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## Decomposition of P<sub>4</sub>O<sub>10</sub> in DMSO

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Intermediate states of degradation of phosphorus pentoxide in dimethyl sulfoxide (DMSO), also known as Onodera reagent<sup>1</sup>, are studied. We found that DMSO is not dissolving P<sub>4</sub>O<sub>10</sub>, but rather reacting with it. A rather complex mixture of phosphate species is formed, many with ester functions. Several not yet described phosphate species could be identified. Finally, we present a possible decomposition scheme of P<sub>4</sub>O<sub>10</sub> in DMSO.

Dimethyl sulfoxide (DMSO) is used in a variety of fields, e.g. in pharmacology<sup>2</sup>, biology<sup>3</sup> and the medical sector<sup>2</sup>. DMSO is a strong polar, nucleophilic and aprotic solvent, which is less toxic than other members of this solvent family, while being able to dissolve many compounds<sup>4</sup>.

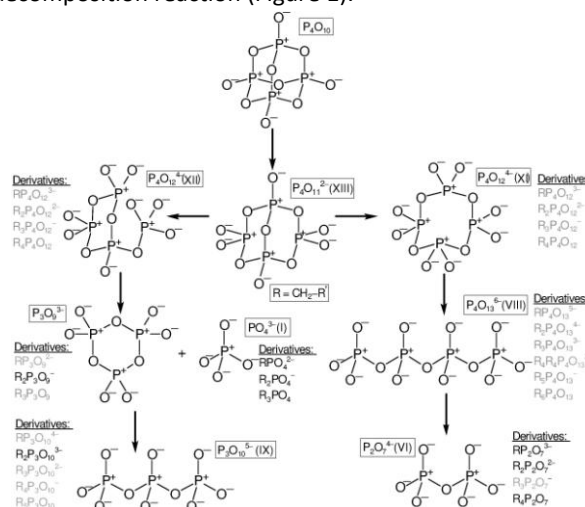
While the aforementioned applications use DMSO as solvent, in organic synthesis it is used as a mild oxidant, which is exemplified by the Pfitzner-Moffatt and the Swern oxidation<sup>5</sup>. During these oxidations, DMSO acts as reactant. Usually, electrophiles are involved and alcohols are oxidized under very mild conditions<sup>6–8</sup>. Despite the amount of literature about DMSO used in oxidations<sup>5–11</sup>, no intermediates of these reactions have been found, but only suggested. One example is the system dimethyl sulfoxide and phosphorus pentoxide, also known as Onodera reagent<sup>1</sup>. Onodera et al. found in 1965 that it is possible to oxidize carbohydrates with dimethyl sulfoxide containing phosphorus pentoxide.

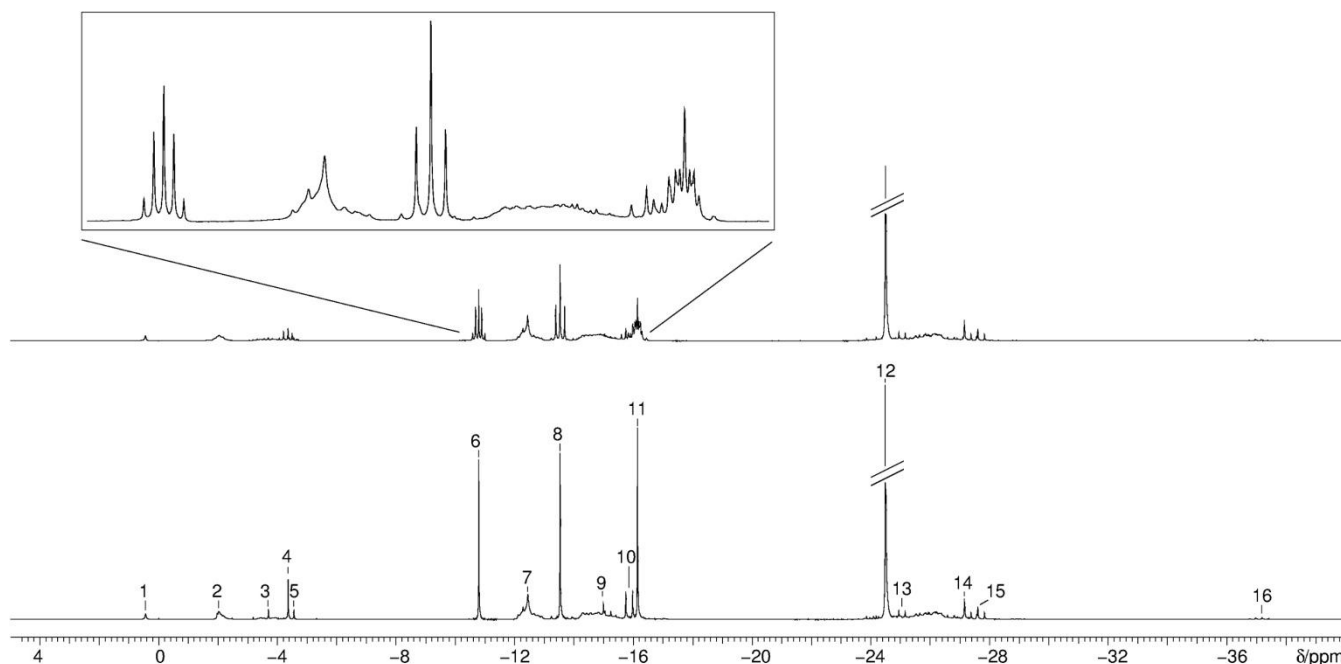
Recently, a low-temperature synthesis of organic and inorganic phosphates was published<sup>12</sup>. The idea of this synthesis is that a nitrate salt M(NO<sub>3</sub>)<sub>x</sub> (M<sup>x+</sup> in this case being a monovalent or divalent inorganic or organic cation) reacts with P<sub>4</sub>O<sub>10</sub> in DMSO. In this manuscript, we present an investigation of the

