Supramolecular Chemistry of Chiral (1R,2S)- Ephedrine Confined within the AFI Framework as a Function of the Synthesis Conditions

*Beatriz Bernardo-Maestro^a, M. Dolores Roca-Moreno^a, Fernando López-Arbeloa^b,
Joaquín Pérez-Pariente^a and Luis Gómez-Hortigüela^{a*}*

^a Instituto de Catálisis y Petroleoquímica, ICP-CSIC. C/ Marie Curie 2, 28049. Madrid,
Spain.

^b Departamento de Química Física. Universidad del País Vasco. Apartado 644, 48080-
Bilbao, Spain.

Corresponding Author: LGH; Email: lhortiguela@icp.csic.es

Telephone: +34-91-5854785; Fax: +34-91-5854760.

Abstract

In an attempt to promote chirality in AFI-based materials through spatial distributions of dopants, a systematic variation of the synthesis conditions of Mg-doped aluminophosphate-based microporous materials using chiral (1R,2S)-ephedrine as structure-directing agent has been carried out in order to understand the supramolecular chemistry and packing arrangements of these molecules when confined within the AFI channels. The formation of ephedrine dimers is strongly dependent on the synthesis conditions, especially the ephedrine/H₂O ratio (higher concentrations of ephedrine favour the incorporation of dimers), crystallization temperature (higher temperatures enhance the supramolecular aggregation) and Mg content (lower Mg contents increase the formation of dimers). The latter influence is explained by molecular simulations in terms of an electrostatic repulsion between the ammonium groups of closely-located adjacent dimers when a high density of protonated ephedrine molecules is required in order to compensate for the high Mg incorporation. In this situation, dimers are only incorporated if the system is forced by increasing the concentration of ephedrine in the gel and increasing the temperature. Our results show that a similar number of ephedrine molecules and Mg dopants are incorporated in the AFI unit cell because of charge-balancing purposes, suggesting a strong electrostatic interaction between both species with opposite charge.

Keywords: Zeolite, Aggregation, Supramolecular, Self-assembly, Ephedrine, Chirality.

1. Introduction

Chirality is the property whereby an object is not superimposable with its mirror-image. Nature is full of chiral objects, a classical example being our asymmetric hands. Homochirality, meaning chirality in its enantiomerically-pure form, is intrinsically linked with life since the biochemical units that provide the building blocks for the construction of living organisms are homochiral (sugars, aminoacids, and nucleotides). At some point at the origins of life, life decided to work on an asymmetric fashion, using biochemical units of only one handedness [1]. Such an asymmetric building of life had a dramatic consequence: different enantiomers of a chiral compound interact differently with living cells. Most of the pharmacological compounds are chiral; in 2006, 80 % of the small molecular compounds approved by the US Food and Drug Administration were chiral, and 75 % of them contained only one of the enantiomers [2]. This is so because, very often, only one enantiomer has the desired therapeutic effect, and even in particular cases the other enantiomer can have teratogenic effects [3]. In this context, there is a very strong interest in developing materials that can discriminate between different enantiomers of a chiral compound, and thus be able to perform enantioselective operations in order to have only the desired enantiomer.

For a system to interact differently with enantiomers of a chiral compound, it needs to be chiral itself. In this context, chirality in inorganic systems is also manifested, with the typical example being chiral quartz, although much more rarely than in bio-organic compounds. Homochirality is in contrast almost never found in inorganic systems (quartz exists in both enantiomorphic forms). However, there is evidence that chiral inorganic surfaces can transfer their chirality to adsorption or catalytic processes and perform enantioselectively [4], and hence the search of homochiral inorganic structures represents a fundamental area of research nowadays [5,6]. In this context, chiral zeolite-

type microporous materials are optimum candidates for achieving such solids since they could combine their characteristic high adsorption capacity, stability and shape-selectivity with a potential enantioselectivity. Indeed, some zeolitic chiral frameworks do exist [7], such as the polymorph A of zeolite BEA [8] or a chiral zincophosphate (CZP) [9], as well as the recently discovered ITQ-37 [10], and HPM-1 [11], the all-silica form of the silicogermanate SU-32 [12], demonstrating the viability of these chiral microporous frameworks. Interestingly, recent research efforts have resulted in a partial enrichment of zeolite Beta in the chiral polymorph A [13]. In addition, some classical frameworks have recently been recognized as being chiral [14]. However, except very rare examples [15], these materials invariably crystallize as racemic conglomerates, i.e. 50:50 mixture of crystals of both handedness. Nonetheless, interesting strategies have been successfully applied in certain cases to enrich the materials in a particular enantiomorph [16].

The traditional strategy to produce chiral zeolite frameworks has been the use of chiral organic molecules as structure-directing agents (SDAs), in an attempt to transfer the chirality from the molecular component to the inorganic framework [17]. The organic SDAs organize the inorganic units into a particular geometry, giving place to the precursors from which crystallization of a particular framework-type will occur. However, although chiral SDAs have directed the crystallization of microporous frameworks, even some of them being chiral [18], no transfer of the chiral nature of the SDA molecule to the inorganic network has occurred since crystals of both handedness invariably crystallized. The reason for such lack of chiral imprinting from the molecular component is two-folded: on the one hand, it might be related to the typical looseness of SDA molecules within the zeolite porous network, which are not tightly confined and therefore the interaction between both is not very strong, providing a free of rotation to

the molecules in the zeolite pores/cavities that could somehow cancel their asymmetric nature; on the other hand, it could also be related to the different dimension of the chiral nature of organic molecules, provided by the presence of stereogenic centres, and hence generating a local asymmetric microenvironment, and that of chiral zeolite frameworks, given by a long-range chiral ordering of achiral TO_4 units (typically as helicoidal channels). If a transfer of chirality is to take place, the free rotation/movement of the molecules should be prevented, and an increase from the chiral dimension of the organic SDA into a supramolecular level in order to adapt to the dimension of the framework chirality should be achieved. In addition, a strong and localized interaction between the organic molecules and the inorganic framework should be established to enhance the chances of transfer of chirality.

In an attempt to achieve these goals, we have recently proposed the use of chiral aromatic molecules as SDAs [19–23]. The rationale behind this is that aromatic molecules tend to form supramolecular aggregates in aqueous solution stabilized by π - π interactions, and hence the atomic dimension of the chirality associated to stereogenic centres of the SDA molecules is expressed at a supramolecular level through the formation of chiral dimers. Besides, the asymmetric nature of the dimers involves also that the packing between consecutive dimers in one-dimensional zeolitic channels would also be asymmetric, where consecutive dimers would best fit at a particular angle (around the longest dimer axis) between consecutive dimers in order to optimize the packing interactions. In this way, the atomic chirality of the organic SDA molecules would be expressed in a long-range supramolecular level, thus adapting to the chiral dimension typical of zeolite frameworks. The formation of large-size supramolecular aggregates confined within the zeolite channels has the additional advantage that, due to

such large size and the development of supramolecular interactions, their movement/rotation will be strongly impeded when occluded within the pores.

