performance of IL. A long cycling life of IL indicates the high stability of IL in CO₂ capture and release. The CO₂ absorption into and release from the IL in repeated cycles illuminates the sustainability for both the regeneration of absorbent and the CO₂ recycling performance, offsetting the relatively high cost of IL for practical application. As aforementioned, although amino-functionalized ILs and protic ILs exhibit high absorption capacity of CO₂, their stabilities during the recycling capture of CO₂ are a severe issue due to solvent degradation/oxidation or solvent loss during the absorption process. Therefore, the combination of phosphonium cations and non-amino functionalized anions could overcome this drawback.

With regard of the low stability of some anions such as phenolate and imidazolate during CO₂ uptake, Pan et al.[9] designed a dual-tuning strategy to achieve both enhanced molar capacity of CO₂ and excellent cycling life by introduction of a large π-conjugated structure into the anion of IL (Scheme 6). The high molar capacity of CO₂ may be as a result of the strengthened dynamic covalent bonds through anion aggregation and the excellent reversibility originates from π-electron delocalization through charge dispersion. The desorption of [P₁₆₆₆₁₄][PNNPhO] was complete at 80 °C under N₂ atmosphere, while on the contrary, there is 0.17 mol CO₂ per mol IL residues remained for [P₁₆₆₆₁₄][PhO] under the same condition (Figures 4a and 4b). In contrast to the poor stability of [P₁₆₆₆₁₄][PhO], an excellent cycling reversibility in [P₁₆₆₆₁₄][PNNPhO] (up to 12 cycles) was observed during the CO₂ absorption and desorption (Figure 4c). Furthermore, thermogravimetric analysis (TGA) revealed that the release of CO₂ captured in [P₁₆₆₆₁₄][PNNPhO] began at 40 °C and was almost complete at 120 °C (Figure 4d), revealing an improved desorption performance as compared to [P₁₆₆₆₁₄][PhO]. However, the main disadvantages of these large π-conjugated ILs are the slow absorption kinetics and low gravimetric capacity of CO₂.

Scheme 6 Structure of anion and cation in large π-conjugated anion-functionalized ILs for CO₂ capture.[9]
Conclusions

Chemisorption of CO₂ by functionalized ILs is an appealing approach for high capacity and selectivity of CO₂. Careful structural design of ILs is essential to achieve desirable absorption enthalpy, favorable stability, fast reaction kinetics and excellent cycling life. In this mini-review, we discuss briefly some typical examples of the amino-functionalized ILs and non-amino anion-functionalized ILs for CO₂ capture. The traditional amino-functionalized ILs show high reactivity to CO₂, however, the uncontrollable viscosity change and high energy demand are the major obstacles to limit their practical application. The introduction of intramolecular hydrogen bonding or intramolecular proton transfer or electrostatic interaction in amino-functionalized ILs can avoid the formation of intermolecular hydrogen bonded networks and contribute to fast absorption kinetics of CO₂. Another promising approach is to develop non-amino anion-functionalized ILs such as substituted azolides or phenolates for fast uptake of CO₂ due to the absence of proton donor and acceptor in these systems. High absorption capacity of CO₂ is one of the most important goals for ILs in CO₂ capture. The use of protic ILs or the introduction of multi-site cooperative interactions is an effective strategy to obtain high gravimetric capacity of CO₂. However, protic ILs are mostly faced with solvent loss or degradation problems during CO₂ uptake. Thus, the selection of phosphonium cations and non-amino functionalized anions to obtain a series of high stable aprotic ILs is much helpful to have a long cycling life during the CO₂ absorption and desorption process. Trihexyl(tetradecyl)phosphonium [P66614] was used as the most common phosphonium cation due to its high stability, however, its large molar mass is against high gravimetric capacity. Therefore, a compromising strategy is required to achieve a commercially practical technology based on functionalized ILs.

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Author Contributions

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References

[1] Dupont, J.; de Souza, R. F.; Suarez, P. A. Z. Chem. Rev. 2002, 102, 3687.
[2] Anderson, J. L.; Dixon, J. K.; Brennecke, J. F. Acc. Chem. Res.
2007, 40, 1208.

[3] Zhang, Z. F.; Xie, Y.; Li, W. J.; Hu, S. Q.; Song, J. L.; Jiang, T.; Han, B. X. Angew. Chem. Int. Ed. 2008, 47, 1127.

[4] Blanchard, L. A.; Hancu, D.; Beckman, E. J.; Brennecki, J. F. Nature 1999, 399, 28.

[5] Cui, G.; Wang, J.; Zhang, S. Chem. Soc. Rev. 2016, 45, 4307.

[6] Bates, E. D.; Mayton, R. D.; Ntai, I.; Davis, J. H. J. Am. Chem. Soc. 2002, 124, 926.

[7] Gutowski, K. E.; Maginn, E. J. J. Am. Chem. Soc. 2008, 130, 14690.

[8] Wang, C.; Luo, X.; Luo, H.; Jiang, D.-E.; Li, H.; Dai, S. Angew. Chem. Int. Ed. 2011, 50, 4918.

[9] Pan, M.; Cao, N.; Lin, W.; Luo, X.; Chen, K.; Che, S.; Li, H.; Wang, C. ChemSusChem 2016, 9, 2351.

[10] Luo, X.; Guo, Y.; Ding, F.; Zhao, H.; Gui, G.; Li, H.; Wang, C. Angew. Chem. Int. Ed. 2014, 53, 7053.

