Influence of the Mg-content on ESR-Signals in Synthetic Calcium Carbonate

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Carbonate crystals doped with various concentrations of Mg2+-ions have been grown by a gel-diffusion method. An increase of the Mg/Ca-ratio to more than about 1 caused a phase change in the crystal lattice from calcite to aragonite. The properties of the ESR-signals of the synthetic carbonates were studied and compared with natural marine carbonates. The following results were derived:

(a) In the presence of Mg2+-ions the synthetic carbonates display the same ESR-signals as natural calcites of marine origin with similar properties (thermal stability, radiation sensitivity).

(b) The saturation value of the signal at \( g = 2.0006 \) in synthetic calcites was found to be strongly related with the Mg-content in the crystals.

(c) The signal at \( g = 2.0036 \) (axial symmetry) which is present in calcite was not influenced by the Mg-concentration. Its saturation value decreases when the crystal phase changed from calcite to aragonite and in complement the signal at \( g = 2.0031 \) appeared.

(d) The signals at \( g = 2.0057 \) and \( g = 2.0031 \) are most probably not of organic origin.

1. Introduction

Carbonate material that was formed in the ocean water (foraminifera, corals, molluscs) exhibits two narrow ESR-signals at \( g = 2.0057 \) (hi) and \( g = 2.0006 \) (h3) and a sharp line at \( g = 2.0036 \) (foraminifera) or at \( g = 2.0031 \) (corals, molluscs*) (Yokoyama et al., 1983; Radtke and Grün, 1988; Skinner, 1983). Carbonates of continental origin (travertines, speleotherms) often show the signal at \( g = 2.0006 \) too (Grün, 1989; Grün et al., 1988; Smith et al., 1985).

Little is known about the origin of these different signals. Generally, the radiation sensitive centers observed in carbonates are assumed to be anion-centers, i.e. centers derived from the host lattice anion \([\text{CO}_3^{2-}]\) or \([\text{HCO}_3^-]\) and from impurity anions like \([\text{PO}_4^{3-}] \) or \([\text{SO}_4^{2-}]\) (Marfunin, 1979; Cass et al., 1974; Serway and Marshall, 1967; Marshall and Serway, 1969). On the other hand impurity cations like \( \text{Y}^{3+} \) or \( \text{Li}^+ \) were reported to play an important role for stabilization of the different centers (Baquet et al., 1975; Marshall et al., 1968). Other centers which are commonly cited in alkali-halides like interstitials and ion vacancies (Royce, 1967) were not observed in carbonate spectra up to the present.

The relevant signals in the ESR-spectra of natural carbonates are:

- \( g = 2.0057 \) (hi): This line earlier was attributed to a humic acid-clay complex (Grün and De Canniere, 1984). However, in 1985 De Canniere et al. claimed that this is improbable because they observed a similar signal \( (g = 2.0051) \) in synthetic calcite without organic matter.

- \( g = 2.0036 \): This signal was already observed to be the \( g \)-value of a center with \( g = 2.0021 \) (De Canniere et al., 1985; Rossi et al., 1985) and attributed to the \( \text{CO}_3^{2-} \)-center because of its close relation to \( g \)-values of that center observed by Servay and Marshall, (1967).

- \( g = 2.0031 \): This signal—observed in corals and molluscs—was attributed to alanine (in molluscs; Ikeda, 1981).

- \( g = 2.0006 \) (h3): The most important signal for ESR-dating of carbonates could not be related to any known center. It was speculated to be a \( \text{CO}_3^{2-} \)-type center (Grün, 1989) although none of the known centers \( (\text{CO}_2^{2-}, \text{CO}_3^{2-}, \text{CO}_4^{2-}) \) fits this \( g \)-value (Marshall and McMillan, 1968; Servay and Marshall, 1967).

To get a better understanding of this problem the systematic approach is to study synthetic carbonate crystals grown under best controlled conditions. Besides spectra of chemical \( \text{CaCO}_3 \) (Wieser et al., 1985) up to now only De Canniere et al. (1985, 1988) reported different spectra of synthetic carbonates. The main problem of synthetic growth is the purity of the ingredients used, because concentrations of impurities lower than 1 ppm should be detectable.
1. Experimental

2.1. Synthesis of the carbonate crystals

The crystals were grown using a gel-diffusion-method (described in detail by Henisch, 1970) in a glass tube from solutions of 0.2 M CaCl₂ and 0.2 M (NaH)CO₃ separated by a gel made of 0.2 M Na meta-silicate (Fig. 1) at room temperature (pH = 8). The crystals grew at the diffusion front in the gel within 2–4 weeks up to a size of 0.2 mm (maximum about 2 mm). The yield was between 100 and 200 mg carbonate in each tube. The crystals were then washed from the gel with distilled water and dried at 60°C.