On the other hand, the main interactions between doped microporous frameworks and organic SDAs are established between the positive charge associated to the N atom of the SDA molecules (being quaternary ammonium or protonated ammonium) and the negative charge associated to the incorporation of low-valence dopants (replacement of Si^{4+} by Al^{3+} in zeolites, or Al^{3+} by Mg^{2+} and other divalent metals in aluminophosphates). Hence, a strong electrostatic interaction between negative charges of opposite sign is established, which could facilitate the transfer of chirality, not to the overall inorganic network of the zeolite framework, but to the relative spatial distribution of dopants embedded in the network. In this sense, if supramolecular dimers of protonated chiral molecules are formed during crystallization of the nascent framework, the ammonium groups of these molecules will tend to drive the incorporation of the dopants close to them to maximize the electrostatic interactions, and hence since the two molecules are spatially connected by the formation of the chiral aggregate, such chirality could be potentially transferred into the spatial distribution of those two dopants, which could then be chirally distributed [24].

In this context, we have recently studied the structure-directing effect of (1R,2S)-ephedrine during the synthesis of an aluminophosphate-based microporous framework, AlPO-5 (AFI-type structure) [25,26], which is composed by 12-ring one-dimensional channels. This chiral molecule has been selected since i) it has two stereogenic centres that impart a strong asymmetric nature to the molecule, and indeed the amine group that will develop the strongest interaction with the negatively-charged dopants in the framework is directly linked to one of those asymmetric atoms, ii) it possesses an aromatic ring that displays a rich supramolecular chemistry, and iii) it has H-bond donor

and acceptor groups that will enable the formation of H-bonds between adjacent dimers, thus stabilizing their formation.

In order to develop chiral spatial distribution of dopants, it is imperative that the protonated molecules that will drive the incorporation of dopants will form supramolecular aggregates when confined within the microporous network, so that there is a spatial connection between both species composing the chiral supramolecular aggregate that could be imprinted into the relative spatial distribution of dopants. In addition, if one seeks to develop an asymmetric long-range (helical) ordering of these dimers that could also be imprinted into the inorganic network, a close interaction between consecutive dimers is to be established, and hence a high packing density of the dimers (in terms of number of molecules per unit cell) is required. Based upon these grounds, in this work we have performed an intensive study of the synthesis conditions of Mg-doped AFI materials using (1R,2S)-ephedrine as SDA in order to, on the one hand, maximize the formation of dimers within the AFI channels and understand the molecular factors governing the supramolecular behaviour of these chiral molecules, and on the other, to maximize the loading of organic molecules within the AFI materials.

2. Experimental

2.1. Hydrothermal synthesis of AFI materials

The experimental protocol for the synthesis of the Mg-doped AFI materials was similar to that reported in our previous works [25,27]. The synthesis of the aluminophosphates was carried out by hydrothermal methods using (1R,2S)-ephedrine (EPH) (Sigma Aldrich, 98%) as SDA; gel molar compositions and synthesis parameters (crystallization temperature) were systematically varied. Mg-AFI materials were prepared from gels having the following

molar composition: x EPH: 1 P_2O_5 : $(1-y/2)$ Al_2O_3 : y MgO : z H_2O ; the different gel compositions and synthesis conditions studied are detailed in Table S1 in the Supporting Information. A detailed preparation protocol of the synthesis gels can be found in our previous publication [25]. The pH of the resulting gels was between 2.7 and 5.6 (depending on the amount of EPH in the gel). The respective gels were introduced into 60 ml teflon lined stainless steel autoclaves and heated statically at the required temperature (140, 165, 180 or 200 °C) under autogenous pressure for 24 h. The resulting solids were separated by filtration, washed with acetone, ethanol and water and dried at room temperature overnight.

2.2. Characterization of the solid samples

The phase selectivity of the solid products was characterized by X-Ray Diffraction (XRD) (Philips XPERT diffractometer using $\text{CuK}\alpha$ radiation with a Ni filter). Thermogravimetric analyses (TGA) were carried out to analyse the incorporation of water and organic molecules, and were registered using a Perkin-Elmer TGA7 instrument (heating rate = 20 °C/min). UV-Visible diffuse reflectance spectroscopy was used to analyse the incorporation of the aromatic moieties of the EPH molecules (UV-Vis Cary 5000 Varian spectrophotometer equipped with an integrating sphere using the synthetic polymer Spectralen as reference).

The samples were also studied by Solid State Magic Angle Spinning Nuclear Magnetic Resonance (MAS-NMR) of several nuclei. These MAS-NMR spectra were recorded with a Bruker AV 400 WB spectrometer, using a BL7 probe for ^{13}C and BL4 probe for ^{31}P . ^1H to ^{13}C cross-polarization (CP) spectra were recorded using $\pi/2$ rad pulses of 4.5 μs for ^1H , a contact time of 5 ms and a recycle delay of 3 s. For the acquisition of the ^{13}C spectra, the samples were spun at the magic angle (MAS) at a rate of 5-5.5 kHz. For

^{31}P , $\pi/2$ rad pulses of 4.25 μs and recycle delays of 80 s were used; these spectra were recorded while spinning the samples at ca. 11 kHz.

The aggregation state of the molecules in the solid samples was studied by UV-Visible fluorescence spectroscopy. Solid state fluorescence emission spectra were recorded in a RF-5300 Shimadzu fluorimeter. The fluorescence spectra were registered in the front-face configuration by a solid sample holder in which the samples were oriented 30° and 60° with respect to the excitation and emission beams, respectively. Fluorescence spectra of the solid samples were recorded by means of thin films supported on glass slides elaborated by solvent evaporation from a dichloromethane suspension of the solid samples.

2.3. Computational details

Molecular-mechanics-based simulations were performed in order to analyze the packing of the (1R,2S)-ephedrine dimers occluded within the 12-MR channels of the AFI framework, and explain the experimental observations regarding the influence of the synthesis conditions on the supramolecular aggregation behaviour. As in our previous work [26], molecular structures of ephedrine molecules and their packing and non-bonding interactions with the AFI framework were described with the cvff forcefield [28]; this forcefield contains a large series of energy terms which suitably describes the molecular structure of organic molecules as well as their interaction with AlPO-based zeolite-like frameworks. The AFI structure was kept fixed during the calculations. All calculations were performed under periodic boundary conditions (PBC).