system P<sub>4</sub>O<sub>10</sub>-DMSO without nitrates present, based on results from <sup>31</sup>P NMR studies in the system followed by a detailed proposal of the reaction mechanism supported by mass spectrometry measurements and DFT calculations. According to our hypothesis, DMSO is not only a solvent but a reactant – actively participating in the named system. Several questions arise. Can we detect stable intermediate molecules? Can we identify novel phosphate species? How does a possible decomposition happen?

In order to answer these questions, <sup>31</sup>P NMR was utilized to identify the P-O-P backbone of possible intermediates. Figure 2 shows a <sup>31</sup>P{<sup>1</sup>H} NMR spectrum (bottom) and the corresponding <sup>31</sup>P spectrum (top). One would expect a broad peak at δ = -45.9 ppm for P<sub>4</sub>O<sub>10</sub>, which is built of Q<sup>3</sup> [PO<sub>4</sub>] tetrahedra

Assigning the decomposition products, which occur during the reaction of P<sub>4</sub>O<sub>10</sub> in DMSO, was done by analyzing the occurring multiplets, their isotropic chemical shifts and J-couplings. Several molecules were identified and spin systems were assigned (Table 1). Having all the occurring phosphate species tabulated, one can derive a scheme for the decomposition reaction (Figure 1).





**Figure 2.** Bottom spectrum:  $^{31}\text{P}\{^1\text{H}\}$  NMR spectrum of  $\text{P}_4\text{O}_{10}$  in DMSO; peak 1:  $\text{H}_3\text{PO}_4$  (I), peak 2: unknown  $\text{Q}^0$ -species, peak 3:  $(\text{OP})(\text{O}-\text{CH}_2\text{R})_3$  (II), peak 4:  $(\text{O}_2\text{P})(\text{O}-\text{CH}_2\text{R})_2^-$ -anion (III), peak 5:  $(\text{O}_3\text{P})(\text{O}-\text{CH}_2\text{R})^2-$  (IV), peak 6:  $(\text{RCH}_2\text{O})_2-(\text{PO})-\text{O}-\text{PO}_3^-$ -anion (V) (P-O-P-bridge is not stable on the NMR timescale), peak 7:  $\text{P}_2\text{O}_7^{4-}$ -anion (VI), peak 8:  $(\text{RCH}_2\text{O})-(\text{PO}_2)-\text{O}-\text{PO}_3^-$ -anion (P-O-P-bridge is not stable on the NMR timescale), peak 9+13: tetraphosphate-anion (VII), peak 10+15:  $\text{PO}_3-\text{O}-\text{PO}_2-\text{O}-\text{PO}_3^-$ -anion (VIII), peak 11:  $(\text{RCH}_2\text{O})_2\text{OP}-\text{O}-\text{PO}(\text{OCH}_2\text{R})_2$  (IX), peak 12:  $\text{P}_4\text{O}_{12}^{4-}$ -anion (X), peak 14: unknown  $\text{Q}^2$ -species, peak 16: unknown  $\text{Q}^3$ -species; R is an unknown residue. Top spectrum:  $^{31}\text{P}$  NMR spectrum of  $\text{P}_4\text{O}_{10}$  in DMSO; areas with occurring multiplets are shown magnified. Roman numbers in brackets function as substance identifiers. Details about isotropic chemical shifts and J-couplings are given in the supporting information.

