Li/MgO with Spin Sensors as Catalyst for the Oxidative Coupling of Methane

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Abstract

Co-doping of Li/MgO, a well-known catalyst for the oxidative coupling of methane, was investigated. It is demonstrated that Gd3+ and Fe3+ can be used as spin sensors in these solids to investigate the structure via EPR spectroscopy. These aliovalent ions occupy Mg2+ sites in the lattice; the expected coupling with charge-compensating neighboring Li+ was detected. A strong increase of the activity was observed. However, all samples suffered from deactivation. The solubility of Gd3+ in MgO turned out to be inhibited. No such restriction was observed for Fe3+.

Keywords: Oxidative Coupling of Methane, Li/MgO, Transition Metal Oxides, Rare Earth Oxide, Cation Substitution, Spin Sensor, EPR

1. Introduction

The oxidative coupling of methane (OCM) (Equation 1) is an attractive direct route for the conversion of methane into value added compounds. Li/MgO was considered to be a potential candidate for a practical application, despite the doubts on the stability.

\[ \text{CH}_4 + \text{O}_2 \rightarrow \text{C}_2\text{H}_6 \text{ or C}_2\text{H}_4 + \text{H}_2\text{O} \]  (1)

A very detailed investigation has shown, that it suffers from an intrinsic instability [1–3], prohibiting any practical application. Furthermore, Li evaporates from the catalyst and only a content of approximately 0.01 - 0.03 wt% Li in MgO is stable [1, 2, 4].

To improve the catalytic performance of Li/MgO, it was doped with numerous additional metal oxides [5–24]. In many cases an improved stability and/or higher selectivity was found, however, deactivation of these catalysts was often retarded, but still observed.

Moreover, doping did not contribute to an understanding of the catalytic system. In an excellent review article, Gellings and Bouwmeester commented that unfortunately many of the publications, dealing with co-doped Li/MgO, have not interpreted the results in terms of the charge compensating defects and the influence of the dopants thereon [25].

The present study shows how the co-dopants Fe and Gd can be used as spin sensors for the EPR spectroscopy to investigate the structure of such materials. Fe and Gd have been chosen as co-dopants, not because they could result in a better catalytic performance than compared to catalysts reported in the literature, but because these high spin ions can serve as sensitive probes for the local structure. However, the anticipated stabilization of the Li-content by these charge compensating ions (Gd3+, Fe3+) might lead to an improved stability of the catalytic performance.

2. Experimental Part

2.1. Preparation

In a catalyst the content of the different metal oxides is calculated in atom percent (at%) based on the total cation content, shown in Equation 2.

\[ \text{Cation A [at\%]} = \frac{\text{Cation A [mol]}}{\sum \text{all Cations [mol]}} \times 100\% \]  (2)

Aqueous solutions of Mg(NO3)2 were prepared by dissolving Mg(NO3)2 × 6H2O (p.A., Merck) in distilled H2O. The solution of Fe(NO3)3 × 9H2O (p.A., Riedel de Haen) and Gd(NO3)3 × 6H2O (99.9 %, Sigma Aldrich) was prepared the same way. The nitrate solutions were

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concurrently added drop wise to stirred ammonia solu-
tion while keeping the pH value above 11. The gelati-
nous precipitates were rinsed with distilled H₂O and
mixed with aqueous LiOH solution (LiOH × H₂O p.A.,
Riedel de Haen) with appropriate Li concentrations in
a tubular mixer. The prepared combination of oxides
were:
1. MgO
2. Gd/MgO
3. Gd-Li/MgO
4. Fe-Li/MgO

Finally, the solution was quick-frozen using liquid
N₂. Afterwards, it was freeze-dried over at least 72 h us-
ing a freeze-dryer (Gamma 2-20 (Christ)). Finally, the
samples were calcined at 900 °C for 1 h in MgO cru-
cibles. A scheme of the preparation procedure is shown
in Figure 1.

![Scheme of the preparation procedure](image)

Some samples were too fluffy after calcination; there-
fore, they were pressed at 100 bar for 10 minutes and
subsequently crushed. All samples were sieved and only
the fraction ≤ 200 µm was used for testing to exclude in-
ternal mass transfer effects.

