

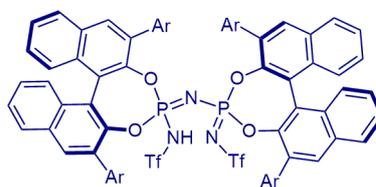
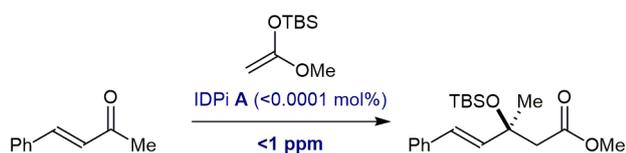
Synform

People, Trends and Views in Chemical Synthesis

2019/01

Approaching Sub-ppm-Level Asymmetric Organocatalysis of a Highly Challenging and Scalable Carbon–Carbon Bond-Forming Reaction

Highlighted article by H. Y. Bae, D. Höfler, P. S. J. Kaib, P. Kasaplar, C. K. De, A. Döhning, S. Lee, K. Kaupmees, I. Leito, B. List



(S,S)-IDPi A [Ar = 3,5-(*n*-hexyl)₂C₆H₃]
 $pK_a = 4.5$, when Ar = Ph (MeCN)

Contact

Your opinion about Synform is welcome,
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Dear Readers,

First of all, Happy New Year!

At the beginning of every year there is a “trend” going on in magazines, newspapers and the online marketing community: asking a number of experts about the upcoming trends in the New Year and beyond. As these articles are very popular, we thought we could apply the same concept to our beloved field of chemistry and ask our Editors for their opinion on the hottest trends or topics in organic synthesis. Answers from a few of us can be found in the first article of this year.

I hope you like the idea, which – I have to confess – is not mine but comes from our creative Marketing Associate Evelyn Hosner. This is a one-off article, so you won't see it again next year!!

The other articles in this issue cover a number of new, exciting organic chemistry topics. Ananikov and colleagues (Russian Federation) report on the performance of nanostructured reagents in cross-coupling reactions. Our *SYNLETT* Editor-in-Chief, Ben List (Germany), describes how it is possible to use tiny, sub-ppm amounts of organocatalyst for achieving stereocontrolled and scalable carbon-carbon bond-forming reactions. Finally, David Milstein (Israel) elaborates on the use of ammonia in dehydrogenative Ru-catalyzed coupling reactions leading to the formation of five- and six-membered nitrogen heterocycles.

Finally, there is more big news I am delighted to share with you. After nearly 10 years in Aberdeen I decided to move south of the border, precisely to Loughborough University in England, where I am taking on the direction of the new Centre for Imaging Science. Leaving Scotland really breaks my heart but hey, we are academics, we move!

In this issue

■ Editorial Board Focus

Trends in Organic Synthesis A3

■ Literature Coverage

Exploring the Performance of Nanostructured Reagents with Organic-Group-Defined Morphology in Cross-Coupling Reaction A5

■ Literature Coverage

Approaching Sub-ppm-Level Asymmetric Organocatalysis of a Highly Challenging and Scalable Carbon-Carbon Bond-Forming Reaction A8

■ Literature Coverage

Acceptorless Dehydrogenative Coupling Using Ammonia: Direct Synthesis of N-Heteroaromatics from Diols Catalyzed by Ruthenium A12

Coming soon A15

Enjoy your reading!!



Contact

If you have any questions or wish to send feedback, please write to Matteo Zanda at: synform@outlook.com

Future Trends for Organic Synthesis: An Opinion from Our Editors

For this month's Editorial Board Focus, we asked some of our Editors about their thoughts on the future of organic synthesis. Here's what they had to say:

Tom Rovis



Where is Organic Synthesis going? Every several years, an event comes along that causes a survey like this where we get all introspective about the field. Inevitably, the answer is something along the lines of "my field is moving in the direction of my research program". Rather than succumbing to this, I choose to paraphrase the late Frank Westheimer: if I knew what was going to be important in 20 years, I'd be doing it right now.

What I do believe is that synthesis will still be important, central and relevant. It is our field that uncovers reactivity and pushes the boundaries of how we assemble molecules. Regardless of where organic chemistry ends up, making molecules will always be important. It is what makes chemistry central to all other areas of science.

Henry Wong



One of the most significant aspects of organic synthesis is its enormous degree of creativity, because organic synthesis can create not only known molecules, but also functional and hitherto unknown molecules. Through its connections with many other scientific disciplines, organic synthesis can also create interdisciplinary frontiers such as chemical biology, new energy sources, and health industries. These new frontiers would in turn induce a great deal of challenge to synthesis, leading it to strive for more scientific creativity, and to reach new heights.