We preferred this gel-diffusion-method for crystal formation because it is slower than the precipitation method (described by De Keyser and Degueldre, 1950; Wray and Daniels, 1957) and thus comes a little closer to crystal formation in nature. Additionally it is possible to dope the crystals continuously while growing by adding solutions of impurity ions. One disadvantage of this method is that a small amount of the sodium silicate gel (<1%) may be incorporated in the crystals. Preliminary studies with precipitated crystals yielded ESR-spectra like those from chemical CaCO₃ (see Wieser et al., 1985).

2.2. Doped crystals

Preliminary experiments were carried out with pure solutions of CaCl₂ and NaHCO₃ to which dissolved impurity ions in concentrations of about 1% (Al³⁺, Sr²⁺, Mg²⁺, K⁺; NO₃⁻, SO₄⁻) were added. Some of the spectra are shown in Fig. 2. The main problem in this series were the large ESR-signals of manganese overlapping the other signals except for CaCO₃ crystals that were doped with Mg²⁺ where the signal at $g = 2.0006$ is also more pronounced.

In a second series of experiments we consequently used p.a. or suprapur substances with trace element concentrations <5 to 20 ppm (Mn: 5 ppm). The Mn-lines in the ESR-spectra of these crystals were smaller by about a factor of 10. We doped the solution of CaCl₂ with solutions at 12 different concentrations of MgCl₂, starting from a Mg/Ca ratio of 4 x 10⁻⁴ (100 ppm) to a Mg/Ca ratio of 4.

2.3. AAS and x-ray diffraction

The Mg²⁺-content of the crystals was measured subsequently by atomic absorption spectroscopy (AAS) at a precision of 5%, because of the small sample weights used (10 mg).

The crystal structure was checked with x-ray diffraction in order to determine the content of calcite and/or aragonite in the crystals at least qualitatively.

2.4. Gamma-ray irradiation and ESR-measurements

All crystals were irradiated with a $^{60}$Co source (dose rate about 50 Gy/min) in 5 steps up to 5 kGy (which was expected to be the saturation level). After each irradiation step the samples were heated at...
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Fig. 2. The spectra shown are doped with various impurities in comparison with a spectrum of natural carbonate (foraminifera). They do not display the characteristic carbonate signals (except the signal at g = 2.0036) and are superimposed by large Mn²⁺-hyperfine lines.

Fig. 3. Molecular ratio of Mg/Ca in the crystals as determined by AAS measurements vs the molecular ratio of Mg/Ca in the solution of CaCl₂. For the samples with the highest Mg-concentration aragonite was detected by x-ray diffraction.

The observed behavior for crystals from Mg rich solutions indicates a phase change in the crystal lattice from calcite to aragonite which is expected for high magnesium content in the liquid (Folk, 1974). This was confirmed by x-ray diffraction of the crystals: in the samples plotted with an asterisk the content of aragonite in the crystals exceeds 30% (increasing with Mg-concentration), while the samples grown at lower Mg-concentration consist of almost pure calcite.

3. Results and Discussion

3.1. Transfer of Mg²⁺-ions into the crystals

The results of the AAS measurements are shown in Fig. 3. We used a log-log plot because of the large range of concentrations and of signals. We find a nearly linear relationship for low Mg-concentrations with a transfer factor of about 0.37. Only the first sample (with no Mg added) shows some deviation from this relationship. This offset may originate from a small Mg contamination (in the range of 50 ppm) in the solutions of CaCl₂ and (NaH)CO₃ and in the gel respectively.

For higher Mg-concentrations we find a sub-linear behavior up to a Mg/Ca ratio of 0.5 (transfer factor decreases to about 0.05; see Katz, 1973: 0.06 at 25°C, at similar concentrations). Increase of the Mg concentration in the solution beyond this value does not lead to an increment of the magnesium content in the crystal: it decreases dramatically (by a factor of about 10). This is related with a transfer factor of about 0.0025.