The atomic charge-distributions of EPH^+ (protonated ephedrinium) and EP^0 (neutral ephedrine amine) were obtained from DFT+D calculations, using the B3LYP hybrid functional and the ESP charge calculation method, setting the total net charge to +1 or 0,

respectively. The framework charges were initially fixed to -1.2 for O, 3.4 for P and 1.4 for Al. In the cases where there is an excess of positive charge (provided by the EPH⁺ molecules), this excess was compensated by uniformly reducing the Al atomic charge until neutrality.

Geometry optimisation and simulated annealing calculations (NVT ensemble) were performed using the Forcite module, as implemented in Material Studio 7.0 [29]. The interaction energies were calculated by subtracting the energy of the molecules in vacuum to the total energy of the systems.

3. Results

Henceforth, the AFI samples synthesized with EPH as SDA and with different compositions will be denoted as MgAlPO-5-1 (synthesized with composition 1: 1 EPH: 1 P₂O₅: (1-y/2) Al₂O₃: y MgO: 100 H₂O), MgAlPO-5-2 (synthesized with composition 2: 2 EPH: 1 P₂O₅: (1-y/2) Al₂O₃: y MgO: 100 H₂O) and MgAlPO-5-3 (synthesized with composition 3: 1 EPH: 1 P₂O₅: (1-y/2) Al₂O₃: y MgO: 50 H₂O), followed by the amount of Mg in the gel (0.11, 0.22 or 0.32) and by the crystallization temperature (140, 165 or 180 °C). A molar composition with a Mg content corresponding to y = 0.22 MgO in the gel involves a theoretical incorporation of 1.33 Mg per AFI unit cell (by replacement of Al³⁺). The theoretical value of organic content incorporated to the inorganic network at this condition should then be of 1.33 EPH⁺ per unit cell to provide charge-balance, which corresponds to the most stable packing of EPH dimers that we found previously by molecular simulations [26]. In contrast, a molar composition with y = 0.11 MgO involves a theoretical value of Mg²⁺ in the AFI framework of 0.66 Mg²⁺ per unit cell. We also studied gels with y = 0.32 MgO, where there is an excess of dopants, to see the effect of this excess on the aggregation.

3.1. Characterization of the materials

The XRD patterns of the aluminophosphate-based materials obtained in this work indicate that the organic molecule selected as SDA, EPH, directs the synthesis towards the crystallization of MgAPO-5 (AFI-type structure) under different gel compositions (see Table S1 and Figure S1-left in the Supporting Information). The AFI-type structure is composed of one-dimensional non-interconnected 12-membered-ring (MR) channels with a diameter of 7.3 Å. The synthesis results suggest that EPH is only able to direct the synthesis towards the AFI-type structure in the presence of Mg dopants. In the case of synthesis carried out without dopants, the XRD patterns show that a tridymite-like dense AlPO framework crystallizes together with an unknown low-dimensional phase. In contrast, the incorporation of dopants as Mg^{2+} into the synthesis gel drives the crystallization towards AFI-type materials (see Table S1).

3.1.1 Composition MgAPO-5-1 (1EPH:100H₂O)

In the case of composition 1 (1 EPH: 1 P₂O₅: (1-y/2) Al₂O₃: y MgO: 100 H₂O), MgAPO-5 (AFI) was obtained in all cases; however, pure AFI materials were only obtained when the molar amount of dopant (y) was 0.22 at high temperature (165 and 180 °C) and when y was 0.32 at all temperatures (Table S1). In the rest of cases (with 0.11 MgO and 0.22 MgO only at low temperature), AlPO-tridymite, the unknown low-dimensional phase and AlPO-C (APC-type framework) were also obtained as secondary phases in different relative amounts depending on the particular case. It is a constant observation that a high amount of dopants (0.22/0.32 MgO) involves a lower amount of the low-dimensional phase (with respect to 0.11 MgO); this clearly evidences that the formation of AFI materials is favoured with a high amount of dopant in the gel.

The TGA profiles of the samples (see Figure 1-left for typical examples of AFI pure phases, and Figure S2 in the Supporting Information for all samples in composition 1) show four different weight loss steps. The first weight loss at temperatures below 200 °C corresponds to desorption of water. The other weight losses at higher temperatures (above 200 °C) correspond to the SDA decomposition and desorption that occurs in different steps. It should be noticed that the TGA profile is notably different in the samples where the presence of the unknown low-dimensional phase was detected by XRD (especially samples obtained at 140 °C), where an extremely large weight loss occurs at temperatures around 270 °C, evidencing a very high amount of organic molecules that hold the low-dimensional AlPO network and a low retention of the EPH molecules in this phase. The profiles of the TGA analyses of these AFI-rich materials show the largest weight loss at very high temperature, around 750 °C, which should correspond to decomposition of organic species after polymerization during the TGA procedure, providing evidence for the strong acidity of these MgAPO-5 samples. In the cases where the AFI framework was obtained as the major phase, the water and organic contents incorporated per unit cell (u.c.) are listed in a table in Figure S2 (Supporting Information). The packing values of organic molecules incorporated per unit cell obtained are lower than the expected value (of 1.33 molecules per unit cell, which corresponds to the maximum organic loading); hence, it becomes evident that the incorporation of molecules under this composition is not optimum. However, care should be taken when analysing the organic contents in this composition since some of the samples contain other secondary phases (especially those obtained with 0.11 MgO) which could deviate the estimation of the real organic content in the AFI phase. CHN chemical analyses could not be trusted due to an incomplete combustion of the samples because of the strong acidity of the samples and the aromatic rings of the organics.

The chemical integrity and the incorporation of EPH inside the framework was verified by ^{13}C CP MAS NMR (Figure 2). Results show that the molecule is incorporated intact within the AFI structure, even in samples obtained at temperatures as high as 180 °C, since all the bands of EPH are clearly observed (see assignments of the different bands in Figure 2 and compare with EPH). However, during the synthesis carried out at 200 °C, all the EPH bands are still present; the aromatic ring of EPH seems to incorporate intact but the aliphatic C bands are less intense. In addition, the samples obtained at 200 °C present a large amount of trydimite as secondary phase and the residual water deriving from the washing procedure had a dark colour indicating that the molecule is starting to degrade. For this reason, in subsequent synthetic experiments, 180 °C was set as the maximum crystallization temperature.

