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Solvent-Free and Safe Process for the Quantitative Production of Phosgene from Triphosgene by Deactivated Imino-Based Catalysts

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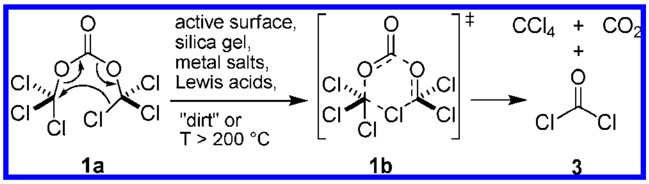
Abstract:

Phosgene is quantitatively formed from solid triphosgene in a solvent-free and safe process without any reaction heat, catalyzed by planar N-heterocycles with deactivated imino functions. The rate of phosgene generation is adjustable to the rate of phosgene consumption in the subsequent phosgenation reaction by thermal control, catalyst concentration, and in some cases, specific properties of selected metal phthalocyanines. A thermal runaway reaction of this process is impossible.

Introduction

Phosgene (**3**) is a highly useful and versatile chemical in performing syntheses.[1a] Although consisting of only four atoms, four important transformations can be carried out with it in organic chemistry: chloro-carbonylation, carbonylation, chlorination, and dehydration, by which chloroformates, carbonates, carbamates, ureas, isocyanates, acyl- and arylchlorides, anhydrides, cyanides, isocyanides, and carbodiimides can be generated, as well as the corresponding heterocycles.[1a−3] Phosgene reacts in a distinct way with high yields and pure products, but it is a strong and malicious toxic gas (bp 8 °C). Great efforts have been made to displace phosgene by numerous substitutes (a comprehensive review on this is given in ref 1c), and its most versatile equivalent is triphosgene (**1**),[4,1] which was introduced in 1987,[4a] because of its high stability as a solid (mp 80 °C) and its low vapor pressure (2×10^{-4} bar at 20 °C).[1d] Triphosgene has proved to be a valuable substitute for phosgene in most reactions, yet several phosgenation reactions are advantageously carried out with phosgene, that is, when excessive triphosgene is difficult to remove during the reaction workup because of its high boiling point of over 200 °C. Its excess can be destroyed by hydrolysis, when phosgenation products are not sensitive to moisture as are carbonates, carbamates, ureas, diarylketones, alkylhalides, cyanides, and isocyanides. However, for chloroformates, acyl chlorides, anhydrides, isocyanates, and carbodiimides, which are very sensitive to hydrolysis, workup after phosgenation reactions by use of water has to be carried out skilfully and is limited to rather small quantities. Phosgene, however, can easily be removed in the workup by evaporation.

Scheme 1. **Decomposition of triphosgene (1a) into carbon tetrachloride, carbon dioxide, and 1 equiv of phosgene (3)**



In production lines, the use of gaseous phosgene is advantageous as a result of its easy charging as well as the facile and quantitative removal of excess. To benefit from the chemical and ecological advantages (fast decomposition by air humidity and less harmful decomposition products in contrast to other substitutes such as thionyl chloride or phosphoryl chloride) of phosgene despite its high toxicity, the concept of the *Safety Phosgenation* has been designed.[1e,5] Core to it is the phosgene production "*on demand of consumer*" without any storage. To avoid both gases chlorine and carbon monoxide for the production of phosgene, solid triphosgene is the safest precursor for production, transport, and storage of phosgene.

Triphosgene completely decomposes by contact with metal salts, Lewis acids, active surfaces such as silica gel, by "dirt", or at temperatures above 200 °C in a spontaneous, uncontrolled, and exothermic reaction into carbon dioxide, carbon tetrachloride, and 1 equiv of phosgene (Scheme 1).[1b,4c] The reaction mechanism is an electrocyclic reaction of the conformer **1a** of triphosgene (which is interchangeable with **1** by free rotation of both trichloromethyoxy groups at rt) through a six-membered transition state **1b**, which causes the simultaneous formation of the three products carbon tetrachloride, carbon dioxide, and phosgene in a molecular ratio of 1:1:1,[1b,4c] measured by a thermogravimetric analyzer interfaced to a Fourier transform

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(1) (a) Cotarca, L.; Eckert, H. Phosgenations−A Handbook; Wiley-VCH: Weinheim, 2003. (b) Cotarca, L.; Eckert, H. Phosgenations−A Handbook; Wiley-VCH: Weinheim, 2003; pp 20−21. (c) Cotarca, L.; Eckert, H. Phosgenations−A Handbook; Wiley-VCH: Weinheim, 2003; pp 44−520. (d) Cotarca, L.; Eckert, H. Phosgenations−A Handbook; Wiley-VCH: Weinheim, 2003; p 41. (e) Cotarca, L.; Eckert, H. Phosgenations−A Handbook; Wiley-VCH: Weinheim, 2003; pp 14−16, 613−615.