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3.2. Comparison of ESR-spectra with natural carbonates

The spectrum of crystals grown at low Mg-concentration (1000 ppm) and irradiated with 500 Gy is compared with calcitic foraminifera (500 Gy) in Fig. 4(a). Qualitatively, there is a very good correspondence of the three signals at g = 2.0006, g = 2.0036 (unsymmetrical, with a small line at g = 2.0021 belonging to it) and g = 2.0057. Additionally we find a small signal at g = 2.0051 in the synthetic crystals, probably the same that was observed by De Canniere et al. (1985) in synthetic calcite and which is present in chemical CaCO₃. This signal is only present in the crystal with lowest Mg-concentrations.

The concordance between natural and artificial samples is also very good when we compare the
ESR-spectra of irradiated crystals doped with high Mg-concentration (Mg/Ca ratio = 1 in the solution) and spectra of aragonitic coral [Fig. 4(b)]. The only difference is the symmetric signal at g = 2.0031 which was not present previously (and no signal at g = 2.0036).

The signals show the same characteristics relative to microwave-power than natural samples: while the signals at g = 2.0057 and g = 2.0006 are not saturated up to 20 mW, those at g = 2.0036 and g = 2.0031 saturate at low power (about 2 and 10 mW respectively).

This concordance of g-values and microwave dependency suggest that the growing conditions have been of such a kind that paramagnetic centers have been created that are very similar to those in natural material. This concordance was not observed for any of the crystals grown in the absence of Mg$^{2+}$ (Fig. 2). One important point to emphasize is the existence of the signal at g = 2.0057 in artificial samples: although we cannot definitely exclude the presence of any organic material in the synthetic crystals, it seems unlikely that organic matter is the origin of this signal.

*For low Mg-concentrations the signal seems to decrease a little for the last irradiation step.
+The saturation dose $D_s$ is defined as the dose required to reach the saturation level multiplied by $(1 - 1/e)$.

3.3. Characteristics of the signals in synthetic carbonates

(ii) Sensitivity on irradiation. The $\gamma$-ray irradiations were carried out in 4 steps (0.5 1 3.5 kGy). Shortly after irradiation the crystals displayed large signals in the region of g = 2.002. This was attributed to the unstable signal at g = 2.0023 (meanlife: 2 y at 10°C, Hennig and Grün, 1983) which is well known from natural carbonates. This signal was sufficiently reduced after heating for 1 h at 160°C, so that it did not disturb measurements of the signal at g = 2.0006.

All signals (except at g = 2.0057) grow with the absorbed dose and display a noticeable saturation behavior*. The measured signals were then fitted to a saturation function (Barabas et al., 1988) to determine its saturation value and saturation dose (assuming zero signal for non-irradiated samples). For the signal at g = 2.0006 the saturation dose $D_s$ was 1.3 ± 0.25 kGy for all samples except those three with the highest magnesium content. In these samples $D_s$ was about a factor of 2 larger. These values agree well with values in the region of 1.0 kGy observed in foraminifera (own data).

For the signal at g = 2.0036 the observed $D_s$ was 3 ± 1 kGy and thus larger than the values for foraminifera ($D_s = 0.8$ kGy). The signal at g = 2.0031 in comparison saturated very fast: its $D_s$ was distinctly less than 1 kGy. It exhibits a similar saturation behavior in corals (Grün, 1988), whereas in molluscs usually it is not increased by irradiation (Radtke et al., 1985).

The signal at g = 2.0057 displayed a small increase (about 10%) after each irradiation step. This enlarge-
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3.4. Dependency of the signals upon Mg²⁺-concentration

To compare the amount of traps in the samples responsible for a certain signal, we assumed that the number of these traps is constant and that all of them can be filled upon (sufficient) irradiation. From the parameters of the fitted irradiation curve we can thus deduce relative values for the number of traps, i.e. the respective saturation level $S_m$ (Barabas et al., 1988). These values were normalized to the specific density of the sample. The quotient $S_m/D_i$ gives the irradiation sensitivity of a specific signal.

(i) Signals at $g = 2.0036$ and $g = 2.0031$. In Fig. 6 the saturation values $S_m$ of the signals at $g = 2.0036$ and $g = 2.0031$ are plotted together vs the Mg/Ca-ratio of the solution. Our results indicate that the value of the signal at $g = 2.0036$ is virtually uninfluenced by the growing Mg-concentration up to a Mg/Ca ratio of 0.1. Therefore we conclude that the Mg-concentration does not influence the amount of traps responsible for the signal at $g = 2.0036$. At further increasing Mg-concentrations in the solution the signal at $g = 2.0036$ diminishes and disappears totally at a Mg/Ca-ratio of more than 1.

