The relation between crystal structure
and the occurrence of quantum-rotor induced polarization

Corinna Dietrich,1 Julia Wissel,1 Oliver Lorenz,1 Arafat Hossain Khan,2 Marko Bertmer,2 Somayeh Khazaei,3 Daniel Sebastiani,3 Jörg Matysik1

1Institut für Analytische Chemie, Universität Leipzig, Linnéstr. 3, 04103 Leipzig, Germany
2Felix-Bloch-Institut für Festkörperphysik, Universität Leipzig, Linnéstr. 5, 04103 Leipzig, Germany
3Institut für Chemie, Martin-Luther-Universität Halle-Wittenberg, Von-Danckelmann-Platz 4, 06120 Halle, Germany

Correspondance: Jörg Matysik (joerg.matysik@uni-leipzig.de)

ABSTRACT
Among hyperpolarization techniques, quantum-rotor induced polarization (QRIP), also known as Haupt effect, is a peculiar one. It is on one hand rather simple to apply by cooling and heating of a sample. On the other hand, only the methyl groups of a few substances seem to allow for the effect, which strongly limits the applicability of QRIP. While it is known, that a high tunnel frequency is required, the structural conditions for the effect to occur are not exhaustively studied yet. Here, we report on our efforts to heuristically recognize structural motifs in molecular crystals able to allow to produce QRIP.
1 INTRODUCTION

NMR spectroscopy is a very versatile analytical method, however, caused by the low Boltzmann ratio, suffers from a lack of sensitivity. Therefore, hyperpolarization methods are presently a “hot” issue (Halse, 2016; Köckenberger and Matsik, 2010; Kovtunov et al., 2018; Wang et al., 2019). Examples of these techniques are dynamic nuclear polarization (Ardenkjaer-Larsen, 2016; Kjeldsen et al., 2018; Lilly Thankamony et al., 2017; Milani et al., 2015; Ni et al., 2013), spin-exchange optical pumping (Hollenbach et al., 2016; Meersmann and Brunner, 2015; Norquay et al., 2018; Walker, 2011), photochemically induced dynamic nuclear polarization (Bode et al., 2012; Kiryutin et al., 2012; Sosnovsky et al., 2019) and para-hydrogen induced polarization (Duckett and Mewis, 2012; Korchak et al., 2009). Another technique is quantum-rotor induced polarization (QRIP) (Dumez et al., 2017; Horsewill, 1999; Icker et al., 2013; Icker and Berger, 2012; Meier, 2018). It was first observed by Haupt in γ-picoline (1, Figure 1) during rapid temperature jumps at very low temperatures (Haupt, 1972, 1973).

It is also possible to access the signal enhancement in liquid state, by freezing 1 at helium temperature and then rapidly dissolving it in deuterated solvents at room temperature and measuring it immediately (Icker and Berger, 2012). With a custom-made setup, we were able to improve the safety and speed of the dissolution and transfer process, resulting in a higher signal enhancement factor of 530 (Dietrich et al., 2019). An example of a QRIP enhanced spectrum is given in Figure 2. The enhancement is limited to the signal of the methyl carbon and exhibits a before unexpected antiphase pattern (Icker and Berger, 2012).

One might expect that more methyl bearing compounds allow for QRIP, which would broaden the applicability of the effect. However, work of Icker and Berger (Icker et al., 2013) indicated that only a few substances with methyl groups can be hyperpolarized in this way and all of the positively tested compounds show a weaker hyperpolarization compared to 1. It is also noted, that QRIP is not limited to methyl groups and might occur in some other molecular rotors. While none of the other systems in (Icker et al., 2013) showed signal enhancement, weak QRIP effects have been observed in the $^{17}$O water-endofullerene complex (Meier et al., 2018). In the present study we focus solely on the structural requirements for the occurrence of QRIP in methyl groups.

Figure 1: γ-picoline (1).
For a deeper understanding of these requirements, we discuss the underlying mechanisms of the effect. Thermodynamically, Q RIP has been interpreted in terms of a resonant contact between a tunnelling reservoir and a Zeeman reservoir (Horsewill, 1999) at low temperatures. The nuclear spin-order is produced via coupling of spin-states to rotational quantum states of the methyl group. At the temperature of liquid helium only the lowest rotational state is occupied. Upon a dramatic temperature jump to room temperature, a measurable non-Boltzmann distribution of nuclear spin states is gained via cross-relaxation effects. These relaxations also explain the antiphase pattern and are further described in (Meier et al., 2013).