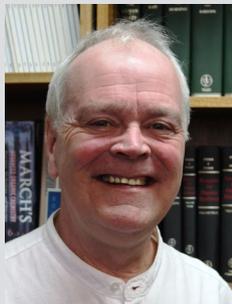
Paul Knochel



One important future goal in organic synthesis will be to prepare organic molecules in the most efficient manner in enough quantities so that the physical, chemical and biological properties of these organic molecules can be easily assessed. Over the recent years, the amount of material for such molecular property determinations has become increasingly smaller,

so that the preparation of complex target molecules can be envisioned to be performed using continuous flow methods. These fully automated machines are able to perform multistep syntheses of elaborated drugs including automatic analyses, purification, spectroscopic characterization as well as optimizations. Combined with retrosynthetic analysis programs, the overnight synthesis of complex natural products or potential drug candidates may become reality and routine. Based on the pioneering works of S. V. Ley,¹ Y. I. Yoshida,² T. Jamison,³ M. Organ⁴ and others,⁵ an important research field in organic synthesis will be the performance of multistep sequences in continuous flow. The performance of organic reactions under these conditions is also a real advantage for generating unstable or dangerous intermediates under reproducible safe conditions, making such reaction intermediates – which were avoided in the past – into acceptable reaction partners for the design of organic target molecules. Although the way towards fully automated organic reactions is still long, feasible and reliable pathways toward such a goal are becoming apparent. The future availability of such automated total synthesis mechanisms would considerably facilitate the life of organic chemists, who would then be able to concentrate more on the design of new organic molecules with ambitious physical, chemical or biological properties. Much work and brilliant perspectives exist for the future generations of organic chemists!

Laurence Harwood



This is in haste but one area where I could see chemistry and biology combining is in a halfway house between whole cell culture and using enzymes. What I am thinking of is using combinations of organelles in a single culture to carry out multiple step conversions, e.g. Golgi bodies + mitochondria in the same medium, each carrying out its transformations as a mini synthesis factory, one organelle producing substrate(s) for the other. This would be more for industrial production than as a laboratory tool but it would need laboratory scale studies to develop and separate the specific organelles and to design the synthetic medium.

Matteo Zanda



As the Editor of *Synform*, I have to admit that I had an advantage over my fellow Editors, because I could read their contributions before writing these few lines. And I can't help but confess that – like Tom Rovis – I am a bit sceptical as I don't think anyone can really gaze into a crystal ball and come up with reliable predictions on what's the next big thing in any area of research,

including organic chemistry of course. It is not like predicting who is going to win the next World Cup, as we all have our biases here and we all probably tend to over-emphasise the field of research we are working in. Nevertheless, I'd still like to predict something, or – better – make an observation: the influence of Artificial Intelligence (AI) on chemistry will become massive. I don't think we'll get to a Terminator-like scenario any time soon – at least I hope not – but AI is already assuming a key role in a number of aspects of modern life, including research, and although the human factor is still vitally important, I suspect that the role of computers, algorithms and AI will continue to become increasingly important, which is pretty much in line with Paul Knochel's observations above on automated synthesis. It's already happening, that's why I don't think this is a prediction. AI will save a lot of our time and help us deal with a number of practical problems in chemical research, for example synthesis planning and execution, structure elucidation and experiment design. We just have to make sure that we use AI in the right way, as we don't want to end up like Sarah Connor and her son, do we ...