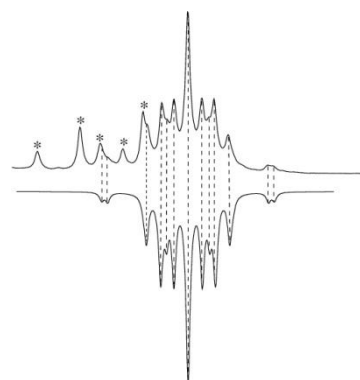
Peak	Molecule (substance identifier)	Spin system	Coupling
1	$\text{H}_3\text{PO}_4$ (I)	A	$A = ^{31}\text{P}$
2	Unknown $\text{Q}^0$ -species	unknown	
3	$(\text{OP})(\text{O}-\text{CH}_2\text{R})_3$ (II)	$\text{A}_6\text{X}$	$A = ^1\text{H}, X = ^{31}\text{P}$
4	$(\text{O}_2\text{P})(\text{O}-\text{CH}_2\text{R})_2^-$ -anion (III)	$\text{A}_4\text{X}$	$A = ^1\text{H}, X = ^{31}\text{P}$
5	$(\text{O}_3\text{P})(\text{O}-\text{CH}_2\text{R})^2-$ -anion (IV)	$\text{A}_2\text{X}$	$A = ^1\text{H}, X = ^{31}\text{P}$
6	$(\text{RCH}_2\text{O})_2-\text{OP}-\text{O}-\text{PO}_3^-$ -anion (V)	$\text{A}_4\text{X}$	$A = ^1\text{H}, X = ^{31}\text{P}$
7	$\text{P}_2\text{O}_7^{4-}$ -anion (VI)	$\text{A}_2$	$A = ^{31}\text{P}$
8	$(\text{RCH}_2\text{O})-(\text{PO}_2)-\text{O}-\text{PO}_3^-$ -anion (VII)	$\text{A}_2\text{X}$	$A = ^1\text{H}, X = ^{31}\text{P}$
9	Tetraphosphate -anion (VIII)	$\text{AXX}'\text{A}'$	$A = ^{31}\text{P}, X = ^{31}\text{P}$
10	$\text{PO}_3-\text{O}-\text{PO}_2-\text{O}-\text{PO}_3^-$ -anion (IX)	$\text{A}_2\text{X}^{[a]}$	$A = ^{31}\text{P}, X = ^{31}\text{P}$
11	$(\text{RCH}_2\text{O})-\text{PO}_2-\text{O}-\text{PO}_2-(\text{OCH}_2\text{R})$ (X)	$\text{A}_2\text{XX}'\text{A}_2'$	$A = ^1\text{H}, X = ^{31}\text{P}$
12	$\text{P}_4\text{O}_{12}^{4-}$ -anion (XI)	$\text{A}_4$	$A = ^{31}\text{P}$
13	Tetraphosphate-anion (VIII)	$\text{AXX}'\text{A}'$	$A = ^{31}\text{P}, X = ^{31}\text{P}$
14	Unknown $\text{Q}^2$ -species	unknown	
15	$\text{PO}_3-\text{O}-\text{PO}_2-\text{O}-\text{PO}_3^-$ -anion (IX)	$\text{A}_2\text{X}^{[a]}$	$A = ^{31}\text{P}, X = ^{31}\text{P}$
16	Unknown $\text{Q}^3$ -species	unknown	

**Table 1.** Assigned spin systems to the molecules found by NMR. R is an unknown residue.

[a]  $^2J(^{31}\text{P}, ^{31}\text{P})$ -coupling of 25.2 Hz.