For Q RIP the tunnel splitting plays an important role. It is defined as the energy gap between the rotational ground state and the first excited state. The height of this difference determines the (low-temperature) population ratio via the Boltzmann factor and thus the overall amplitude of the imposed spin symmetry constraint. Thus, it can be expected that high tunnel frequencies are strongly favorable for observing Q RIP effects. In fact, 1 has an exceptionally high tunnel frequency of 520 µeV (~ 4 cm⁻¹) (Prager and Heidemann, 1997). The tunnel frequency is also linked to the capability of the methyl group to rotate freely (Barlow et al., 1992). Therefore, structural motifs with free methyl groups are especially interesting. In the case of 1, the crystal structure shows a rather special feature. Each methyl group is paired with another one and the pairs are all aligned perfectly in a face-to-face manner. Around both methyl pairs, the chemical environment creates rotational potential energy barriers (often with a C₃ or C₆ symmetry). There is a strong coupling of both these methyl groups (due to their spatial proximity) with a 2π/6 phase difference, which means that the superposition of the two rotational potential energy functions becomes surprisingly flat (i.e. the hills of the first rotational potential just fit to the valleys of the second potential function). This in turn leads to the possibility for joint rotation of the methyl groups at very low rotational barrier, virtually a free rotation, eventually resulting in a very high tunnel splitting (Khazaei and Sebastiani, 2017).

In the present work, we therefore search for substances which have one or several of these features: methyl groups with low steric hindrance, methyl groups in a similar distance to each other and face-to-face arrangement as in 1, and methyl groups with concerted rotations.

Figure 2: a) Q RIP enhanced ¹³C spectrum of γ-picoline (1) measured without proton decoupling, recorded with one scan after the cooling and dissolution procedure. Acetone-d₆ was used as solvent. b) Reference spectrum recorded after full relaxation with 100 scans. The signals of acetone-d₆ (labelled with asterix, *) and TMS (‡) are strongly visible in the reference spectrum.
MATERIALS AND METHODS

2.1 Liquid-state NMR

Experiments were carried out on a Bruker Fourier-300 and a Bruker DRX-400 spectrometer. For the QRIP studies, samples were cooled for 90 min in liquid helium and subsequently mixed with deuterated solvents at room temperature. The mixture was transferred to the magnet and measured immediately. This procedure was carried out manually or with the self-built transfer system where the mixing and the transfer of the solution into the magnet is carried out in one step during 35 s (Dietrich et al., 2019). If suitable, the transfer system has been preferred, due to faster sample transfer into the magnet. In cases of insufficient solubility, solely the manual procedure has been found to be applicable. To validate structures and determine the signal enhancement factor, reference spectra were measured after full relaxation of the enhancement. Therefore, multiple scans were recorded, whereas QRIP enhanced spectra have been obtained with a single scan.

2.2 Solid-state NMR

For the solid-state experiments under magic-angle-spinning (MAS), a Bruker Avance III spectrometer (400 MHz 'H frequency) was used. In order to test for QRIP enhancement, the powder sample was packed into a 4-mm zirconia rotor, closed with a zirconia cap and cooled for 90 min in liquid helium (4.2 K). After cooling, the rotor was transferred manually into the magnet and spectra were recorded at room temperature. For the measurement under vacuum, the powder sample was filled into a glass tube (3 mm outer diameter) and evacuated over 2 days. Afterwards, the glass tube was sealed and fitted into the 4-mm zirconia rotor with polytetrafluoroethylene stoppers (Khan et al., 2018). The rotor was closed with a zirconia cap and used as before. In every case, non-decoupled Hahn echo pulse sequences were used and the spinning frequency was set to 8 kHz. Again, reference spectra with multiple scans were recorded afterwards.

2.3 Signal enhancement factor

To compare QRIP enhanced spectra with one scan to reference spectra with multiple scans, the enhancement factor \( \varepsilon \) has been calculated by using equation 1. \( (S/N)_{Q RIP} \) is the signal to noise ratio of the QRIP-enhanced signal and \( (S/N)_{ref} \) is the signal to noise ratio of the reference spectrum with multiple scans. The number of scans is given as \( n_{ref} \) (Dietrich et al., 2019). S/N ratios were obtained from the Topspin 3.1 software.

\[
\varepsilon = \sqrt{n_{ref}} \cdot \frac{(S/N)_{Q RIP}}{(S/N)_{ref}} \tag{1}
\]

2.4 Inelastic neutron scattering

Inelastic neutron scattering (INS) measurements were carried out at the TOF-TOF instrument at the Forschungs-Neutronenquelle Heinz Maier-Leibnitz (Garching, Technical University of Munich) (Lohstroh and Evenson, 2015).

2.5 X-ray diffraction

For the powder X-ray diffraction (PXRD) patterns, the samples were placed in 0.5 mm Ø capillaries and measured using a STOE STADI P diffractometer (Cu Kα radiation; equipped with a MYTHEN (DECTRIS) detector). Measurements were carried out at the Institute of Inorganic Chemistry, University of Leipzig.

2.6 Synthesis

\( \gamma \)-Picoline hydrochloride (2) was commercially available (Carbosynth Limited), while \( \gamma \)-picoline nitrate (3) and \( \gamma \)-picoline hydrosulfate (4) were synthesized according to instructions from (Wang et al., 2015) and (Ullah et al., 2015).
3 EXPERIMENTAL RESULTS AND DISCUSSION

In order to find clues for the structural requirements for the allowance or restriction of QRIP a variety of compounds is investigated and the enhancement factor ε obtained (Table 1).