(2) Recent online information: www.ch.tum.de/oc1/HEckert/research.htm.

(3) (a) Senet, J. P. *The Recent Advance in Phosgene Chemistry*; SNPE: Paris, 1997; Vol. 1. (b) Pasquato, L.; Modena, G.; Cotarca, L.; Delogu, P.; Mantovani, S. J. Org. Chem. **2000**, *65*, 8224–8228. (c) Senet, J. P. *Sci. Synth.* **2005**, *18*, 321–377. (d) Dunlap, K. L. In *Kirk-Othmer Encyclopedia of Chemical Technology*, 5 ed.; Wiley: New York, 2006; Vol. 18, pp 802−814. (e) Nielsen, D. H.; Burke, T. G.; Woltz, P. J. H.; Jones, E. A. J. Chem. Phys. **1952**, *20*, 596–604. (f) Gordon, E. P.; Enakaeva, V. G.; Korotchenko, A. V.; Mitrokhin, A. M. *Russian Patent RU 2299852*, 2007.

(4) (a) Eckert, H.; Forster, B. Angew. Chem. **1987**, *99*, 922–923; *Angew. Chem., Int. Ed.*, **1987**, *26*, 894–895. (b) Eckert, H. *TUM-Mitteilungen (Technische Universitaet Muenchen)* **2006**, *3*, 68–69. (c) Cotarca, L.; Delogu, P.; Nardelli, A.; Sunjic, V. Synthesis **1996**, 553–576. (d) *Triphosgene*; Ubichem: U.K., 1999; CD-ROM. (e) Su, W.; Zhong, W.; Bian, G.; Shi, X.; Zhang, J. Org. Prep. Proced. Int. **2004**, *36*, 499–547.

(5) (a) Eckert, H.; Drefs, N. *Chemanager* **2006**, (3), 10. (b) http://www.buss-ct.com/e/reaction_technology/Phosgene_Generation.php?navid=41.

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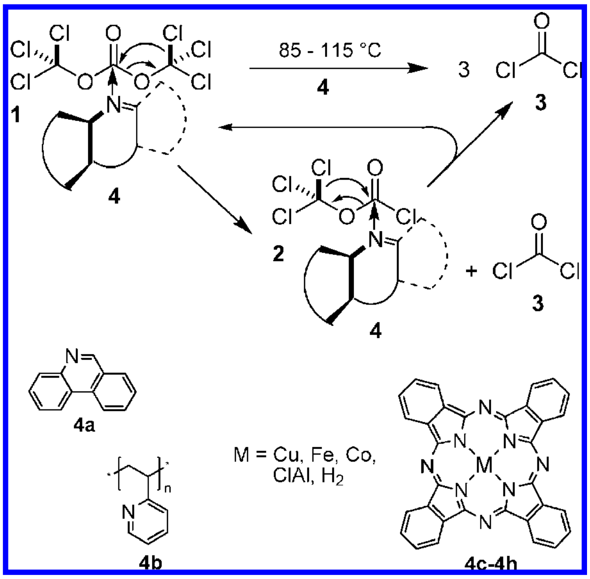
Scheme 2. **Controlled transformation of triphosgene (1) into 3 equiv of phosgene (3) catalyzed by 4**



infrared spectrometer (TGA-FTIR). For the thermal decomposition of triphosgene, decomposition enthalpies of $\Delta H_{\mathrm{dec}} = -200$ to -278 J g^{-1} have been published.[4c,d]

Until now phosgene has been prepared from triphosgene in a practical way only in solution in an uncontrolled reaction by use of tertiary amines, pyridine in dichloromethane or tetrahydrofuran, or catalysis by Aliquat 336 in hexane.[3b] Also inert high temperature solvents have been used to achieve phosgene from triphosgene without diphosgene impurities.[3f]