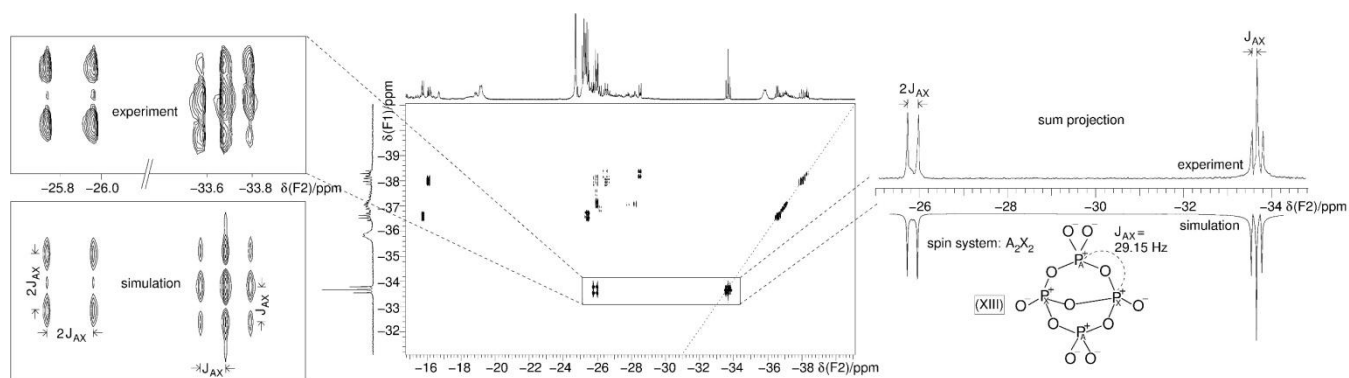
The molecule  $(\text{RCH}_2\text{O})-\text{PO}_2-\text{O}-\text{PO}_2-(\text{OCH}_2\text{R})$  (X) could be identified by performing simulations with the program

SIMPSON<sup>13</sup>. We found a spin system of higher order,  $\text{A}_2\text{XX}'\text{A}_2'$ , with a  $^2J(^{31}\text{P}, ^{31}\text{P})$  J-coupling of 22.8 Hz and a  $^3J(^1\text{H}, ^{31}\text{P})$  J-coupling of 16.1 Hz. The experimental data have been compared with the simulation (Figure 3).



**Figure 3.** Top: measured  $^{31}\text{P}$  liquid-state NMR spectrum. The multiplet can be seen in Figure 1 in the insert box at  $\delta = -16.4$  ppm. Bottom: simulated  $^{31}\text{P}$  liquid-state NMR spectrum of the  $\text{A}_2\text{XX}'\text{A}_2'$ -spinsystem.  $(\text{RCH}_2\text{O})_2\text{OP}-\text{O}-\text{PO}(\text{OCH}_2\text{R})_2$  (X) is responsible for that splitting, R being an unknown residue. Asterisks mark other phosphate species.

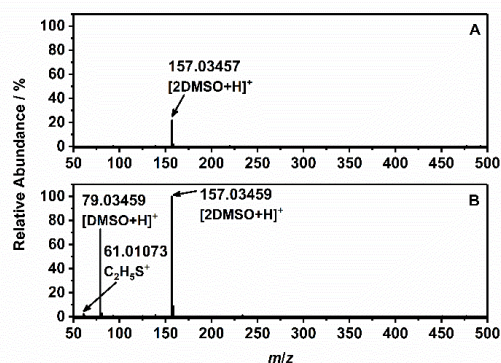
To investigate the, to this point, unknown  $\text{Q}^3$ -species, a 0.5 mmol/l solution of  $\text{P}_4\text{O}_{10}$  in  $d_6$ -DMSO was analyzed by  $^{31}\text{P}$  COSY NMR (Figure 4). The resulting COSY spectrum was treated as follows: first the sum projections were extracted, J-couplings, isotropic chemical shifts and multiplets were taken from a single pulse  $^{31}\text{P}$  NMR experiment, if extraction was possible. Then 2D COSY spectra were simulated with the program SIMPSON<sup>13</sup>, and from these sum projections were extracted (input files for the simulations see supporting information). Simulations for the molecule  $[\text{P}_4\text{O}_{11}]^{2-}$ , which is the first decomposition product (Figure 4), show a J-coupling  $^2J(^{31}\text{P}_A, ^{31}\text{P}_X)$  of 29.15 Hz.



**Figure 4.** Zoom in of a  $^{31}\text{P}$  COSY spectrum (middle). On the x and y axis  $^{31}\text{P}$  single excitation spectra are shown. On the right top the sum projection of the section from the COSY spectrum surrounded by the box is shown versus a simulated sum projected of a  $\mu$ -oxido-cyclotetraphosphate-anion (XIII) with an  $A_2X_2$  spin system. On the left top a zoom in the section is shown versus the simulation of the COSY spectrum of the  $A_2X_2$  spin system. Details about isotropic chemical shifts and J-couplings are given in the supporting information.