The incorporation of Mg into the AFI structure was studied by ^{31}P MAS NMR, which is able to discriminate different coordination environments of Mg. The fact that Mg^{2+} is diamagnetic induces a very small broadening on the P resonances, which makes ^{31}P MAS NMR a very useful technique to demonstrate the isomorphous substitution of Al^{3+} by Mg^{2+} [30]. ^{31}P NMR results are reported in Figure 3: the spectra of the series of MgAPO-5-1 materials show the main resonance at -30 ppm, which corresponds to a tetrahedral P(4Al) environment in the AFI network, in which the coordination shell surrounding P (after the O bridges) is four Al atoms [31]. In addition, a peak at -24 ppm is observed due to the presence of P (1Mg,3Al) environments (Figure 3) [32], clearly evidencing the incorporation of Mg in tetrahedral positions in the AFI network by isomorphous substitution of Al. As expected, at low Mg contents in the gel ($y = 0.11$), the intensity of the peak corresponding to P (1Mg,3Al) is lower with respect to the sample obtained with a higher Mg amount ($y = 0.22$). Deconvolution of the ^{31}P NMR spectra was carried out using individual Gaussian lines in order to calculate the amount

of Mg incorporated in tetrahedral positions in the AFI framework. The relative intensities of the P environments P (nAl,(4-n)Mg) are extracted from the area under the curves of the different components, and the Mg content per AFI unit cell is calculated (from the P/Mg ratio, taking into account that the AFI unit cell contains 12 P atoms) using the following expression [33] (eq. 1):

$$\frac{P}{Mg} = \frac{\sum_{n=0}^4 P(nAl)}{\sum_{n=0}^4 0.25 (4 - n) I_p(n - Al)} \quad (\text{Eq. 1})$$

where $I_{P(n-Al)}$ is the area under the P(nAl,(4-n)Mg) peak. In order to get a good adjustment of the deconvolution to our experimental spectra, a third additional component at lower fields was required. A third component at around -18 ppm could be assigned to the presence of P(2Mg,2Al) environments. Such type of P environments should not be especially favoured in AlPO frameworks since it would involve the presence of two closely located negative charges in the inorganic network. In any case, if we assign a third component to this type of P(2Mg,2Al) environments, the calculated Mg contents that result from eq. 1 (for samples obtained with 0.22 MgO) are as high as 1.6 Mg/u.c. Besides, if we assign a fourth component at around -12 ppm to P(3Mg,1Al) environments, Mg contents higher than 2 Mg/u.c. are obtained. Such values of Mg content are clearly unreasonable since they would involve organic contents larger than 1.6 EPH⁺/u.c. for charge-balancing purposes, which cannot be accomplished in the AFI channels (the maximum packing value of EPH dimers suggested by simulations was 1.33 EPH/u.c.). For this reason, we have assigned a third component in our ³¹P NMR spectra to P-X species, being P-OH or PO⁻ groups, coming from the presence of amorphous AlPO impurities or other defects which would contribute to such wide ³¹P resonance. Results of Mg contents (per unit cell) calculated after deconvolution of the ³¹P NMR spectra are reported in Table 1. In the case of samples obtained with 0.11 of

Mg in the synthesis gel, the incorporation of Mg is always higher (0.92 Mg/u.c. at 165 °C and 0.86 Mg/u.c. at 180 °C) than the content in the synthesis gel (0.66 Mg/u.c.). In contrast, samples obtained with a higher amount of Mg in the synthesis gel (MgAPO-5-1_0.22) at both temperatures (165 and 180 °C) incorporate a higher amount of Mg than in the previous case, 1.10 and 1.09 Mg/u.c., respectively. However, these values are smaller than the 1.33 Mg/u.c. theoretical content given by the gel composition, suggesting that this gel composition does not maximise the Mg incorporation. The dopant content has been also calculated by ICP and related with the results of ^{31}P MAS NMR.

Solid state UV-visible fluorescence spectroscopy was then applied in order to study the aggregation behaviour of the molecules when confined within the different Mg-doped AFI materials (Figure 4). The study of the aggregation of these molecules in aqueous solution was reported in a previous publication [25]. In the present work, the influence that different synthesis parameters have over the aggregation in the solid samples is analyzed. The incorporation of EPH monomers gives a band centred at 280 nm, coming from the emission of the aromatic ring. Such emission is red-shifted to longer wavelengths when aggregates are formed, because the π - π stacking of the aromatic rings provokes a stabilisation of the π^* molecular orbitals that reduces the energy difference between the energy levels. Fluorescence results evidence that the aggregation of EPH, indicated by the emission bands at wavelengths higher than 330 nm, increases dramatically with the crystallization temperature, regardless of the Mg content in the gel, as shown by the more intense emission bands registered in the samples obtained at 180 °C that corresponds to aggregates of EPH (Figure 4-bottom). If we compare the spectra of samples obtained with the same Mg content in the gel at different temperatures (distinguished by the color of the line in Figure 4), we clearly observe a

progressive decrease of the band corresponding to monomers at 280 nm. Two bands centred at around 375 and 425 nm corresponding to aggregates are distinguished, although the origin for this difference is not clear at the moment. They both should be assigned to supramolecular dimers since no higher-order multimolecular aggregates can fit within the one-dimensional AFI channels with a diameter of 7.3 Å. The aggregate at the longer wavelength of 425 nm must develop a stronger π - π interaction between the aromatic rings of EPH that causes a longer red-shift of the emission band. This could be due to a stronger overlapping (stacking) of the aromatic rings caused by a higher organic loading, or maybe to the presence of the molecules in different charge-states.

Another clear observation of the aggregation behaviour as a function of the Mg content in the solids has been identified: lower amounts of Mg in the gel involve a stronger aggregation: the aggregation trend progressively decreases upon an increase of the Mg content in the gel (from 0.11 to 0.22 and to 0.32 MgO), with a consequent enhancement of the band corresponding to monomers (at 280 nm). Such effect is observed at the three temperatures (red lines in Figure 4 show a higher intensity of the monomer band).

The incorporation of the aromatic ring of EPH into the solids have also been studied by UV diffuse reflectance spectroscopy (Figure 5). All the spectra display two bands centred at around 200 and 260 nm (the latter with a vibronic structure) characteristic of the absorption of phenyl rings. Interestingly, we observe the appearance of new spectroscopic features at higher wavelengths when the crystallization temperature is increased, with wide bands showing up between 300 and 500 nm. As previously observed by fluorescence spectroscopy, an increase in the crystallization temperature leads to a higher presence of supramolecular aggregates. Therefore, we assign these absorption bands between 300 and 500 nm to the presence of aggregates, which is specially noticeable in the samples obtained at 180 °C. The appearance of these red-

shifted features in the UV absorption spectra upon aggregation is in line with reports in the literature in related systems [34], and again is caused by the stabilisation of π^* lowest unoccupied molecular orbital upon π - π stacking. Hence, UV absorption spectroscopy can also be used to analyze the incorporation of aggregates.

Although our study have so far shown clear trends of the aggregation with respect to the synthesis conditions, in particular to the amount of Mg in the gel and the crystallization temperature, which allowed to obtain AFI materials where all the EPH molecules incorporate as supramolecular aggregates (especially in samples obtained at 180 °C), nevertheless the incorporation of Mg and organic molecules has not been maximised (to the theoretical value of 1.33/u.c. given by the maximum loading of EPH molecules when AFI channels are completely filled by EPH dimers). For this reason, and in order to further explore the aggregation trend as a function of the gel composition (in terms of organic and water contents), new experiments with different compositions have been studied.