REFERENCES

- (1) (a) T. Brodmann, P. Koos, A. Metzger, P. Knochel, S. V. Ley *Org. Process Res. Dev.* **2012**, *16*, 1102–1113. (b) S. V. Ley, D. E. Fitzpatrick, R. M. Myers, C. Battilocchio, R. J. Ingham, *Angew. Chem. Int. Ed.* **2015**, *54*, 10122–10136.
- (c) C. Battilocchio, F. Feist, A. Hafner, M. Simon, D. N. Tran, D. M. Allwood, D. C. Blakemore, S. V. Ley *Nat. Chem.* **2016**, *8*, 360–367.
- (2) (a) H. Kim, A. Nagaki, J.-i. Yoshida *Nat. Commun.* **2011**, *2*, 264. (b) A. Nagaki, K. Imai, S. Ishiuchi, J.-i. Yoshida *Angew. Chem. Int. Ed.* **2015**, *54*, 1914–1918.
- (3) (a) H. Seo, M. H. Katcher, T. F. Jamison *Nat. Chem.* **2017**, *9*, 453–456. (b) S. Mascia, P. L. Heider, H. Zhang, R. Lakerveld, B. Benyahia, P. I. Barton, R. D. Braatz, C. L. Cooney, J. M. B. Evans, T. F. Jamison, K. F. Jensen, A. S. Meyerson, B. L. Trout *Angew. Chem. Int. Ed.* **2013**, *2*, 12359–12363.
- (4) (a) M. Teci, M. Tilley, M. A. McGuire, M. G. Organ *Org. Process Res. Dev.* **2016**, *20*, 1967–1973. (b) M. Teci, M. Tilley, M. A. McGuire, M. G. Organ *Chem. Eur. J.* **2016**, *22*, 17407–17415.
- (5) (a) D. Ghislieri, K. Gilmore, P. H. Seeberger *Angew. Chem. Int. Ed.* **2015**, *54*, 678–682. (b) T. N. Glasnov, C. O. Kappe *J. Heterocycl. Chem.* **2011**, *48*, 11–30.

Matteo Zanda

Exploring the Performance of Nanostructured Reagents with Organic-Group-Defined Morphology in Cross-Coupling Reaction

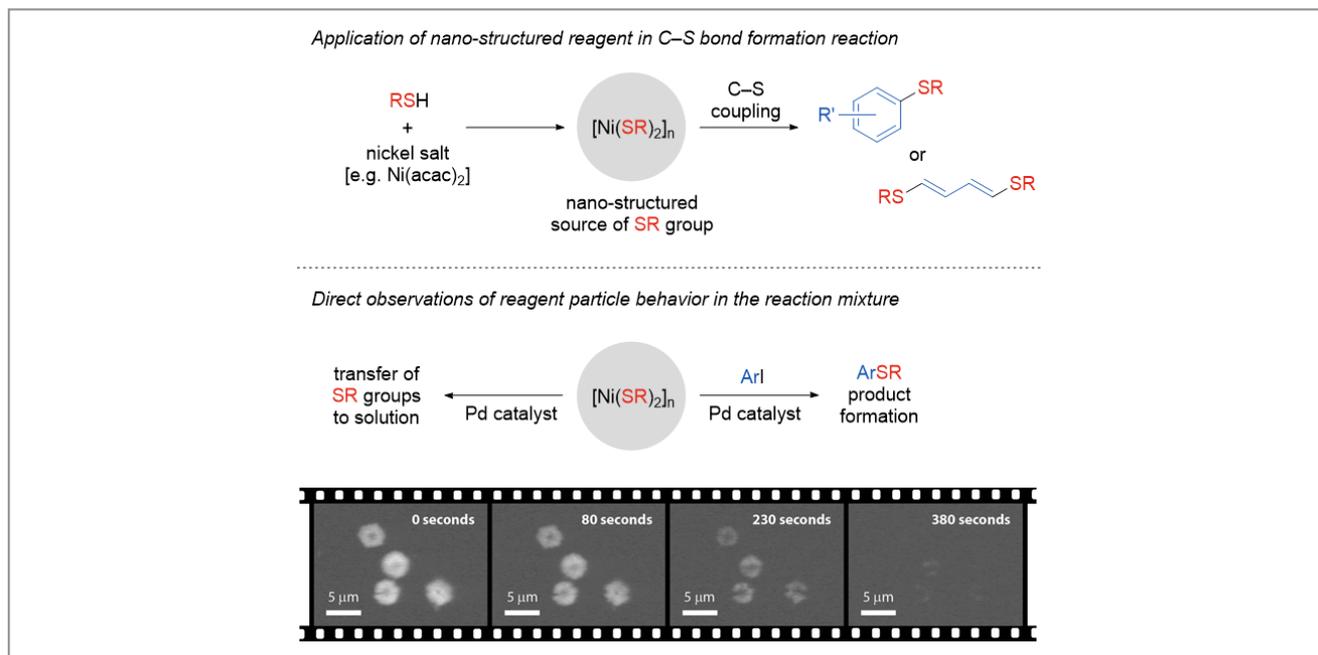
Nat. Commun. **2018**, *9*, 2936

During recent decades tight bonds have arisen between various fields of chemistry, physics and other natural sciences and have pushed forward complex multidisciplinary approaches for solving many scientific problems. The group of Professor Valentine P. Ananikov at the Russian Academy of Science (Russian Federation) has striven to extend the tools, methods and, in general, the paradigm of nano-science to the classical synthetic organic chemistry. “The main idea was to use nano-structured reagents for the synthesis of typical small organic molecules in order to reveal the possibility of tuning the reactant properties at the micro- and nano-levels,” explained Professor Ananikov.