Table 1: Overview of all substances which were experimentally or theoretically (crystal structure analysis) examined in this study.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>substance</th>
<th>QRIP ε</th>
<th>Nr.</th>
<th>substance</th>
<th>QRIP ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>γ-picoline</td>
<td>60</td>
<td>18</td>
<td>sodium acetate</td>
<td>low</td>
</tr>
<tr>
<td>2</td>
<td>γ-picoline hydrochloride</td>
<td>-</td>
<td>19</td>
<td>acetonitrile</td>
<td>low</td>
</tr>
<tr>
<td>3</td>
<td>γ-picoline nitrate</td>
<td>-</td>
<td>20</td>
<td>acetone</td>
<td>low</td>
</tr>
<tr>
<td>4</td>
<td>γ-picoline hydrosulfate</td>
<td>-</td>
<td>21</td>
<td>α-picoline</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>toluene</td>
<td>3</td>
<td>22</td>
<td>p-xylene</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>lithium acetate dihydrate</td>
<td>20</td>
<td>23</td>
<td>p-cresol</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>N-(p-tolyl)acetamide</td>
<td>-</td>
<td>24</td>
<td>m-cresol</td>
<td>low</td>
</tr>
<tr>
<td>8</td>
<td>2,5-dimethyl-1,3-dinitrobenzene</td>
<td>-</td>
<td>25</td>
<td>1,3-dibromo-2,4,6-trimethylbenzene</td>
<td>28</td>
</tr>
<tr>
<td>9</td>
<td>N-(tert-butyl)acetamide</td>
<td>-</td>
<td>26</td>
<td>2-methoxynaphthalene</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>Ethyl carbamate</td>
<td>-</td>
<td>27</td>
<td>2,6-di-t-butylnaphthalene</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>2-nitropropane</td>
<td>-</td>
<td>28</td>
<td>cholesterol</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>N’-(3,4-difluorobenzyldiene)-4-methylbenzenesulfonohydrazide</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>toluene@calix[4]arene</td>
<td>n.a.</td>
<td>-</td>
<td>ZIF-67</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>toluene@4-t-butylcalix[4]arene</td>
<td>n.a.</td>
<td>-</td>
<td>ZIF-67</td>
<td>-</td>
</tr>
</tbody>
</table>

3.1 Chemical analogues of γ-picoline

To gain a better understanding of the conditions for the occurrence of the effect, this heuristic study aims at finding connections between the various structural properties of a substance and the observed signal enhancement by QRIP. First, molecules that are similar to 1 in their molecular structure were searched and as a result very close analogues, three different salts of 1, were found (Figure 3).

All salts are solids at room temperature and are soluble in H2O. Hence, D2O was used as solvent for the liquid-state NMR experiments. For the QRIP experiments, the manual transfer was chosen, since the high viscosity of D2O hinders the liquid flow in the transfer system and results in air bubbles in the NMR tube inside the magnet which will lead to a disturbed signal. From each salt, 50 µmol were cooled for 90 min at 4.2 K, quickly dissolved in D2O, the solution (inside the NMR tube) was shortly held in an ultrasonic bath to remove air bubbles and then transferred and measured. Even though the chemical structure and especially the chemical environment of the methyl group seem similar to 1, no QRIP enhancement was observed for any of the three salts 2 to 4 in the 13C NMR spectra. The 13C NMR reference spectra are similar to the one of 1, with slight chemical shift changes (see Table 2).
Table 2: $^{13}$C NMR reference spectra of \( \gamma \)-picoline and its derivatives recorded on a Bruker Fourier-300 spectrometer. D$_2$O was used as solvent. The chemical shifts are given in ppm.

<table>
<thead>
<tr>
<th>substance</th>
<th>C—CH$_3$</th>
<th>N—CH—CH</th>
<th>CH—CH—C$_3$</th>
<th>CH$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma )-picoline (1)</td>
<td>152.5</td>
<td>150.9</td>
<td>128.0</td>
<td>23.0</td>
</tr>
<tr>
<td>( \gamma )-picoline hydrochloride (2)</td>
<td>161.7</td>
<td>140.0</td>
<td>127.9</td>
<td>21.9</td>
</tr>
<tr>
<td>( \gamma )-picoline nitrate (3)</td>
<td>164.4</td>
<td>142.8</td>
<td>130.6</td>
<td>24.5</td>
</tr>
<tr>
<td>( \gamma )-picoline hydrosulfate (4)</td>
<td>164.5</td>
<td>142.8</td>
<td>130.7</td>
<td>24.5</td>
</tr>
</tbody>
</table>

Remarkably, also other chemical analogues, like the \( \alpha \)-form and the \( \beta \)-form of picoline, show no signal enhancement as was shown already before in the work of M. Icker et al. (Icker et al., 2013). They also have studied toluene (5), which is in its chemical structure very similar to 1 and shows little QRIP enhancement. Hence, we conclude that not the molecular structure is decisive for successful induction of QRIP and that already small modifications of the molecular structure can decide upon either QRIP induction or quenching.

Searching for other parameters controlling the occurrence of QRIP, we recognize that lithium acetate dihydrate (6), which is no picoline analogue, shows moderate QRIP enhancement (weaker than 1, stronger than 5).