While the signal at $g = 2.0036$ decreases, the signal at $g = 2.0031$ is not present at low Mg concentrations and increases for high Mg-concentrations.

It is most probable that the described behavior of these signals corresponds to an observed phase change of the synthetic crystals from calcite to aragonite. This is also characteristic for natural calcitic samples (foraminifera) where the signal at $g = 2.0036$ is present while natural aragonitic samples (corals) display the signal at $g = 2.0031$.

As reported by Rossi et al. (1986) the signal at $g = 2.0036$ is the $g$-perpendicular of a paramagnetic site with $g$-parallel = 2.0021. We came to similar conclusions for our natural and synthetic samples. The CO₃²⁻-center is most probably responsible for this signal (Servay and Marshall, 1967). Thus we deduce that this center, which displays axial symmetry in calcite, changes to cubic symmetry in aragonite exhibiting a $g$-factor $1/2(2 \times 2.0036^2 + 2.0021^2) ≈ 2.0031$ which agrees with the observed value. This may be due to larger inter-atomic distance in aragonite resulting in less interaction with the crystalline field (Plato and Schneider, 1971; Goldsmith and Graf, 1958). So, one and the same paramagnetic center could be responsible for the signals at $g = 2.0036$ and at $g = 2.0031$.

However, it is not yet clear which anion plays the role of stabilization of the center.

(ii) Signal at $g = 2.0006$. The saturation level of the signal at $g = 2.0006$ displays a quite different behavior with Mg-increase [Fig. 7(a)]. Up to a Mg/Ca ratio of 0.005 the signal seems to be unaffected by the Mg concentration but for higher concentrations it increases on a straight line with a slope between 0.5 (square-root) and 1 (linear). For a Mg/Ca ratio >0.5 it displays a nearly constant value*.

The situation is similar if we look at the saturation values as a function of the Mg-content in the crystals [Fig. 7(b)]. We find a nearly proportional increase of signal and Mg-content, starting at a Mg/Ca-ratio of 0.001 to a ratio of about 0.02 (about 6000 ppm), which is the highest Mg-content observed in the synthetic crystals. At higher Mg-concentration of the solution, the Mg-content of the crystals decreases by about a factor of 10 and the signal height remains constant. The decrease of Mg in the crystals goes along with the observed phase change from calcite to aragonite.

Another important feature of this signal was described in detail by Barabas et al. (1988), the decrease of the saturation value by heating. Preliminary annealing experiments with our synthetic crystals confirm that the traps responsible for the signal at $g = 2.0006$ disappear by heating, i.e. the saturation level $S_m$ decreases with heating time, although the effect could not be quantified up to the present time. The same effect was observed for the saturation...
levels of the signals at $g = 2.0006$ in a deep-sea core (Barabas, 1989). The saturation levels of foraminifera—i.e. trap concentrations—decreased with the edge of the core, resulting in a lifetime of about $10^6$ years (at 2°C; Fig. 6), even though the Mg concentration remains constant.

Although we do not yet know how the Mg$^{2+}$-ions change the properties of the carbonate crystals our results indicate that it is the Mg-content which is responsible for the signal at $g = 2.0006$ observed in synthetic and natural carbonates.

4. Conclusions

We observe in synthetic carbonate crystals doped with Mg$^{2+}$:

(i) ESR-spectra which display signals at the same $g$-factors, and with same properties as in natural carbonates.

(ii) An increase of the signal at $g = 2.0006$ with Mg-concentration in the doping solution.

(iii) Change from the signal at $g = 2.0036$ to $g = 2.0031$ parallel to the phase change from calcite to aragonite.

Additionally the presence of the signals at $g = 2.0057$ and $g = 2.0031$ indicates that it is most probable that none of these signals originates from organic matter.

**Post scriptum**

Latest experiments show that it is indeed the Mg$^{2+}$-presence and not the growing by gel-diffusion which influences the ESR-signal at $g = 2.0006$. Carbonate crystals grown with the precipitation method (according to De Keyser and Degueldre, 1950) display the characteristic ESR-signals in the presence of Mg$^{2+}$-ions as well.

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**References**