Results and Discussion

By means of a specific catalyst **4**, however, liquid triphosgene (**1**, mp 80 °C) can be transformed solvent-free and quantitatively under heating with an oil-bath or an IR-heater in a controlled and adjustable process into 3 equiv of phosgene (Scheme 2).[6] Diphosgene is formed as an intermediate, which immediately reacts to form phosgene. Highly specific catalysts are those who effect (i) an electronic push of the weak nucleophilic imino-group of **4** to the carbonyl group of triphosgene (**1**), (ii) the leaving of a trichloromethoxy group, (iii) the generation of a carbonyl group from the latter by migrating a chloride to the remaining trichloromethoxycarbonyl group and thus forming one phosgene (**3**) and diphosgene (**2**), (iv) the leaving of the second trichloromethoxy group, and (v) the generation of a carbonyl group by migrating a chloride to the remaining acyl chloride group and thus forming two molecules of phosgene (**3**). Simultaneously the size and planar structure of **4** prevents as a barrier between both trichloromethyl groups in **1** the formation of the six-membered transition state **1b** and thus makes the reaction of Scheme 1 impossible.

All of this will be realized by designing both the electronic and steric properties of catalysts **4a**−**4h** (Scheme 2 and Table 1).[6] Because these are insoluble in molten triphosgene, catalysis according to Scheme 2 runs in a heterogeneous reaction. All catalysts **4a**−**4h** fulfill the above criteria and are stable and recyclable. Outstandingly stable over many catalytic cycles are **4d**−**4h** with a metal phthalocyanine (MPc)[8a,b] structure (belonging to the most stable organic compounds of all); their activity can be tuned by the properties of the central metals in **4d**−**4h** and the crystal modifications of the complexes, as for **4d** versus **4e**. So the α-CuPc (**4d**) is 90 times more reactive than its *β*-form (**4e**), as calculated with the reaction data from Table 1, entries 7 and 9. Even after intensive use of **4d** over 10 years with a hundred batches of phosgene production, no decline in the catalytic efficiency of **4d** has been observed, which corresponds to a TON (turnover number) of 5×10^4 (entry 8). Reaction rates can be conveniently adjusted by either catalyst concentration (0.02−2 mol %)[7] or temperature control (80−115 °C) and can easily reach a TOF (turnover frequency) of 1.2×10^3 h^{-1} (entry 6). This is an appropriate TOF value for managing the kinetics to adjust the rate of phosgene generation to the rate of phosgene consumption of the subsequent phosgenation reaction in an optimal way. Reaction times in the range of some minutes up to 1 h can preferably be achieved with **4a**−**4f** as catalysts. For reaction times over many hours **4g** and **4h** are the appropriate catalysts. In all reactions of triphosgene with **4a**−**4h** the resulting phosgene is of high purity, >99%. Mere pyridine served as a reference substance, but it effects instantaneous decomposition of triphosgene and is not at all appropriate to produce phosgene in a solvent-free way (entry 13, Table 1). Uncatalyzed reaction of triphosgene under the conditions of Table 1 is not observed (entry 1, Table 1).

Reaction in Scheme 2 is controlled by temperature. Using **4h** (Table 2) an increase of 25 °C in reaction temperature from 90 to 115 °C effects an acceleration of the volume flow of phosgene and thus of the reaction rate by a factor of 7. The reaction of Scheme 2 yields a further effect on safety: by turning off the heater, transformation of triphosgene comes to a halt and liquid triphosgene crystallizes, whereby its vapor pressure plunges down. The reaction can simply be continued by heating again.

This thermochemical performance is proven by differential scan calorimeter (DSC) measurements of the process. The conversion enthalpy of triphosgene into phosgene (Scheme 2, catalyst α-CuPc) is $\Delta H_{\mathrm{conversion}} = +9$ J g^{-1} at 81 °C; the reaction is slightly endothermic. The scan ran up to 250 °C with 10 °C/min, and this fast acceleration of temperature did not provide the behavior of a run away (Figure 1). The enthalpy of the thermal decomposition of triphosgene (Scheme 1) is $\Delta H_{\mathrm{decomp}} = -217$ to -243 J g^{-1}, starting at 213 °C; this reaction is moderately exothermic. Since the range (80−115 °C) of the slightly endothermic conversion reaction (Scheme 2) is more than 100 °C below the moderate exothermic decomposition reaction (Scheme 1), a thermal runaway is impossible. Beyond this, the process guarantees an emergency stop by simply cutting off heat.

Phosgenation Reactions

The controlled production of phosgene from triphosgene can be performed with an external phosgene generator with a

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(6) Eckert, H.; Dirsch, N.; Gruber, B. (former Dr. Eckert GmbH, now Buss Chem Tech AG) German Offen. DE 19740577, 1999 (Sep. 15, 1997), *Chem. Abstr.* **1999**, *130*, 211406.; WO 9914159, 1999; Eur. Pat. EP 1017623, 2002; U.S. Patent US 6399822, 2002; Japanese Patent JP 2001516692, 2001.