2.2. Characterization

The Li-content of the different samples was quanti-
fied via atomic absorption spectroscopy, using a AAS
NovAA 400 G device from Analytik Jena via flame.
The Fe and Gd-content was determined via induc-
tively coupled plasma atomic emission spectroscopy,
using a Horiba Scientific ICP Model Ultima 2.
The specific surface area was determined by a Mi-
cromeritics Gemini III 2375 Surface Area Analyzer, us-
ing N₂ adsorption at -196 °C. Before measuring, the
samples were degassed at 300 °C and 0.15 mbar at least
for 30 minutes. The surface areas were calculated by the
method of Brunauer, Emmett and Teller.

Powder X-Ray diffractograms were obtained (CuKα1
radiation, with a wavelength 0.154 nm) using a Bruker
AXS D8 ADVANCE X-ray diffractometer.

EPR experiments were performed with a BRUKER
E680 spectrometer. The spectrometer was operated in
conventional continuous wave (cw) as well as in pulsed
mode. Data were taken from "as prepared" compounds.

2.3. Catalysis

A 6-fold parallel reactor (Integrated Lab Solutions
Berlin and Premex Reactor AG) was used for the de-
termination of the catalytic activity, with packed-bed,
linear, tubular reactors made of quartz glass. For each
catalytic run, 50 mg catalyst were diluted with approx-
imately 1.5 ml quartz sand (Merck). Below and above
the catalyst bed, a small amount of pure quartz sand was
put to ensure proper heat transfer. The applied reaction
conditions were: 750 °C reactor temperature, 60 ml/min
gas flow and a feed gas composition of CH₄:O₂:N₂ =
4:1:4. The analysis was performed with a gas chro-
matograph Agilent 7890 A. The conversion and selec-
tivity is calculated with a mass balance based on the in-
let and outlet concentration of reactants and products,
see Equations 3 and 4, taking into account the different
numbers of C-atoms in the different molecules. The car-
bon balance was always well above 95 %. The forma-
tion of CO was not observed in any of the experiments,
CO₂ was the only observed total oxidation product and
and no visible formation of deposited carbon was found.

\[
X = \frac{\sum \text{(Reaction Products)}}{\sum \text{(Reaction Products)} + \text{unconverted Reactant}} \tag{3}
\]

\[
S_A = \frac{\text{Product A}}{\sum \text{(Reaction Products)}} \tag{4}
\]

3. Results and Discussion

In Table 1 an overview over the target and the actual
loading of Li and the Gd or Fe-content, the BET surface
area and the present phases, detected via XRD is given.
The intended and the loading of Li, Fe and Gd of the
prepared catalysts agree very well. The ratio TM/Li is
in both cases near 1 and the BET surface area does not
vary too strongly.

XRD patterns of the Gd-Li/MgO sample indicate
the formation of Gd₂O₃ besides the main phase MgO,
shown in Figure 2. Thus, a low solubility of Gd³⁺ in
Table 1: Li, Gd and Fe-content of the different catalysts, the ratio dopant to Li, the specific surface area, determined before reaction, the sample color and the detected phases.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Target-Content</th>
<th>Measured-Content</th>
<th>Atom Ratio</th>
<th>BET [m$^2$/g]</th>
<th>Color</th>
<th>XRD Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>Li [at%]</td>
<td>Dop. [at%]</td>
<td>Li [at%]</td>
<td>Dop. [at%]</td>
<td>-</td>
<td>34.4 white</td>
</tr>
<tr>
<td>Gd/MgO</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>-</td>
<td>37.0 white</td>
</tr>
<tr>
<td>Fe-Li/MgO</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>1.0</td>
<td>29.4 light yellow</td>
</tr>
<tr>
<td>Gd-Li/MgO</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>1.1</td>
<td>16.7 white</td>
</tr>
</tbody>
</table>

MgO can be assumed, which could be caused by the larger ionic radius of Gd$^{3+}$ of 94 pm (coordination number 6) compared to the radius of Mg$^{2+}$ of 72 pm (coordination number 6). No such restrictions were observed for Fe$^{3+}$ (ionic radius: 55 pm for coordination number 6). The Fe-Li/MgO sample showed solely the XRD peaks of the MgO phase indicating an entire incorporation of the Li and Fe ions in MgO. The peak positions of the MgO pattern were marginally affected. An overview of the detected phases is shown in Table 1.