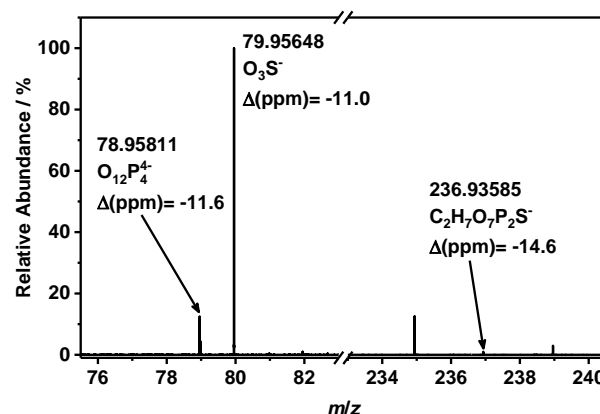
The sum projection of the experiment is in good agreement with the sum projection extracted from simulation. This is also supported by experimental 2D COSY spectrum and the 2D simulation itself, meaning that the hypothesis of  $\mu$ -oxido-cyclotetraphosphate-anion –  $[\text{P}_4\text{O}_{11}]^{2-}$  – ( $A_2X_2$  spin system) could be confirmed as the first step of the decomposition reaction. A  $[\text{N}(\text{PPh}_3)_2]^+$  salt of this species was recently synthesized<sup>14</sup>. The aforementioned conclusions resulting from  $^{31}\text{P}$ NMR interpretation are supported by mass spectrometric analysis of the  $\text{P}_4\text{O}_{10}$ -DMSO mixture. The reaction mixture is deposited on a stainless-steel mesh and subsequently probed by the flowing atmospheric-pressure afterglow (FAPA)<sup>15</sup> ambient desorption/ionization source. Resulting gas-phase ions are detected by a high-resolution mass spectrometer (HR-MS) in positive-ion mode (Figure 5).

ions cannot be observed in the mass spectrum of pure DMSO (Figure 5A and S1), which supports the hypothesis that  $\text{C}_2\text{H}_5\text{S}^+$  is formed by the reaction of DMSO and  $\text{P}_4\text{O}_{10}$ . Mass spectra detected in negative-ion mode give further information on possible reaction products. In Figure 6, the species  $\text{P}_4\text{O}_{12}^{4-}$  is detected at  $m/z$  78.95811 (MA -11.3 ppm), and the sum formula  $\text{C}_2\text{H}_7\text{O}_7\text{P}_2\text{S}^-$  can be related to  $m/z$  236.93585 (MA -14.6 ppm). These findings correlate well with the results of the  $^{31}\text{P}$  NMR measurements. Additionally, various oxidized sulphate- and phosphate-species (Figure 6 and S2) can be observed in negative-ion mode. These species might result from oxidation processes in the reaction mixture or gas-phase reactions after the liquid is desorbed from the sample target.



**Figure 5.** Positive-ion mode mass spectra of (A) DMSO and (B) the  $\text{P}_4\text{O}_{10}$ -DMSO mixture detected via FAPA-MS. A) Mass spectrum of pure DMSO shows dimer formation from solvent molecules. B) Mass spectrum of the DMSO/ $\text{P}_4\text{O}_{10}$  mixture. Peak identification was carried out by high-resolution mass spectrometry with a relative mass accuracy of  $\leq 4$  ppm. Peak heights in (A) and (B) were normalized to the largest peak ( $m/z$  157) in (B) for visualization purposes.

In the mass spectrum of the mixture (Figure 5B) protonated DMSO dimer cations ( $[\text{M}_2+\text{H}]^+$ , mass-to-charge ratio ( $m/z$ ) 157.03457, mass accuracy (MA) -3.7 ppm) and protonated DMSO molecules ( $[\text{M}+\text{H}]^+$ ,  $m/z$  79.02109, MA -0.8 ppm) are the two dominant species detected directly after the sample is deposited between the FAPA desorption/ionization source and MS. Furthermore,  $\text{C}_2\text{H}_5\text{S}^+$  ions ( $[\text{M}-\text{O}-\text{H}]^+$ ,  $m/z$  61.01073, MA 1.4 ppm) can be observed in the Onodera reagent. In comparison to these results,  $\text{C}_2\text{H}_5\text{S}^+$



**Figure 6.** Excerpt of the negative-ion mode mass spectrum of the Onodera reagent. Peak identification was carried out by accurate mass measurements (MA  $\leq$  -14.6 ppm).