Comparing the crystal structures, we found that both 1 and 6 exhibit pairs of methyl groups facing each other in a 180° angle (Figure 4 a and c), crystal structures from (Galigné et al., 1970; Ohms et al., 1985), while the methyl groups in 5 have no such symmetry (Figure 4 b), crystal structure from (van der Putten et al., 1992). This might explain the different tunnel frequencies, which directly affect QRIP (see Table 3) (Icker et al., 2013; Meier et al., 2013). Since there is hardly “empty” space in condensed phase, in most crystal structures methyl groups cannot rotate freely. Only the direct compensation of two rotational barriers of two methyl groups which show a 180° face-to-face arrangement allows for almost "frictionless" rotations of the coupled methyls ("concerted" rotations, (Khazaei and Sebastiani, 2017)). Therefore, such a spatial arrangement in the crystal might provide a rare but well-defined structural feature allowing for induction of QRIP.
Table 3: Comparison of structural properties and QRIP: methyl-methyl- (Me-Me-) distances were measured carbon to carbon, angles between methyl groups were measured along the path from quaternary carbon via methyl carbon to the methyl carbon of the neighbor molecule (received from crystal structure data (Faber et al., 1999; Galigné et al., 1970; Ohms et al., 1985; van der Putten et al., 1992)); tunnel frequencies from (Prager and Heidemann, 1997) and QRIP signal enhancement factor $\varepsilon$ from (Icker et al., 2013). Additionally to the name of the substance, the crystal structure code is given in parentheses.

<table>
<thead>
<tr>
<th>substance (structure code)</th>
<th>Me-Me-distance [Å]</th>
<th>Me-Me-angle</th>
<th>tunnel frequency [µeV (cm$^{-1}$)]</th>
<th>QRIP $\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-picoline (1, ZZZIVG)</td>
<td>3.44</td>
<td>177°-180°</td>
<td>520 (~ 4)</td>
<td>60</td>
</tr>
<tr>
<td>$\gamma$-picoline hydrochloride (2, DICCEX)</td>
<td>6.31</td>
<td>99°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>toluene (5, TOLUEN)</td>
<td>4.02/4.14</td>
<td>94°-165°</td>
<td>28.5/26.0 (~ 0.2)</td>
<td>3</td>
</tr>
<tr>
<td>lithium acetate dihydrate (6, LIACET)</td>
<td>3.22</td>
<td>180°</td>
<td>250 (~ 2)</td>
<td>20</td>
</tr>
</tbody>
</table>

The present work aims for further corroborating the experimental evidence of this correlation. Hence, our next step has been the systematic search for substances, which have structural properties similar to $\gamma$-picoline (1) in regards to the methyl-methyl distance and the face-to-face arrangement of the methyl groups. To this end, we searched for compounds of matching crystal structures.

3.2 Systematic crystal structure search

To find promising candidates for QRIP signal enhancement, the Cambridge Crystallography Database was searched for substances with similar distances and angles between methyl groups compared to those values given in Table 3. Other desired properties were relatively small molecular size (to have a high methyl concentration and better chances to observe signal) and commercial availability. All six selected substances are listed in Table 4.

Table 4: investigated compounds 7-12 from the systematic crystal structure search. Methyl-methyl- (Me-Me-) distances were measured carbon to carbon, angles between methyl groups were measured along the path from quaternary carbon via methyl carbon to the methyl carbon of the neighbor molecule. The crystal structure data was obtained from the Cambridge Crystallography Database. Additionally to the name of the substance, the crystal structure CODE is given in parentheses.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$-(p-tolyl)acetamide (7, ACTOLD)</td>
<td></td>
<td>3.61</td>
<td>153°/170°</td>
</tr>
<tr>
<td>2,5-dimethyl-1,3-dinitrobenzene (8, AYOYAP)</td>
<td></td>
<td>3.55</td>
<td>168°</td>
</tr>
<tr>
<td>$N$-(tert-butyl)acetamide (9, APUYIU)</td>
<td></td>
<td>3.58</td>
<td>161°</td>
</tr>
</tbody>
</table>
Although distances and angles between methyl groups of those compounds are in the range between compounds 1 and 5, none of these compounds show a perfect face-to-face alignment of the methyl groups, and no QRIP enhancement was observed for any of them. The most probable reason is the occurrence of steric hindrance around the methyl groups in the crystal packing. This might affect the free rotation of the methyl groups, and, thus lead to lower tunnel frequencies inhibiting QRIP. Despite similar angles and distances of methyl groups, the impact of steric effects of the whole structure is difficult to estimate. To validate this correlation, theoretical calculations as in (Khazaei and Sebastiani, 2016, 2017) and experimental measurements of tunnelling frequencies are desirable. Another limitation can be a low concentration of methyl groups. In case of low QRIP (as exhibited in 5), higher amounts of the sample were necessary to observe a QRIP enhanced signal, i.e. 150 µmol for a good signal, whereas for 1 50 µmol are sufficient to observe an intense QRIP enhanced signal. For compounds 7 to 11, depending on the solubility between 50 and 100 µmol substance were used and in the case of 12 only 30 µmol was suitable.