EPR spectra of Gd-Li/MgO samples exhibit the characteristic powder pattern of Gd$^{3+}$ in its $\frac{7}{2}$ spin state. Replacing Mg$^{2+}$ substitutionally, the local site symmetry significantly restricts the number of spin Hamilton parameters as was described by Abraham et al. for a single crystal of MgO [27]. For co-doping, local Gd$^{3+}$ - Li$^+$ clusters are anticipated. Such an arrangement would break the local site symmetry, introducing for instance otherwise forbidden second rank tensor elements. For the Gd-Li/MgO sample, a small but significant deviation from the single crystal parameter set [27] is found, as expected being caused by co-doping with Li. Comparing with Gd/MgO powder samples, an almost identical EPR pattern is observed (see Figure 3). Apparently, the preparation and sintering process used induces

Figure 2: XRD patterns of MgO, Fe-Li/MgO and Gd-Li/MgO (bottom to top).

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Figure 3: EPR spectra of Gd/MgO (blue trace) and Gd-Li/MgO (red trace) taken at 80 K. The narrow spikes can be attributed to trace amounts of Mn$^{2+}$.

Figure 4: EPR spectrum of Fe-Li/MgO taken at 80 K. The dotted line is a least squares fit resulting in $B_{40} = 5$ MHz and $B_{44} = 30$ MHz, quite close to the values of 5.16 MHz and 25.6 MHz, determined by Boldu et al. from single crystals data [26].

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distortions from perfect cubic symmetry, which in turn also lead to the appearance of the observed additional spin Hamilton parameters. Using pulsed EPR instead of conventional cw detection, a true EPR absorption spectrum can be detected instead of a field derivative pattern. Using this detection method, additional broad signals covering a much larger field range from 220 to 480 mT could be recorded exclusively for the co-doped sample, indicative of a significant distortion of the local symmetry. We ascribe this pattern as resulting from the formation of next neighbor correlated pairs. A detailed analysis will be presented in a forthcoming publication.

Cw EPR signals observed for the Fe-Li/MgO powder samples can be fitted by using spin Hamilton parameters very similar to the parameter set reported by Boldu et al. for Fe-doped single crystals of MgO [26], as shown in Figure 4. This indicates that the topology of the Fe site is not significantly disturbed by adjacent Li ions. Because of very fast spin relaxation, no pulsed EPR spectra could be detected. For this reason no effect of co-doping could be detected by EPR for this compound.

The CH₄ conversion, the selectivity for C₂ and CO₂ (CO formation was not observed) for all 3 materials is shown in Figure 5. The catalytic performance of pure MgO is low, however, it does not deactivate significantly.

Co-doping with charge compensating Fe leads to a significantly increased CH₄ conversion, however, total oxidation prevails. Using Gd instead for charge compensation, an initial activity comparable with Fe-Li/MgO at a significantly higher C₂ selectivity, however the XRD results indicate a formation of Gd₂O₃ beside Gd-MgO solid solution. This could be responsible for the higher activity, as Gd₂O₃ exhibits a considerable OCM activity [28]. However, this catalyst also suffers from deactivation. A steady state has not been reached within 16 h.

4. Summary and Conclusion

Co-doping of Li/MgO catalysts with charge compensating ions was performed with a constant atomic ratio of Li to dopant of 1:1. These aliovalent ions turned out to occupy Mg²⁺ sites in the lattice. The solubility of Gd³⁺ in MgO turned out to be limited. No such restrictions were observed for Fe³⁺. The anticipated Li-stabilization by co-doping Li/MgO with Fe³⁺ and Gd³⁺ apparently seems to take place. An indication of the expected coupling with charge compensating neighboring Li⁺ was detected via EPR for the Gd-Li/MgO sample. Therefore, the application potential of dopants as EPR spin sensors for solids has been demonstrated.
The co-doping results in active catalytic materials, however, deactivation is not suppressed. Doping with Fe leads to a significantly increased CH₄ conversion, however, total oxidation is dominating. Gd-Li/MgO showed an improved performance with respect to conversion and selectivity, however, the activity might be due to the formation of Gd₂O₃ on the MgO, as detected via XRD.

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References