The transition-metal-catalyzed C–S cross-coupling reaction was chosen as a proof of principle of their hypothesis. “From the practical point of view, this reaction is of particular importance because it allows the synthesis of organic sulfides to be carried out under mild conditions with a broad scope of substrates,” said Professor Ananikov. Nickel thiolate coordina-

tion polymer $[\text{Ni}(\text{SR})_2]_n$ was chosen as a candidate for unveiling the role of nano-structured reagents. “The wide range of thiolate morphologies can be generated in the simple reaction between nickel salt ($\text{Ni}(\text{acac})_2$, for example) and various thiols (RSH),” added Professor Ananikov, who continued: “Nickel thiolates had already demonstrated excellent performance as nano-catalysts in the transfer of SR groups to unsaturated carbon–carbon bonds. Thus, we decided to use nickel thiolate as a source of SR groups for the cross-coupling with organo-halides (Figure 1).”

The nano-nature of the reagent gave the group one more outstanding opportunity – the direct observation of the reaction progress with electron microscopy. “In situ electron microscopy studies, including challenging observations in the liquid phase, are currently at the forefront of materials science and energy research; however, applications for organic reactions are still limited,” explained Professor Ananikov. As further discussed by co-author of the paper, Dr. Kashin: “Elec-

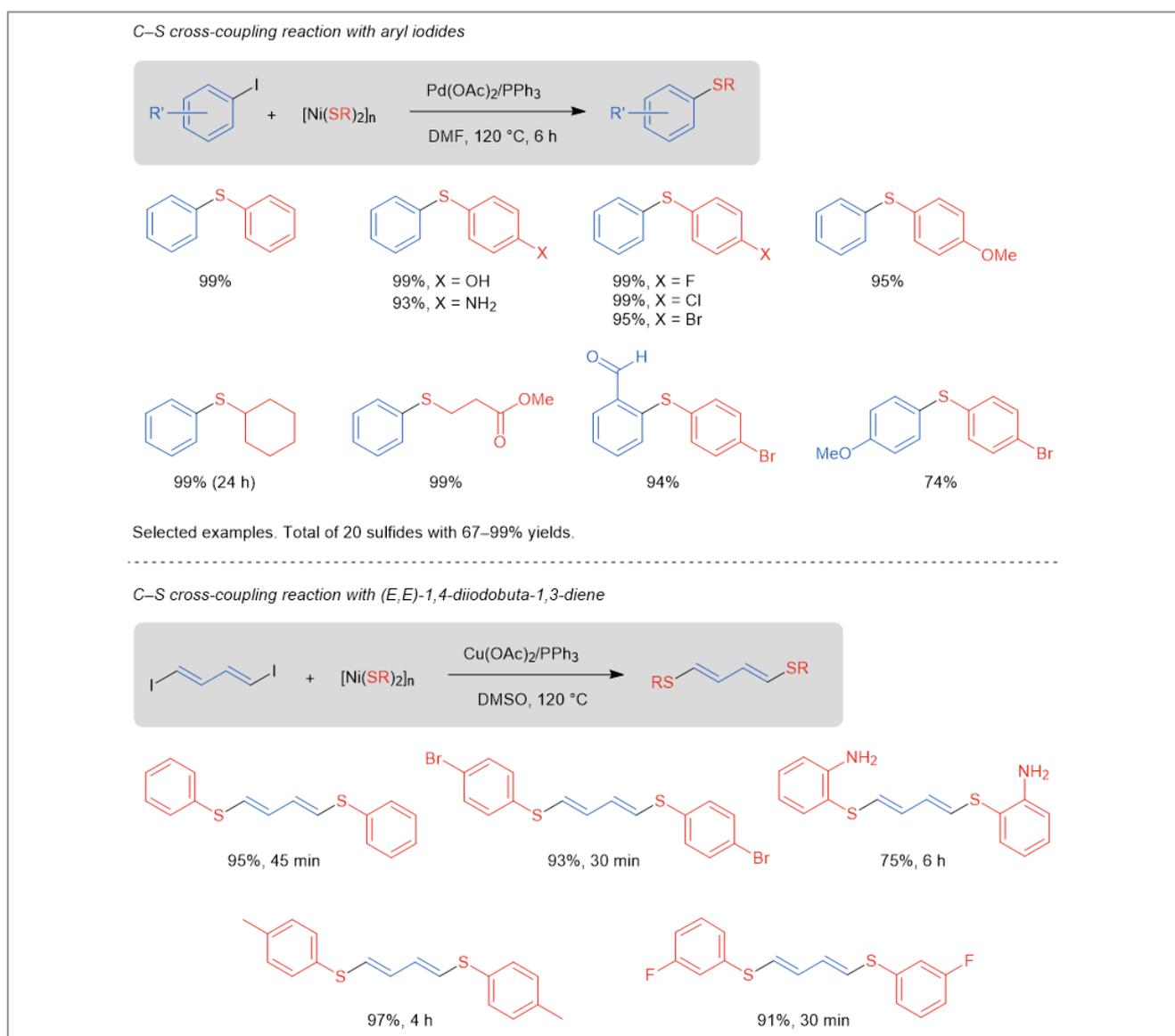


Scheme 1 Top: New synthetic approach for C–S cross-coupling based on nano-structured reagent. Bottom: Electron microscopy observations of the reaction progress.

tron microscopy allowed us to observe evolution of the particles during the chemical reaction (Scheme 1). A combination of microscopy with molecular-level mass spectrometry observations and kinetic measurements allowed us to establish the mechanism of the reaction and reveal the impact of nano-level properties of the reactant on its performance. The leading role of the interface processes and the strong correlation between reaction rate and reagent particle morphology were demonstrated.”

Synthesis of sulfides from nickel thiolates and various organohalides was performed under catalytic conditions with

the use of metal acetate (palladium or copper) pre-catalyst in combination with PPh_3 ligand. “A palladium-based catalytic system allowed us to carry out the coupling of aryl iodides with nickel thiolates, resulting in the formation of aryl sulfides with yields up to 99% (Scheme 2),” remarked Dr. Kashin. He continued: “The reaction tolerated a wide range of functional groups. In addition, we showed the way to access sulfur-containing dienes. In this case, (*E,E*)-1,4-diiodobuta-1,3-diene was synthesized according to the procedure designed previously in our laboratory and was used as a substrate. Due to its high reactivity, it was possible to employ a cheaper copper