(7) Mole percent **4** referring to 3 phosgene equivalents of **1**.

Table 1. **Catalysts (4) and reaction data of Scheme 2 with conversions of 10−5,000 g of triphosgene (1) into phosgene (3)**

entry	**4**	catalyst	mol % of **4**[7]	bath temp [°C]	reaction temp [°C]	reaction time [min]	TON	TOF [h^{-1}]	yield of **3** [wt %]
1		None		115		*a*			0
2	**4a**	phenanthridine	0.1	115	95	21	10^3	2.9×10^3	98
3	**4b**	poly(2-vinyl-pyridine)	1	100	90	5	10^2	1.2×10^3	96
4	**4b**	poly(2-vinyl-pyridine)	0.1	100	90	60	10^3	10^3	98
5	**4c**	H_2*Pc*	1	100	90	4	10^2	1.5×10^3	97
6	**4d**	α-CuPc[b]	1	100	90	5	10^2	1.2×10^3	96
7	**4d**	α-CuPc	0.2	100	90	35	5×10^2	8.6×10^2	100
8	**4d**	α-CuPc	0.2	100	90	35×100[c]	5×10^4	8.6×10^2	98−100[c]
9	**4e**	*β*-CuPc	2	115	105	100	50	30	98
10	**4f**	CoPc	2	100	90	15	50	2×10^2	99
11	**4g**	FePc	2	115	105	1200	50	2.5	99
12	**4h**	ClAlPc	2	115	105	300	50	10	99
13		pyridine	0.2	85		*d*			*e*

[a] After 300 min **1** is regained quantitatively and unchanged. [b] Pc = Phthalocyanine. [c] 100 batches under the same conditions as entry 7. [d] 1 drop (10 mg) of pyridine added to 5 g of liquid **1** causes an abrupt decomposition. [e] Products could not be analyzed.

Table 2. **Thermal control of Scheme 2 with 2 mol %[7] of 4h: volume flow of phosgene produced from 10 g of triphosgene**

entry	reaction temp [°C]	volume flow of **3** [mL/min]
14	90	6.3
15	100	11.5
16	115	44.8

reaction rate perfectly adapted to the rate of consumption of phosgene during the phosgenation in the phosgenation reactor (Figures 2 and 3). Thus the actual amount of phosgene mainly originates from the volume (wake space) of the generator, which should be kept as small as possible. Hence a maximum of safety can be provided to the user. Thus, amounts of 1 g up to 5,000 g of triphosgene per batch have been converted into phosgene.

Another simplified application of the process is the controlled, internal *in situ* generation of phosgene from triphosgene by **4a**−**4h** within the phosgenation reactor (Figure 4) with the same advantage of balanced phosgene generation as in the external device. In this modus the most appropriate catalyst is **4b**, because it can be best filtered off. Constrictions could take place when nucleophilic reagents as (most) amines react very fast with triphosgene and thus great excesses of phosgene are formed. The solvent might dissolve the gas, but this is no longer a safety phosgenation. In these cases the external phosgene generator would be indicated (see above, Figure 2).

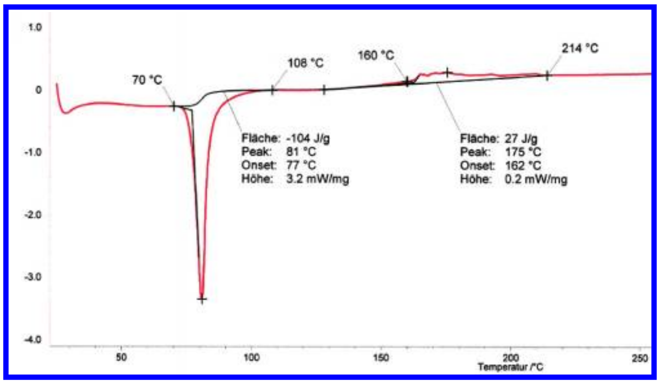

Figure 1. **DSC of the conversion of triphosgene to phosgene. Triphosgene with 1.5% α-CuPc, *T* = 10 °C/min.**