3.1.2 Composition MgAPO-5-2 (2EPH:100H₂O)

In an attempt to enhance the aggregation trend and maximise the organic incorporation in the AFI channels, we increased the amount of EPH in the synthesis gel to 2; the gel composition was now 2 EPH: 1 P₂O₅: (1-y/2) Al₂O₃: y MgO: 100 H₂O. In this composition, MgAPO-5 was only obtained at the highest temperature (180 °C) but with a very minor amount of the same low-dimensional phase as found previously. At lower temperatures, this low-dimensional phase predominates (see Table S1 in the Supporting Information). In general terms, a higher crystallization of the low-dimensional phase is clearly observed under this composition compared to composition 1 with a lower concentration of EPH in the gel. The major presence of this unknown low-dimensional

phase can be ascribed then to the higher concentration of organic molecules. An increase in the concentration of EPH involves a stronger aggregation, as observed previously by fluorescence spectroscopy of the aqueous solutions of ephedrine hydrochloride of increasing concentrations [25]. The consequent higher crystallization of the low-dimensional phase upon an increase of the EPH concentration in the gel suggests a strong aggregation of EPH molecules in this low-dimensional phase. Combined with the first diffraction angle in the XRD pattern observed at very low angle (at around $4.5\ 2\theta$ deg, suggesting a large unit cell) and the very high organic content found by TGA in samples enriched in this phase (Figure 1-right), we propose a structure of this framework composed by a bilayer of EPH molecules stabilised by hydrophobic interactions between the aromatic rings, and hydrophilic interactions of the polar groups with the AlPO network, as schematically shown in Figure S3 in the Supporting Information. Crystallization of this phase seems to be favored at higher organic concentrations and low temperatures, and with a low amount of Mg. Similar type of frameworks with a bilayer of organic amines have been previously observed [35].

The thermogravimetric analyses of samples which contained AFI as the major phase (Figure 1-left and Figure S4-right in the Supporting Information) show a larger incorporation of organics in the solids compared to the materials obtained with composition 1 (Table 1). The incorporation of organic molecules within the channel increases slightly with the temperature at the expense of the incorporation of water which decrease with the temperature; nevertheless, the number of water molecules might be overestimated because of the presence of a minor amount of the unknown dense-like phase. The number of organic molecules incorporated compares reasonably well with the organic content in the gel (1.33 EPH/u.c.), evidencing that the increase of

the SDA concentration in the gel brings a higher packing of the organic molecules in the AFI channels.

As in previous cases, the amount of Mg^{2+} incorporated to the network was determined by ^{31}P MAS NMR (Table 1 and Figure S5-right in the Supporting Information, black line). The spectra of sample MgAPO-5-2_0.22_180 shows a larger content of Mg^{2+} in the AFI framework (1.36 Mg/u.c.) compared to that obtained with a lower amount of EPH in the gel (composition 1); this higher Mg incorporation is accompanied by a higher incorporation of organic molecules (1.46 EPH/u.c., Table 1) to provide charge-balance (this EPH packing value might be slightly overestimated by the presence of a minor amount of the low-dimensional phase). Indeed, these values suggest that both the incorporation of EPH and Mg are in reasonable good agreement with the theoretical packing value of 1.33 molecules/u.c. where the AFI channels are completely filled by EPH dimers. ^{13}C CP MAS NMR spectra (Figure S5-left in the Supporting Information, black line) shows that the molecules incorporate intact inside the AFI channels also under this composition.

Fluorescence spectroscopy of these samples were performed in order to analyze if the higher concentration of the SDA molecules in the gel influences their aggregation behaviour within the AFI materials (Figure 6-left); only samples which showed a major presence of the AFI phase were studied. Results showed the same effect as observed in previous cases: the aggregation increases with the temperature, as evidenced by the fact that the emission of monomers is only observed at 165 °C. The higher SDA concentration used in this composition has given place to a much higher aggregation of the occluded EPH molecules samples compared with composition 1 (compare for instance samples obtained with 0.22 MgO at 165 °C, in Figures 4 and 6, where a much stronger presence of monomers is observed for composition 1). The aggregation

behaviour of the molecules within the AFI channels is again supported by UV diffuse reflectance spectroscopy (Figure S4-left in the Supporting Information). The same effect as the one identified by fluorescence spectroscopy is observed: the aggregation increases with the temperature. This is apparent since the additional band observed at around 350 nm is more prominent at 180 °C.

In sum, these results suggest that the higher concentration of EPH in the gel gives place to a higher incorporation of organic molecules in the AFI channels, all of them arranged exclusively as dimers if the crystallization temperature is high, and consequently a higher incorporation of Mg into the AFI network in order to provide charge-balance. However, under this composition, the AFI-framework was only obtained in a narrow range of conditions due to the high concentration of organic molecules that leads to the formation of the low-dimensional phase because of the strong aggregation. For this reason, and in order to obtain crystalline AFI materials over a wider range of conditions than in composition 2 and a stronger aggregation than in composition 1, a new composition was studied in which we reduced the water content to 50.

3.1.3 Composition of MgAPO-5-3(1EPH:50H₂O)

The rationale to study this composition is to maintain the same SDA/H₂O ratio that was used in composition 2 to keep the same high aggregation trend but with a lower amount of SDA (with respect to T atoms) in the gel in order to reduce the formation of the low-dimensional phase and favor the crystallization of the AFI structure. The new composition used was: 1 EPH: 1 P₂O₅: (1-y/2) Al₂O₃: y MgO: 50 H₂O, where y was 0.11 and 0.22. XRD patterns show that the AFI framework crystallized in all cases. However, minor amounts of AlPO-tridymite, the low-dimensional phase and MgAPO-36 (ATS) were also obtained under certain conditions as secondary phases, especially at

low temperature and low Mg content (see Table S1 in the Supporting Information). It is interesting to note that the formation of the low-dimensional phase is much weaker under this composition.

The incorporation of EPH into the AFI materials was verified by ^{13}C CP MAS NMR (Figure S5-left in the Supporting Information). ^{31}P MAS NMR results (Figure S5-right in the Supporting Information) again showed that the incorporation of Mg in the AFI network increases when the amount of dopant in the synthesis gel is increased from 0.11 to 0.22 MgO. Deconvolution of the spectra showed a Mg content of 1.11 and 1.37 Mg/u.c. for samples obtained with 0.11 and 0.22 MgO in the gel (theoretical Mg contents of 0.66 and 1.33 per AFI u.c., respectively) at 180 °C, respectively. The latter value is very close to the theoretical stable packing of 1.33 EPH/u.c., which is very close as well to the Mg content for the sample obtained with the same amount of Mg in the gel but in composition 2 (2EPH:100H₂O) (1.36 Mg/u.c., see Table 1).