Compounds 8 and 12 were further investigated, since they were the 2 most promising candidates of this series regarding the methyl methyl alignment. Interestingly, their methyl groups are in almost perfect face-to-face alignment (see Figure 5 (Johnston and Crather, 2011) and Figure 6 (Wang and Yan, 2015)). On the other
hand, they differ in the alignment of the attached phenyl rings compared to 1. While the phenyl rings of two molecules lie in the same plane for 8 and 12, they are tilted 90° to each other in case of compound 1 (Figure 4 a)). Whether this structural difference has an impact on QRIP requires further theoretical investigations. Since two dissolution experiments for 12 (30 µmol) and three dissolution experiments for 8 (30-50 µmol) showed no QRIP, we tried to figure out the reason for this result. To rule out that the obtained substances are amorphous or possess another crystal structure as compared to the literature, we performed X-ray diffraction (XRD) and confirmed the correct crystal structure of compounds 8 and 12.

Furthermore, the tunnel frequency has been investigated by inelastic neutron scattering (INS). A multi-peak fit allowed to determine the first two transitions for each compound. For compound 8 we determined values of 40±10 µeV and 150±10 µeV (0.3 cm⁻¹ and 1.2 cm⁻¹). For compound 12 we found 50±10 µeV and 160±10 µeV (0.4 cm⁻¹ and 1.3 cm⁻¹). These values lie in the range between the tunnel frequencies of 5 and 6 (26/28 µeV and 250 µeV), which both exhibit QRIP enhancement, but to a lower extent than 1. Therefore, in regards to the tunnel frequencies, QRIP in compounds 8 and 12 is conceivable but very likely to exhibit only a weak enhancement.

It is noteworthy, that in 8 each molecule possesses 2 methyl groups, thus the methyl concentration is higher compared to tests on 1 and is not expected to be the limitation (30-50 µmol of 8 equals 60-100 µmol methyl groups). On the other hand, steric hindrance due to the NO₂ groups in close proximity to the methyl group might limit QRIP. In the case of 12, there is no such hindrance through intramolecular factors, however, intermolecular hindrance is conceivable and the low concentration (30 µmol) is a probable limitation. Additionally, the size of the molecule can result in a faster decay of QRIP due to longer correlation times.

### 3.3 Aspirin

Next to the crystallographic databank approach, we searched for compounds having a particularly low frequency mode of the methyl group. In its crystal structure, aspirin (acetylsalicylic acid, 13) has a particularly low frequency mode near 30 cm⁻¹ (3.7 meV), attributed to the concerted motions of methyl groups (Reilly and Tkatchenko, 2014). Compound 13 became an object of interest, since it exhibits some similarity to the compound 1, in which the collective coupled motions of methyl groups are contributing to QRIP and the calculated methyl rotational barrier height of 1 is about 3.57 meV (Khazaei and Sebastiani, 2016). Analysing the crystal structure of 13, we found no face-to-face methyl pairs (ACSALA (Arputharaj et al., 2012)). The closest methyl pairs are in a distance of 4.43 Å to each other and the angles between them are 100°/147°. Multiple dissolution experiments showed no QRIP enhancement. According to (Prager and Heidemann, 1997), the tunnel frequency of 13 is 1.22 µeV (0.01 cm⁻¹), which is much lower than the tunnel frequencies of 1 and 2 (see Table 3). In fact, the mere coupling between two methyl groups (be it via a face-to-face arrangement or via lateral coupling similar to a cogwheel couple) is not sufficient for allowing a free rotation (leading to high tunnel splittings). A mandatory additional condition is that the rotational barriers created by the crystal surroundings have just the correct offset to each other. Assuming the common C₃v symmetries for the rotational barriers, this means that the maximum of the rotational potential for one of the methyl groups has to coincide exactly with the minimum of the rotational potential of the other one. This additional condition seems to be not fulfilled for aspirin, leading to the absence of QRIP enhancement.
1 **3.4 Calixaren complexes**

Furthermore, we considered two types of compounds following our "chemical intuition": calixarene compounds and metal-organic frameworks. Calixarenes can occur in a cone shape and are therefore able to host smaller molecules like toluene (Gutsche et al., 1981). Because of the highly symmetric structure inside the calixarene cone, we suspected a favourable situation for the methyl group of the guest toluene molecule to rotate freely. Thus, there might be a possibility to observe QRIP enhancement in this complex. Hence, we tested two calixarenes as hosts: calix[4]arene (14) and 4-t-butylcalix[4]arene (15) (see Figure 7).

![Figure 7: Structures of calix[4]arene (14) and 4-t-butylcalix[4]arene (15).](image)

Complexes toluene@calix[4]arene (16) and toluene@4-t-butylcalix[4]arene (17) were synthesized by mixing a surplus of toluene with each calixarene at room temperature and letting the excess liquid dry (Andreetti et al., 1979).