[11] Chen, F.-F.; Huang, K.; Zhou, Y.; Tian, Z.-Q.; Zhu, X.; Tao, D.-J.; Jiang, D.-E.; Dai, S. Angew. Chem. Int. Ed. 2016, 55, 7166.

[12] Huang, Y.; Cui, G.; Zhao, Y.; Wang, H.; Li, Z.; Dai, S.; Wang, J. Angew. Chem. Int. Ed. 2017, 56, 13293.

[13] Pan, M.; Vijayaraghavan, R.; Zhou, F.; Kai, M.; Li, H.; Wang, C.; MacFarlane, D. R. Chem. Commun. 2017, 53, 5950.

[14] Pan, M.; Zhao, Y.; Zeng, X.; Zou, J. Energy Fuels 2018, 32, 6130.

[15] Zhang, J.; Zhang, S.; Dong, K.; Zhang, Y.; Shen, Y.; Lv, X. Chem. Eur. J. 2006, 12, 4021.

[16] Gurkan, B. E.; de la Fuente, J. C.; Mindrup, E. M.; Ficke, L. E.; Goodrich, B. F.; Price, E. A.; Schneider, W. F.; Brennecki, J. F. J. Am. Chem. Soc. 2010, 132, 2116.

[17] Goodrich, B. F.; de la Fuente, J. C.; Gurkan, B. E.; Lopez, Z. K.; Price, E. A.; Huang, Y.; Brennecki, J. F. J. Phys. Chem. B 2011, 115, 9140.

[18] Goodrich, B. F.; de la Fuente, J. C.; Gurkan, B. E.; Zadigian, D. J.; Price, E. A.; Huang, Y.; Brennecki, J. F. Ind. Eng. Chem. Res. 2011, 50, 111.

[19] Meng, Y.; Wang, X.; Zhang, F.; Zhang, Z.; Wu, Y. Energy Fuels doi: 10.1021/acs.energyfuels.8b01348.

[20] Saravanamurugan, S.; Kunov-Kruse, A. J.; Fehrmann, R.; Riisager, A. ChemSusChem 2014, 7, 897.

[21] Zhang, F.; Gao, K.; Meng, Y.; Qi, M.; Geng, J.; Wu, Y.; Zhang, Z. Int. J. Greenhouse Gas Control 2016, 51, 415.

[22] Zhang, Y.; Zhang, S.; Lu, X.; Zhou, Q.; Fan, W.; Zhang, X. Chem. Eur. J. 2009, 15, 3003.

[23] Jiang, Y.-Y.; Wang, G.-N.; Zhou, Z.; Wu, Y.-T.; Geng, J.; Zhang, Z.-B. Chem. Commun. 2008, 505.

[24] Yu, H.; Wu, Y.-T.; Jiang, Y.-Y.; Zhou, Z.; Zhang, Z.-B. New J. Chem. 2009, 33, 2385.

[25] Niedermaier, I.; Bahlmann, M.; Papp, C.; Kolbeck, C.; Wei, W.; Calderón, S. K.; Grabau, M.; Schulz, P. S.; Wasserscheid, P.; Steinrück, H.-P.; Maier, F. J. Am. Chem. Soc. 2014, 136, 436.

[26] Ma, J.; Zhou, Z.; Zhang, F.; Fang, C.; Wu, Y.; Zhang, Z.; Li, A. Environ. Sci. Technol. 2011, 45, 10627.

[27] Wang, C.; Luo, H.; Jiang, D.-E.; Dai, S. Angew. Chem. Int. Ed. 2010, 49, 5978.

[28] Wang, C.; Luo, H.; Luo, X.; Li, H.; Dai, S. Green. Chem. 2010, 12, 19.

[29] Oncsik, T.; Vijayaraghavan, R.; MacFarlane, D. R. Chem. Commun. 2018, 54, 2106.

[30] Vijayaraghavan, R.; Pas, S. J.; Izgorodina, E. I.; MacFarlane, D. R. Phys. Chem. Chem. Phys. 2013, 15, 19994.

[31] Li, S.; Zhao, C.; Sun, C.; Shi, Y.; Li, W. Energy Fuels 2016, 30, 8535.

[32] Zhang, J.; Jia, C.; Dong, H.; Wang, J.; Zhang, X.; Zhang, S. Ind. Eng. Chem. Res. 2013, 52, 5835.

[33] Lv, B.; Jing, G.; Qian, Y.; Zhou, Z. Chem. Eng. J. 2016, 289, 212.

[34] Zhou, Z.; Zhou, X.; Jing, G.; Lv, B. Energy Fuels 2016, 30, 7489.

[35] Zhang, F.; Fang, C.; Wu, Y.; Wang, Y.; Li, A.; Zhang, Z. Chem. Eng. J. 2010, 160, 691.

[36] Jing, G.; Zhou, L.; Zhou, Z. Chem. Eng. J. 2012, 181—182, 85.

[37] Camper, D.; Bara, J. E.; Gin, D. L.; Noble, R. D. Ind. Eng. Chem. Res. 2008, 47, 8496.

[38] Zhao, Y.; Zhang, X.; Zhen, Y.; Dong, H.; Zhao, G.; Zeng, S.; Tian, X.; Zhang, S. Int. J. Greenh. Gas Control 2011, 5, 367.

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