Fluorescence spectroscopy (Figure 6-right) showed the same effect as in previous compositions: the increment of the temperature involves a higher aggregation. In this composition, the aggregation of EPH is much more evident than with 100H₂O in the gel (composition 1). Again the same two bands (at 375 and 450 nm) assigned to dimer aggregates are observed, with the latter being more intense. In samples obtained at 180 °C, EPH molecules are exclusively incorporated as aggregates (regardless of the Mg content). The presence of monomers is only detected in samples obtained at 165 °C. Again, UV diffuse reflectance spectroscopy also endorsed the fluorescence results about the aggregation behaviour since more intense bands registered between 300-500 nm were observed for samples obtained at 180 °C with respect to that obtained at 165 °C (Figure S6-left in the Supporting Information).

TGA results of these samples (Figure S6-right in the Supporting Information) showed similar weight losses as in previous cases, corresponding to desorption of water (below 200 °C) and organics (above 200 °C). The organic contents of the AFI unit cell (Table 1) clearly indicate a lower incorporation of organics for the sample obtained with a lower Mg content (1.10 EPH/u.c.) than those obtained with more Mg (around 1.27 EPH/u.c.). Interestingly, these organic contents found by TGA are very similar to the Mg contents found by ^{31}P NMR (1.11 and 1.37 Mg/u.c. for samples obtained with 0.11 and 0.22 MgO, respectively), evidencing the charge-balancing role of EPH and hence their incorporation as protonated species and their strong electrostatic interaction with Mg dopants.

3.2. Computational Results

Our experimental results using composition 1 (1EPH:100H₂O) show that the aggregation of ephedrine molecules occluded within the AFI channels increases when the Mg content in the gel, and consequently in the solids, decreases. We now wanted to unravel the chemical reason for such behaviour from a molecular level. In a previous work [27] we observed a notable effect of the protonation state of the molecules on the aggregation: molecules loaded in neutral state (by post-synthesis adsorption treatments) tend to enhance the incorporation as aggregates, possibly due to a lower electrostatic repulsion between consecutive dimers. We then wondered if a similar electrostatic repulsion between consecutive dimers located close to each other under high Mg contents could explain the experimental observations.

In an attempt to study this, we calculated the interaction energy for AFI systems (with 1x1x3 supercells) where we loaded a single molecule in a monomer configuration (thus excluding packing interactions) or 4 molecules in a dimer configuration (2 dimers) with

different charge-states. The final location and interaction energies of the systems were obtained by simulated annealing calculations. We also calculated the dimerization energy (per molecule) as the difference in the interaction energy (normalized per molecule) between the molecules when they arrange as monomers or as dimers as a function of the charge-state of the molecules (Table 2).

We first analysed the results when all the molecules are protonated (entry 1 in Table 2, ‘all-charged’ system). The total interaction energy is much higher for the system with four molecules (dimers), but of course this is due to the higher number of guest species (4) compared to 1 in the ‘monomer’ system. However, when we normalized the interaction energy per molecule, we observe a higher stability when the molecule is arranged as monomers than as dimers, possibly due to an electrostatic repulsion between the charged ammonium groups. Indeed, the dimerization energy in this case is positive, and so less stable, which means that dimers will only be formed under this high packing value of 1.33 if there is a compensation for such lower stability, like for instance the interaction with net negative charges associated to the incorporation of dopants (1 dopant per protonated molecule).

We then studied a system where half of the molecules are protonated (EPH^+) and half neutral (EP^0). In this case, there are three possible molecular arrangements of the two types of molecular species (see Figure 7): with ‘alternated’ neutral and protonated species (dimer-alternated: $[\text{EPH}^+ \cdots \text{EP}^0]$ $[\text{EPH}^+ \cdots \text{EP}^0]$ $[\text{EPH}^+ \cdots \text{EP}^0]$, Figure 7-top) (brackets indicate the dimers), or with non-alternated neutral and protonated species, which can be in ‘consecutive’ configuration, with two types of dimers, one formed by protonated and one formed by neutral species (dimer-consecutive: $[\text{EPH}^+ \cdots \text{EPH}^+]$ $[\text{EP}^0 \cdots \text{EP}^0]$ $[\text{EPH}^+ \cdots \text{EPH}^+]$, Figure 7-middle), or in ‘facing’ configuration, with dimers formed by neutral and protonated species but in a different orientation (dimer-facing:

[EPH⁺...EP⁰] [EP⁰...EPH⁺] [EPH⁺...EP⁰], Figure 7- bottom). We note that only in the last configuration (dimer-facing), the two positive charges associated to the N atoms of adjacent dimers are facing to each other (see Figure 7, positively-charged N atoms are displayed as yellow balls), and therefore sit very close to each other (see N⁺...N⁺ distances in Table 2). The interaction energies for the three arrangements are reported in Table 2. The first clear observation is that the system where the protonated N atoms of consecutive dimers are facing to each other (dimer-facing) is much less stable. This is due to the electrostatic repulsion between the positive charges associated to the ammonium groups of consecutive dimers. The other two configurations (dimer-alter and dimer-consec) do not involve a close location of the ammonium groups in consecutive dimers (see Figure 7 and N⁺...N⁺ distances in Table 2), and consequently they are much more stable (by more than 12 kcal/mol per molecule) since they prevent the electrostatic repulsion between ammonium groups. Indeed, a quasi-linear relationship between the interaction energy (and hence the stability) and the closest distance between the charged N⁺ atoms of the ammonium groups of the protonated EPH⁺ species is observed (Figure S7 in the Supporting Information), again evidencing that a close location of ammonium groups in consecutive dimers involves a strong electrostatic repulsion that destabilizes the systems. The dimerization energy in the cases that such close location is prevented ('alternated' and 'consecutive') are in fact favourable (-6.3 and -5.4 kcal/mol). Finally, a similar stability of the molecules arranged as monomers or as dimers was observed when all the ephedrine species were neutral, indicating a low packing interaction in this arrangement.