In both cases, we did not succeed to obtain a sufficiently high concentration in solution in order to perform QRIP experiments. This is due to the weak solubility of the calixarene complexes in CDCl$_3$, acetone-d$_6$ and toluene-d$_8$, often resulting in opaque solutions or white suspensions with precipitate even for low concentrations. For compound 16 the solubility is higher than for 17. In the best case, we achieved an almost clear solution of 20 mg of 16 in CDCl$_3$. Due to the higher mass of the complex in comparison to 1, the resulting concentration is below what we expect to be observable by means of QRIP with the current setup. In future studies, calixarene complexes might be studied by solid-state NMR, avoiding the solubility issue. Furthermore, complexes with rather soluble calixarenes (Rehm et al., 2009) might provide an opportunity.

**3.5 Metal Organic Frameworks (MOFs)**

Compared to molecular crystals, MOFs provide an alternative approach to observe freely rotating methyl groups. Methyl groups with low steric hinderance are, for example, expected in MOFs such as ZIF-8 and ZIF-67 (zeolitic imidazole framework, see Figure 8). The difference in these two compounds lies in the different metal centre atoms: Zn(II) in ZIF-8 and Co(II) in ZIF-67. Due to the specific structure allowing for pore formation, the methyl groups are pointing toward the center of these pores and thus can rotate freely, which has been shown at cryogenic temperatures (Li et al., 2018; Zhou et al., 2008).

![Figure 8: Structure of probed MOFs: ZIF-8 and ZIF-67.](image)
Due to the low solubility and in order to avoid hindrance of free rotating methyl groups by solvent molecules inside the pores, the measurements were carried out in solid-state NMR. To ensure that carbon signal of both samples can be observed in general, reference spectra were recorded before and after the QRIP experiments. The assignments of the signals are given in Table 5.

<table>
<thead>
<tr>
<th>substance</th>
<th>assignment</th>
<th>N→C(CH₃)≡N</th>
<th>N→CH=CH≡N</th>
<th>CH₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZIF-8</td>
<td>143.4</td>
<td>128-110</td>
<td>17-7</td>
<td></td>
</tr>
<tr>
<td>ZIF-67</td>
<td>143.3</td>
<td>130-110</td>
<td>17-7</td>
<td></td>
</tr>
</tbody>
</table>

In both cases, ¹³C QRIP experiments were performed under MAS-conditions. The resulting spectra showed no signal enhancement. A possible explanation for the absence of QRIP can be the adsorption of air molecules inside the pores of the ZIFs (Fairen-Jimenez et al., 2011), which might hinder the free rotation of the methyl groups. To exclude this, subsequent measurements under vacuum were performed. Also in this case, both ZIF samples did not show QRIP.

It is noteworthy, that Co(II) is paramagnetic and hence, signal broadening and otherwise unexpected chemical shifts (Bertini et al., 2005; Gueron, 1975; Vega and Fiat, 1976) were expected. However, the obtained reference spectrum of ZIF-67 shows no significant difference in the chemical shift in comparison to the Zn(II) analog. The signals are slightly broadened. Furthermore, an especially narrow line (20 Hz for ZIF-8, and 74 Hz for ZIF-67) at the far left of the spectrum is observed. The ¹³C MAS NMR spectra were recorded without proton-decoupling since decoupling is expected to interfere with the QRIP effect. Therefore, CH and CH₃ signals of the ZIFs are broad, while the quaternary carbon is less affected. For the latter the closest proton is the one from the methyl group with a distance between the quaternary carbon and the methyl proton of 2.14 Å for ZIF-8 and 2.06 Å for ZIF-67. From this distance we calculated a CH-dipole-dipole coupling of 3083 Hz (ZIF-8), 3456 Hz (ZIF-67), which is averaged out at the chosen spinning speed of 8 kHz. With this and the high structural symmetry, resulting in a low chemical shift anisotropy, the narrow line can be explained.

For both ZIFs reference spectra with reasonable signal intensity were recorded after 1.000 scans for the regular packing method and 10.000 scans for the advanced packing method with glass tubes. Following equation 1 the signal enhancement factor ε should be at least 32 (regular packing, or 100 for advanced packing) in order to observe signal with one scan. Smaller signal enhancement via QRIP is conceivable but could not be observed with the current setup. An intrinsic limitation to QRIP might be the proximity between the methyl groups inside the pores (ZIF-8: 5.0 Å, crystal structure data from (Morris et al., 2012); ZIF-76: 4.6 Å (Kwon et al., 2015); measured from carbon to carbon). This might also lead to the absence of signal. Considering the broad variety of MOFs, it is conceivable, that some of them bear methyl groups, which rotate more freely or undergo concerted rotations, which are accessible for QRIP (Gangu et al., 2016; Gonzalez-Nelson et al., 2019; Kuc et al., 2007; Tarasi et al., 2020; Tian et al., 2007).