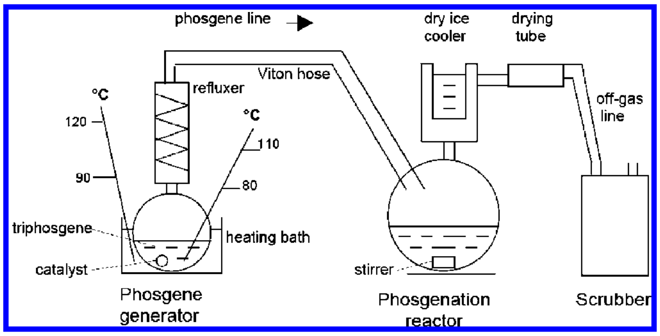

Figure 2. **Device for the safety phosgenation with external phosgene supply from triphosgene in separate flasks.**

Figure 3. **Typical glassware standard equipment for the safety phosgenation with phosgene supply from triphosgene: (A) phosgene generator (*V* = 1 L, *T* = 85 °C) loaded with 600 g of triphosgene; (B) refluxer (water cooled, *T* = 15 °C); (C) phosgene line (Viton hose); (D) phosgenation reactor (*V* = 10 L, *T* = 110 °C); (E) refluxer (cryostat cooled, *T* = −30 °C); (F) off-gas line (Viton hose) from the top of the refluxer (E); (G) cooling trap (dry ice cooled, *T* = −60 °C); (H) off-gas line; (I) cryostat. The assembly of the equipment is somewhat reduced to effect more clarity of the ensemble.**

Experimental Section

IR: Perkin-Elmer 177 Grating Spectrometer. ^{13}C NMR: Bruker AM 360 Spectrometer.

Compounds **1** and **4a**−**4 h** are commercially available products from Sigma-Aldrich, with the following purities:

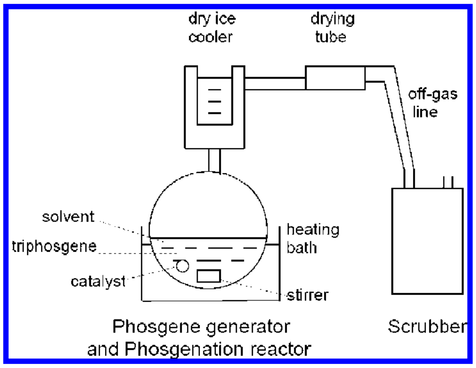

Figure 4. **Device for the safety phosgenation with internal phosgene supply from triphosgene in the same flask.**

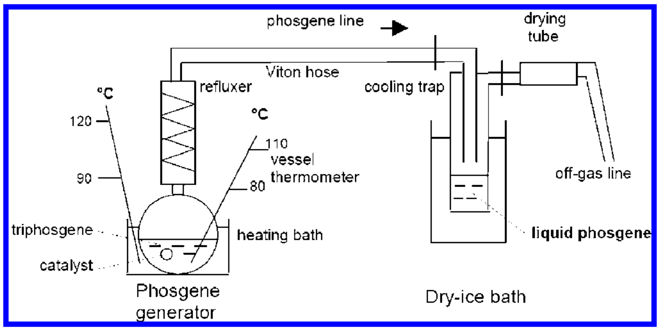

Figure 5. **Device for the production of safer phosgene from triphosgene.**

1, 98% (IR $\nu_{C=O}$ 1820 cm^{-1}, ^{13}C NMR δ 108.0, 140.9); **4a**, 98%; **4c**, n.a.; **4d**, 99%; **4e**, 97%; **4f**, 97%; **4g**, 90%; **4h**, 85%.

Working with Phosgene. In this section phosgene will be generated and handled in a range of 100 g, i.e., 22 L of toxic gas with a TLV of 0.1 ppm. Therefore special safety precautions have to be arranged. All work with phosgene has to be carried out in a hood with a strong exhaust on the highest level. In the hood frontside has to be placed a $COCl_2$ gas monitor, TLV 0−10 ppm.[10] Persons who work in the laboratory must wear a badge with a colorimetric $COCl_2$ dosimeter sheet.[10] Inside and outside the laboratory a gas mask with filter B (acid gases) must be accessible. The gas mask has to be borne when working in the hood. The sliding window(s) of the hood must fully be closed. When the gas monitor alerts, switch off heating bath(s) and leave the laboratory. Then follow the material safety data sheet and the safety regulations of your institution.