Our simulation results so far suggest that under high packing values, an electrostatic repulsion between the closely located charged ammonium groups might destabilize the formation of dimers. In order to verify this, we calculated the interaction energies (per

unit cell) of systems where we loaded two dimers (with all the molecules protonated, EPH^+) at different distances between consecutive dimers (we will refer to this as *interdimer* distance); in this way, we systematically varied the organic content (packing density) of the AFI unit cell. In order to fix such interdimer distance, we added fixed Ar atoms at both extremes of the channels, and then systems with different initial interdimer distances were geometry-optimised. The interaction energies as well as the interatomic distance between the protonated N atoms in adjacent dimers as a function of the organic content are reported in Figure 8. Packing values higher than 1.35 molecules per unit cell involve a dramatic increase of the energy due to steric repulsions because of the high constraintment, and consequently these high packing values will not occur. When the packing reaches values of 1.33 and below, the slope of the energy profile decreases, which means that the steric repulsions and the too-tight fitting are reduced. In this case, the energy continues decreasing (but with a lower slope) down to packing values of 1.15 molecules per unit cell, where the energy reaches a plateau. Such softer decrease of the energy (and hence increase of the stability) is again due to a reduction of the electrostatic repulsion between close charged ammonium groups, as evidenced by the increase of the stability upon a reduction of the $\text{N}^+ \cdots \text{N}^+$ distance (Figure 8, red line). In conclusion, our simulation results show that when dimers are located close to each other with all the molecules protonated under high packing organic densities, an electrostatic repulsion between the closely located charged ammonium groups is established that can disfavour the formation of dimers under high packing values, which are concomitant to high Mg contents in the synthesis gels for charge-balance purposes. Lower Mg contents will require a lower packing density of protonated molecules, and hence these will locate further away from each other, thus enabling the formation of dimers because of a lower electrostatic repulsion between the ammonium groups.

Formation of dimers under high Mg contents will only be achieved if we force the system in order to overcome the electrostatic repulsion generated by closely packed dimers of protonated ephedrine molecules, like increasing the temperature or increasing the concentration of ephedrine in the synthesis gels.

4. Discussion

In this work, we have performed a systematic variation of the synthesis conditions of Mg-doped AlPO frameworks in an attempt to produce AFI materials where the EPH molecules are arranged exclusively as dimers and with a high organic content so that there is a close interaction between consecutive dimers in order to promote an asymmetric helicoidal arrangement of these dimers that could be transferred into the AFI network. In all the systems studied, we have observed a close agreement between the number of EPH molecules and the Mg content in the AFI unit cell (Table 1). This suggests that the EPH molecules are incorporated as protonated species in order to provide charge-balance to the negative charge associated to the isomorphic substitution of Mg^{2+} by Al^{3+} , suggesting a strong electrostatic interaction between both net charges that could favour a potential transfer of chirality from the organic arrangement into the spatial distribution of dopants. In fact, our results suggest that the AFI framework only crystallizes in the presence of at least 1 Mg per unit cell, even if the Mg content in the gel is lower (0.66, corresponding to a molar composition of 0.11MgO), which evidences the important stabilising role of these electrostatic interactions in the crystallization of AFI in this system; in fact, AlPO-5 does not crystallize from undoped gel systems.

Using a composition of 1EPH:100H₂O (composition 1) in the gel, we have observed a low incorporation of Mg and consequently a low incorporation of organic. Besides, the supramolecular aggregation trend under this composition is not especially favoured, and

indeed it is dependent on the Mg content: low Mg contents enhances the incorporation of aggregates. Such behaviour is explained by our simulations: high Mg contents involve a high incorporation of protonated organic species to provide charge-balance. If these molecules arrange as dimers, the high density of organic molecules would involve a close location of consecutive dimers, which generates a electrostatic repulsion between the positively-charge ammonium groups of EPH molecules in adjacent dimers that destabilizes the dimers. In contrast, lower Mg contents in the gel involve a lower density of EPH molecules in the solid to provide charge-balance, and hence the distance between adjacent protonated dimers will be larger, reducing the electrostatic repulsion between the ammonium groups and hence favouring the formation of dimers for low Mg contents.

On the other hand, we have observed a clear effect of the crystallization temperature on the aggregation, where higher temperatures always favour the incorporation of aggregates, although the chemical reason for this is not clear at the moment.

Only when the concentration of EPH molecules is increased to a relative H₂O/EPH ratio of 50 (2EPH:100H₂O in composition 2 or 1EPH:50H₂O in composition 3), the concentration of EPH in the solids reaches the aimed values close to 1.33 EPH/u.c. with a complete supramolecular aggregation, and a similar value of Mg content. These observations involve that only when the systems are forced to incorporate dimers by using these high EPH concentrations and high Mg contents, the electrostatic repulsion between consecutive dimers closely located is overcome; indeed, such electrostatic repulsion will be compensated by the stabilization provided by the electrostatic interaction with the negative charge associated to Mg. In any case, composition 3 (1EPH:50H₂O) is preferred since it reduces the formation of the undesired low-dimensional AlPO phase.

With these optimized compositions, two different situations are found as a function of the Mg content in the gel (see Figure 9): with a low Mg content in the gel, the Mg-AFI system tends to incorporate around 1 Mg and a similar amount of EPH per unit cell arranged as dimers, where consecutive dimers will be apart from each other avoiding the electrostatic repulsion between ammonium moieties, and therefore they will not interact to each other (Figure 9-top); water or even neutral EPH species will probably fill the void space (nonetheless, care should be taken upon these affirmations due to the minor presence of trydimite in this sample that could slightly deviate the real organic/water content). Under a high Mg content in the gel, the high Mg incorporation will require a high organic density and in this case, adjacent dimers will locate close to each other and will develop strong interdimer interactions (Figure 9-bottom). These two situations are in line with the observations from our molecular simulations (Figure 8), where two saddle points in the potential energy surface as a function of the organic content for values around 1.1 and 1.3 molecules per unit cell were observed. The less stable situation (in terms of packing interactions) of 1.33 EPH/u.c. is only achieved when the system is forced by a high EPH concentration and high Mg content in the gel. Finally let us have a word about the implications of our results on the induction of chirality in these materials through chiral spatial distributions of dopants. In order to promote a helicoidal distribution of dopants, a strong interaction between dopants and EPH molecules is required. Our observations about the similar incorporation of organic molecules and Mg in the AFI unit cell, because of charge-balancing purposes, suggest a strong electrostatic interaction between ammonium and Mg, thus enhancing the possibility of transferring the chirality from the organic arrangement into the distribution of dopants. In the case of achieving a high incorporation of organics and Mg (around 1.33 per unit cell), dimers will locate close to each other and therefore will

develop strong interdimer interactions that could promote a helicoidal supramolecular arrangement since the best packing between dimers involves a rotation of 30° (around the channel axis) between consecutive dimers, as observed in our previous computational work [26]. Such helicoidal arrangement could be transferred to the spatial distribution of dopants through the electrostatic interactions between Mg and ammonium (Figure 9-bottom). In contrast, a low Mg content in the gel results in an incorporation of close to 1 EPH and 1Mg per unit cell, which involves a long distance between consecutive protonated dimers which will therefore not interact to each other, and hence will be isolated. In this case, the presence of dimers (connecting two EPH molecules) involves that the spatial distribution of the two Mg incorporated per dimer will also be driven by their interaction with the ammonium groups of the dimer, and hence will be ordered following the chirality of the dimer. However, since dimers do not interact to each other, no long-range ordering of Mg will occur, but chiral microenvironments (associated to each dimer) could be developed because of the asymmetry of the EPH dimers (Figure 9-top). If achieved, this type of chiral materials where chirality comes from the asymmetric ordering to the dopants could have relevant applications in enantioselective process, such as the adsorption of chiral amines or alcohols, as well as in catalysis processes, such as the asymmetric aperture of epoxides.