### 3.6 Analysis of previous data

Aiming for heuristic data on the relation between structure and the hyperpolarization obtained by QRIP, we revisited the crystal structures of compounds studied in (Icker et al., 2013) and (Icker, 2013). From all substances which were available in the Cambridge Crystallography Database, angles and distances between methyl pairs were extracted. Here, we searched specifically for methyl pairs with a similar distance as found in 1 (3.44 Å) and excluded all methyl pairs with a distance > 4.4 Å. The results are given in Table 6. If available, the tunnel frequencies (Prager and Heidemann, 1997) were included to Table 6 as well. Interestingly, many methyl pairs with a distance in the range 3.45-4.37 Å were found, which is quite similar to 1 and makes methyl coupling conceivable. On the other hand, no other face-to-face methyl groups were found. Angles close to 180° do not seem to be a sufficient argument to predict QRIP enhancement, as the comparison of two of the compounds shows: while 24 exhibits an 174° angle at a methyl-methyl distance of 4.06 Å it yields only a week
polarization. Furthermore, a rather strong QRIP effect is observed in 25 where the most promising methyl pair has similar distance (3.78 Å), however, at the same time, it is less aligned with angles of 142°/158°. The surprisingly high polarization in 25 is still below 1 but larger than in 6 which is particularly curious since both 1 and 6 exhibit face-to-face methyl groups, while 25 does not. Although the structure of 25 does not fit our assumptions to gain QRIP, the tunnel frequency is surprisingly high, which fits the presence of QRIP. It is possible, that the occurrence of multiple methyl groups in one molecule and multiple methyl pairs in the crystal structure are favourable for the likelihood of concerted rotations. However, those structural factors alone are also not sufficient for the prediction of QRIP, as other not or less polarizable substances like 7-9 (multiple methyl groups) contradict a general trend.

Table 6: List of compounds tested for QRIP in (Icker et al., 2013) and (Icker, 2013). Methyl methyl distances and angles between methyl groups were measured from the crystal structure data. Tunnel frequencies were taken from (Prager and Heidemann, 1997). Additionally to the name of the substance, the crystal structure CODE is given in parentheses.

<table>
<thead>
<tr>
<th>substance (structure code)</th>
<th>Me-Me-distance [Å]</th>
<th>Me-Me-angle</th>
<th>tunnel frequency [µeV (cm⁻¹)]</th>
<th>QRIP ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>sodium acetate (18, BOPKOG)</td>
<td>4.24</td>
<td>123°/142°</td>
<td>1.5 (~ 0.01)</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>3.45</td>
<td>90°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>acetonitrile (19, QQQCIV)</td>
<td>3.95</td>
<td>139°</td>
<td>-</td>
<td>low</td>
</tr>
<tr>
<td>acetone (20, HIXHIF)</td>
<td>3.76</td>
<td>133°/176°</td>
<td>0.4 (~ 0.003)</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>3.91</td>
<td>132°/158°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>α-picoline (21, ZZZHKQ)</td>
<td>4.09</td>
<td>63°/152°</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>p-xylene (22, ZZZITY)</td>
<td>3.71</td>
<td>90°/160°</td>
<td>0.97 (~ 0.008)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4.14</td>
<td>99°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>p-cresol (23, CRESOL)</td>
<td>4.01</td>
<td>95°/113°</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3.99</td>
<td>79°/176°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>m-cresol (24, MCRSOL)</td>
<td>4.06</td>
<td>174°</td>
<td>-</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>3.89</td>
<td>83°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3.94</td>
<td>83°/114°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1,3-dibromo-2,4,6-trime-thylbenzene (25, EJEROA)</td>
<td>3.77</td>
<td>134°</td>
<td>390 (~ 3.1)</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>3.78</td>
<td>142°/158°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.08</td>
<td>129°/156°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3.74</td>
<td>80°/83°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.03</td>
<td>99°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2-methoxynaphthalene (26, SAYRIT)</td>
<td>3.60</td>
<td>66°/172°</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4.05</td>
<td>73°/107°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.21</td>
<td>125°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2,6-di-t-butylnaphthalene (27, KOKQUW)</td>
<td>3.75</td>
<td>155°/161°</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3.95</td>
<td>109°/124°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.28</td>
<td>106°/136°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>cholesterol (28, CHOEST)</td>
<td>4.37</td>
<td>98°/138°</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4.31</td>
<td>91°/148°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.31</td>
<td>89°/115°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3.56</td>
<td>84°/108°</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

The aim of this study was to gain further understanding of the structural requirements of methyl bearing substances allowing for QRIP signal enhancement in NMR spectroscopy. Starting from the well-studied compound 1 we found that its derivatives (2-4) do not exhibit QRIP. This indicates that structural similarity on a molecular
level is insufficient for QRIP prediction. The weak polarization in 5 and absence of QRIP in \(\alpha\)-picoline and \(\beta\)-picoline (Icker et al., 2013) support this lack of correlation.

To better understand the specialty of 1, we studied the crystal structure and recognized a rare structural feature: in its crystal structure pairs of methyl groups are aligned in a perfect 180° face-to-face manner. For the underlying tunnel effects freely rotating methyl groups and high tunnel frequencies are favorable. Via concerted rotations the face-to-face methyl groups in 1 can rotate exceptionally frictionless, like interacting gear wheels (Khazaei and Sebastiani, 2017; Meier et al., 2013).