Safer Production of Phosgene from Triphosgene on a Molar Scale. (Table 1, entry 7; Figure 5) In a hood with a powerful exhaust a 250 mL two-necked vessel fitted with thermometer and magnetic stirrer is charged with 100 g (0.337 mol) of **1** and 1.15 g (0.002 mol) of **4d**. To the top neck of the vessel is adapted a refluxer, which is connected upside with a Viton-hose to a 250 mL cooling trap, which ends in a drying tube and an off-gas line into the exhaust. The equipment is flushed with dry nitrogen, and the cooling trap is submerged into an acetone−dry ice bath. The phosgene generator is heated by an oilbath (bath temperature 100 °C). When some of **1** is molten, **3** begins to evolve. When all of **1** is molten, a constant flow of **3** emerges until the reaction has ended. Along the way the reaction temperature rises to a constant 90 °C, and initially sublimed **1** is washed back to the vessel by intermediately generated liquid **2**, which has been carried away with the flow of **3**. The reaction ends after 35 min, and dry **4d** remains at the bottom of the vessel and can be reused in the next run. Now the vessel thermometer is replaced by a gas inlet and nitrogen is blown slowly through the device for 1 min to carry over remaining (gaseous) **3** into the cooling trap. CAUTION: The cooling trap, containing liquid **3**, is disconnected from the Viton hose and the off-gas line, taken out of the dry ice bath, quickly wiped off the acetone, and immediately weighed within the hood neary the air suction hole by putting the charged cooling trap into an adapted foamed plastic form on the scale of the weighing machine. Yield is 100% (100 g,[9] 1 mol) of **3**, and the purity is >99% (IR, $\nu_{C=O}$ 1827 cm^{-1}).[3e] To clean the equipment, hoses, reaction residues, and all other items, which have been contaminated with phosgene or triphosgene, are treated with ethanol for at least 15 min. The alcoholic waste is disposed of as chloride-containing organic solvent decay.

The above procedure can be analogously used for phosgenation reactions according to Figures 2 and 3. Important is the use of a dry ice cooler at the top of the vessel (could also be a refluxer with a connected cryostat, cooling medium temperature below −30 °C), so that phosgene cannot pass off at all.

Conclusion and Outlook

The presented catalyzed process has the capability to produce phosgene from the solid and safe precursor triphosgene, with some outstanding properties and advantages:

1. The process transforms solid triphosgene (safe in transport and storage) quantitatively into phosgene by a thermally controlled reaction.
2. Contrary to the exothermic phosgene production from chlorine and carbon monoxide, the phosgene generation reaction from triphosgene runs without any reaction heat and thus a thermal runaway is impossible; in addition, the process guarantees an emergency stop by cutting off the heat.
3. The process fulfills the criteria of "safety phosgenation on demand of consumer": the rate of phosgene generation is adjustable to the rate of the consumer reaction by thermal control.
4. The process provides pure phosgene gas without any solvent, and thus there is no reservoir of phosgene within

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(8) (a) Leznoff, C. C.; Lever, A. B. P. *Phthalocyanines, Properties and Applications*; VCH: Weinheim, NY, 1989. (b) Lever, A. B. P. *Adv. Inorg. Chem. Radiochem.* **1965**, *7*, 28–114. (c) Ebert, N. A.; Gottlich, H. B. J. Am. Chem. Soc. **1952**, *74*, 2806.

(9) The weighing error of this procedure mainly comes from icy condensed humidity at the cool glassware of the cooling trap and is less than 0.5 g, determined by a series of weighings under the same conditions, the same equipment, temperature ($T = -78$ °C), and handling time <10 s, but without **3**. Under these conditions evaporation of **3** (bp 8 °C) hardly ever happens and can be ignored.

(10) Monitox plus gas monitor ($COCl_2$) and phosgene badges from Compur http://www.compur.com/gasmessgeraete/front_content.php?idcat=7&changelang=3.

a great excess of volatile (and highly inflammable) solvent, which volatilizes this phosgene reservoir in the case of the equipment's accidental destruction.

5. Many synthetic chemists need phosgene but do not like gas bottles and bombs of phosgene or chlorine and carbon monoxide standing around in their laboratories. They can use avantageously the process to produce phosgene gas from solid triphosgene. The engineering and technology company Buss Chem Tech recommends the process for phosgene uptake rates up to 30 kg h^{-1} under semi-industrial conditions.[5b] Within this range the production of safer phosgene from triphosgene is even more cost-efficient than from chlorine and carbon monoxide.

Acknowledgment

The thermochemical data of triphosgene and its conversion into phosgene with a differential scan calorimeter (DSC) were thankworthy accomplished by Novasep AG, Dynamit Nobel GmbH, Leverkusen, Germany. Technical support on the analytical data about the purity of phosgene according to ref 3b was given by L. Cotarca.

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