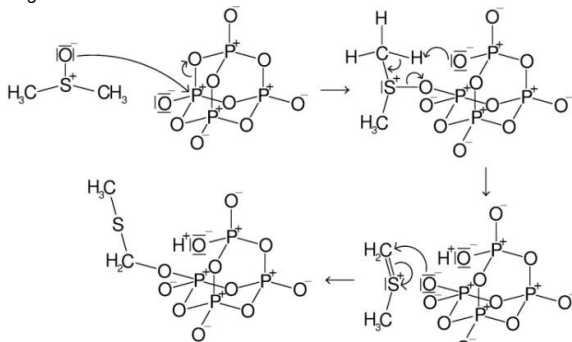
From the six calculated isomers of  $[\text{C}_2\text{H}_5\text{S}]^+$  the cyclic singlet structure is the most stable one according to our DFT calculations, irrespective of the temperature and the method to compute the energies. It may be noted though, that the next stable structure (singlet  $[\text{H}_2\text{C}-\text{S}-\text{CH}_3]^+$ ) has an energy difference below 20 kJ/mol and therefore is assumed to be easily accessible at elevated temperatures (Table 2).<sup>16–20</sup>

**Table 2.** Results of the DFT calculations at PBE1PBE/aug-cc-pVTZ level, energy values are given at 430 K, which is approximately the temperature of the MS experiments. Thermal correction, hindered rotor correction and  $\Delta E$  are given in kJ/mol.  $\Delta E_{\text{total}}$  is the total energy difference between the present and the lowest energetic isomer.

Isomer	Structure	Thermal correction	Hindered rotor correction	$\Delta E_{\text{total}}$
$\text{C}_2\text{H}_5\text{S}^+$		27.23	-0.063	317.29
Cyclo- $\text{C}_2\text{H}_5\text{S}^+$		21.2	0	0
$\text{H}_2\text{C-S-CH}_3^+$		24.11	-3.473	18.36

One way to explain the formation of the intermediate states, might be a Pummerer-like rearrangement<sup>21–24</sup> reaction (Scheme 1).

**Scheme 1.** Schematic drawing of the suggested reaction mechanism between DMSO and  $\text{P}_4\text{O}_{10}$ . The first step of a possible cracking of the adamantane cage of  $\text{P}_4\text{O}_{10}$  is shown. The suggested pathway follows a Pummerer-like rearrangement<sup>21–24</sup>.



The nucleophilic oxygen atom of DMSO attacks one phosphorus atom of the adamantane-like cage of phosphorus pentoxide, while the P-O binding breaks, forming an intermediate adduct. Afterwards, one hydrogen is shifted towards the newly formed negatively charged oxygen and the spare electron pair forms a double bond between carbon and sulfur, meaning that a  $\text{C}_2\text{H}_5\text{S}^+$  molecule is formed as intermediate. Finally, oxygen attacks the carbon of the  $\text{C}_2\text{H}_5\text{S}^+$  molecule and a phosphate ester is formed.

For the first decomposition step the following hypothetical reaction equation applies.



The decomposition mechanism of  $\text{P}_4\text{O}_{10}$  in DMSO suggests the formation of stoichiometric amounts of protons which, as Lewis acids, further accelerate the decomposition reaction of the nucleophilic compound DMSO. This is in agreement with the observation that multidimensional NMR only serves to identify the initial products. The lifetime of the produced oligophosphates becomes shorter the longer the reaction is ongoing, so that multidimensional NMR becomes prohibitively long, i.e. the decomposition reaction has an autocatalytic character.

To conclude, our study reveals that a complex mixture of phosphate esters is formed from the reaction of DMSO and

$\text{P}_4\text{O}_{10}$ , including uncommon phosphate species like the  $\mu$ -oxido-cyclotetraphosphate-anion,  $(\text{P}_4\text{O}_{11})^{2-}$ , and species like the O-phosphono-cyclotriphosphate-anion,  $(\text{P}_3\text{O}_9\text{PO}_3)^{4-}$ <sup>25</sup> and remains to be isolated. The suggested mechanism may help to direct the understanding of more complex name reactions, which build on  $\text{P}_4\text{O}_{10}$ /DMSO mixtures.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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