In order to investigate the predictability and applicability of QRIP, we therefore searched for substances which show one or multiple of the aforementioned qualities: free rotation, promising alignment, high tunnel frequency of the methyl group, or concerted rotations of methyl groups. Thus, different approaches were tested.

First, we searched for compounds with similar methyl-methyl distances and angles as in 1 and found substances 7-12. While all of them exhibit similar distances between methyl groups, they have no face-to-face arrangement of methyl groups and showed no QRIP enhancement. We conclude that either steric hindrance or missing positive interference of the methyl group is quenching the effect due to the less favorable arrangement.

Next, aspirin (13) was tested since it is described to have concerted motions of methyl groups. However, no QRIP enhancement was observed. We conclude that concerted rotations alone are insufficient. An additional condition is that the rotational barriers created by the crystal surroundings have just the correct offset to each other. This means that the maximum of the rotational potential for one of the methyl groups has to coincide exactly with the minimum of the rotational potential of the other one.

We further suspect freely rotating methyl groups in complexes of toluene in calixarene cones and in MOFs. While the free rotation in calixarene complexes derives from a very symmetric surrounding of the methyl group the MOFs show methyl groups in a relatively empty space. To this end, we did not succeed to perform QRIP measurements on calixarene complexes, due to its low solubility. In MOFs we did not observe QRIP enhancement.

Finally, we revisited previously studied compounds from (Icker et al., 2013) and compared QRIP enhancement to methyl-methyl distances and angles. In the analyzed crystal structures of 18-28 we found no face-to-face methyl groups, but a variety of angles and distances between methyl pairs. However, no general trend or correlation between distances/angles and the enhancement factor was found. On the contrary, we found that 25 shows a higher polarization than 6, despite the missing face-to-face arrangement. Although we were not able to recognize structural patterns in the crystal structures related to the appearance of QRIP, we confirm that a high tunnel barrier is required to induce QRIP.

To explain why promising candidates like 8 and 12 did not show QRIP and 6 exhibits weaker QRIP than 1 (both show face-to-face methyl groups only with a slight difference in the methyl-methyl distance) we conclude that similarly as in 13 the necessary offset between rotational barriers of the methyl group is not given and thus QRIP is quenched. We also recognize, that mechanisms other than pairwise concerted rotation of two face-to-face methyl groups are not the only and possibly not even the best way to lower the rotational barrier of methyl rotation in a crystalline environment. Further candidates include a gear-like coupling of two adjacent methyl groups (which, however, we did not observe in any real molecule), and phonon modes of the molecular crystal, which could couple to the rotational motion of a methyl. Further, cross relaxation is an essential part of the QRIP and competing relaxation pathways would quench the effect. However, we did not focus on examining those effects in this work.

For further studies in this field \(^{13}C\) labelling can be a valid solution to find weaker enhancement potentials in some of the studied and possibly in other compounds.

To summarize we find with this study that even small structural differences can quench the QRIP effect by strongly affecting the tunnel frequency. Whether the crystal structure is a determining factor in general can
hereby neither be confirmed nor excluded. Therefore, we do not recognize a simple approach to predict QRIP from structural assessment. Thus, a broader applicability of the effect on, for example, protein methyl groups is not to be expected.

Data availability. NMR spectra were originally recorded with TopSpin and processed with MestreNova. The TopSpin files include the raw data as well as the pulse sequences. Those files and the XRD data (Origin files) are available from zenodo.org with https://doi.org/10.5281/zenodo.5078040.

Supplement. The Supplement contains the following information: spectra of \( \gamma \)-picoline derivatives, crystal structure of \( \gamma \)-picoline hydrochloride and pictures of the glass tubes for MAS-NMR under air exclusion. The supplement related to this article is available online at: xxxxxx.

Author contributions. JM and DS designed the research. JW synthesized the \( \gamma \)-picoline derivatives. AHK prepared the glass tube samples for MAS-NMR under air exclusion. CD, JW, OL, JM and DS interpreted the data. The paper was written with contributions from all the authors. All authors approved the final version of the paper.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue “Geoffrey Bodenhausen Festschrift”. It is not associated with a conference.

Acknowledgements. The authors thank Prof. Dr. Stefan Berger, Dr. Maik Icker and Dr. Matthias Findeisen (Leipzig University) for helpful discussions. We also thank Dr. Wiebke Lohstroh (Heinz Maier-Leibnitz Zentrum, Technische Universität München) and Dr. Astrid Schneidewind (Jülich Center for Neutron at MLZ, Forschungszentrum Jülich) for the INS measurements, and Oliver Erhart (Leipzig University) for the XRD measurements. Furthermore, we thank Dr. Michael Ruggiero (University of Vermont) for providing us with the ZIF-8 and ZIF-67 samples and Prof. Berthold Kersting und Dr. Peter Hahn (Leipzig University) for providing the calixarene samples.

Financial support. This work was supported by the Deutsche Forschungsgemeinschaft (DFG) under Grant number MA 4972/5-1.

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