5. Conclusions

Mg-doped AFI materials have been prepared using (1R,2S)-ephedrine as structure-directing agent under a range of synthesis conditions. A strong dependence of the supramolecular aggregation of these molecules confined within the AFI channels as a function of several synthetic parameters has been found, what would enable a control on the incorporation of aggregates. High crystallization temperatures promote the

formation of dimers. High concentrations of ephedrine (in terms of EPH/H₂O ratios) also favour the supramolecular aggregation, although a low-dimensional phase where ephedrine molecules must be strongly aggregated is also formed. The formation of this undesired phase is reduced when the EPH/(Al+P) ratio is decreased in the gel, while keeping the H₂O/EPH ratio as 50 to enhance the incorporation of dimers. Our results show that low Mg contents also favour the formation of dimers, which is explained because high Mg contents require a high density of organic molecules closely packed to provide charge-balance, and in this case adjacent dimers would locate close to each other, siting ammonium groups of consecutive dimers close to each other and hence provoking an electrostatic repulsion that destabilizes these dimers. Very similar contents of Mg and EPH molecules incorporated in the AFI unit cell are found in all cases, what evidences that EPH incorporates as protonated species in order to provide charge-balance, and suggests a strong electrostatic interaction between both species.

The combination of the experimental results and molecular simulations have shown that at high Mg contents in the gel, around 1.33 Mg and 1.33 EPH species per unit cell are loaded, which is the maximum organic packing that can be fitted within the AFI unit cell arranged as dimers. In this case, the high packing density involves a close location of consecutive dimers, and hence a strong interaction between their asymmetric atoms, what could promote an asymmetric helicoidal arrangement of dimers that could potentially be transferred to the spatial distribution of dopants through strong electrostatic interactions between the net charges.

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Supporting Information

Additional characterization of the obtained materials is reported as Supporting Information.

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Tables

Samples	'y': molar composition of MgO in gel	Mg/u.c.		Organic/u.c.
		Gel	NMR ^b	TGA ^c
Composition 1-165 °C	0.11	0.66	0.92	-
Composition 1-180 °C	0.11	0.66	0.86	1.07
Composition 1-165 °C	0.22	1.33	1.10	1.10
Composition 1-180 °C	0.22	1.33	1.09	1.07
Composition 2-165 °C	0.11	0.66	-	-
Composition 2-180 °C	0.11	0.66	-	-
Composition 2-165 °C	0.22	1.33	-	1.33
Composition 2-180 °C	0.22	1.33	1.36	1.46
Composition 3-165 °C	0.11	0.66	-	-
Composition 3-180 °C	0.11	0.66	1.11	1.10
Composition 3-165 °C	0.22	1.33	-	1.28
Composition 3-180 °C	0.22	1.33	1.38	1.27

Table 1. Mg and organic contents as determined by the different techniques; ^a Mg per unit cell derived from chemical analysis; ^b Mg per unit cell derived from ³¹P MAS-NMR; ^c Organic per unit cell derived from TGA.

System	Molecules	Config.	Total I.E.	I.E. per molec	Dimerization E	N ⁺ ...N ⁺ Distance
All charged	1EPH ⁺	Monomer	-39.6	-39.6	---	---
	4EPH ⁺	Dimer	-145.9	-36.5	+3.1	3.93
Half neutral + Half charged		Dimer-alter	-204.8	-51.2	-6.3	12.56
	2EP ⁰⁺	Dimer-consec	-201.3	-50.3	-5.4	11.03
	2EPH ⁺	Dimer-facing	-150.2	-37.6	7.3	3.87
		Monomer*	---	-44.9	---	---
All neutral	1EP ⁰	Monomer	-50.2	-50.2	---	---
	4EP ⁰	Dimer	-197.8	-49.5	+0.7	---

Table 2. Interaction energies (total I. E. per 1x1x3 AFI system, and normalized per molecule) as a function of the charge-state of the molecules and the configuration, dimerization energy per molecule, and closest N⁺...N⁺ distance (of protonated ammonium groups) (Å). All the energies are given in kcal/mol. *: the interaction energy for the monomer configuration in the system with half neutral+half charged molecules was calculated as the average between ‘all-charged-monomer’ and ‘all-neutral-monomer’ configurations.

Figure 1. Examples of typical TGA of MgAPO-5 (MgAPO-5-3_0.22_180) and of the low-dimensional phase (MgAPO-5-2_0.11_165).

Figure 2. ^{13}C CP-MAS-NMR of the Mg-AFI materials prepared with composition 1 at different crystallization temperatures. ^{13}C CP-MAS-NMR of solid (1R,2S)-ephedrine (EPH) is also shown for comparison purposes.

Figure 3. ^{31}P MAS-NMR spectra of the MgAPO-5 samples obtained with composition 1: (a) MgAPO-5-1_0.11_180; (b) MgAPO-5-1_0.22_180.

Figure 4. UV-Visible Fluorescence spectra of the AFI materials obtained with EPH and composition 1 at 140 °C (top-left), 165 °C (top-right) and 180 °C (bottom-left). Two different bands corresponding to monomer and aggregates are differentiated.

Figure 5. UV-Visible diffuse reflectance spectroscopy of different AFI materials prepared with composition 1 at different temperatures and 0.11 (left) or 0.22 (right) MgO in the gel.

Figure 6. UV-Visible fluorescence spectra of the AFI materials obtained with composition 2 at 165 and 180 °C (left) and with composition 3 at 165 and 180 °C (right).

Figure 7. Different molecular arrangements when half molecules are neutral (displayed in orange) and half protonated (displayed in yellow): alternated $[\text{EPH}^+ \cdots \text{EP}^0] [\text{EPH}^+ \cdots \text{EP}^0]$ (top), consecutive $[\text{EPH}^+ \cdots \text{EPH}^+] [\text{EP}^0 \cdots \text{EP}^0]$ (middle) and facing $[\text{EPH}^+ \cdots \text{EP}^0] [\text{EP}^0 \cdots \text{EPH}^+] [\text{EPH}^+ \cdots \text{EP}^0]$ (bottom); N atoms are displayed as balls.

Figure 8. Evolution of the interaction energy (in kcal/mol per u.c., blue line, left axis) and closest $\text{N}^+ \cdots \text{N}^+$ distance (in Å, red line, right axis) as a function of the packing value.

Figure 9. Illustration of the packing arrangements proposed under a low (top) and high (bottom) Mg content in the gel.