Scheme 2 Scope of the C–S cross-coupling reaction with the use of nano-structured reagents.

catalyst and obtain the corresponding dienes in high yields (Scheme 2)."

"Obviously, the current work is substantially a proof of concept," said Professor Ananikov. "We hope that our findings will give rise to studies at the border between nano-chemistry and classical organic synthesis and will encourage researchers to use electron microscopy in the studies of organic reaction mechanisms."

He concluded: "As demonstrated in the present study, video monitoring is especially powerful for observing nano-scale and micro-scale processes during catalytic synthesis. We anticipate that recording videos of chemical transformations will become a widespread tool for investigating organic reactions in the near future."

About the authors



The team that worked on the project. From left to right: Prof. Valentine P. Ananikov, Dr. Alexey S. Kashin, Dr. Evgeniya S. Degtyareva, Mr. Dmitry B. Eremin.

Alexey S. Kashin graduated from Higher Chemical College of the Russian Academy of Sciences (Russian Federation) with an MSc degree (chemistry) in 2011. Since 2009, he has been working at Zelinsky Institute of Organic Chemistry (Russian Federation), where he received his PhD degree (organic chemistry) in 2014 and took up a senior researcher position in 2017. His research interests are focused on transition-metal catalysis, in situ mechanistic studies, electron microscopy and X-ray spectroscopy.

Evgeniya S. Degtyareva graduated from Platov South Russian State Polytechnic University (NPI, Russian Federation) in 2012 with an MSc degree and moved to Zelinsky Institute of Organic Chemistry (Russian Federation) for her PhD studies. She received her PhD degree (organic chemistry) in 2017 and took up a researcher position in 2018. Her research interests are focused on organosulfur chemistry, transition-metal catalysis and utilization of fossil resources in fine organic synthesis.

Dmitry B. Eremin received his summa cum laude in chemistry from Lomonosov Moscow State University (Russian Federation) in 2014 and moved to Zelinsky Institute of Organic Chemistry (Russian Federation) for his graduate studies under the supervision of Prof. Dr. Valentine P. Ananikov. Currently, he is a fourth-year graduate student, working on mechanistic insights into catalytic reactions. His research interests are focused on mass spectrometry, organometallic chemistry and in situ spectroscopic studies.

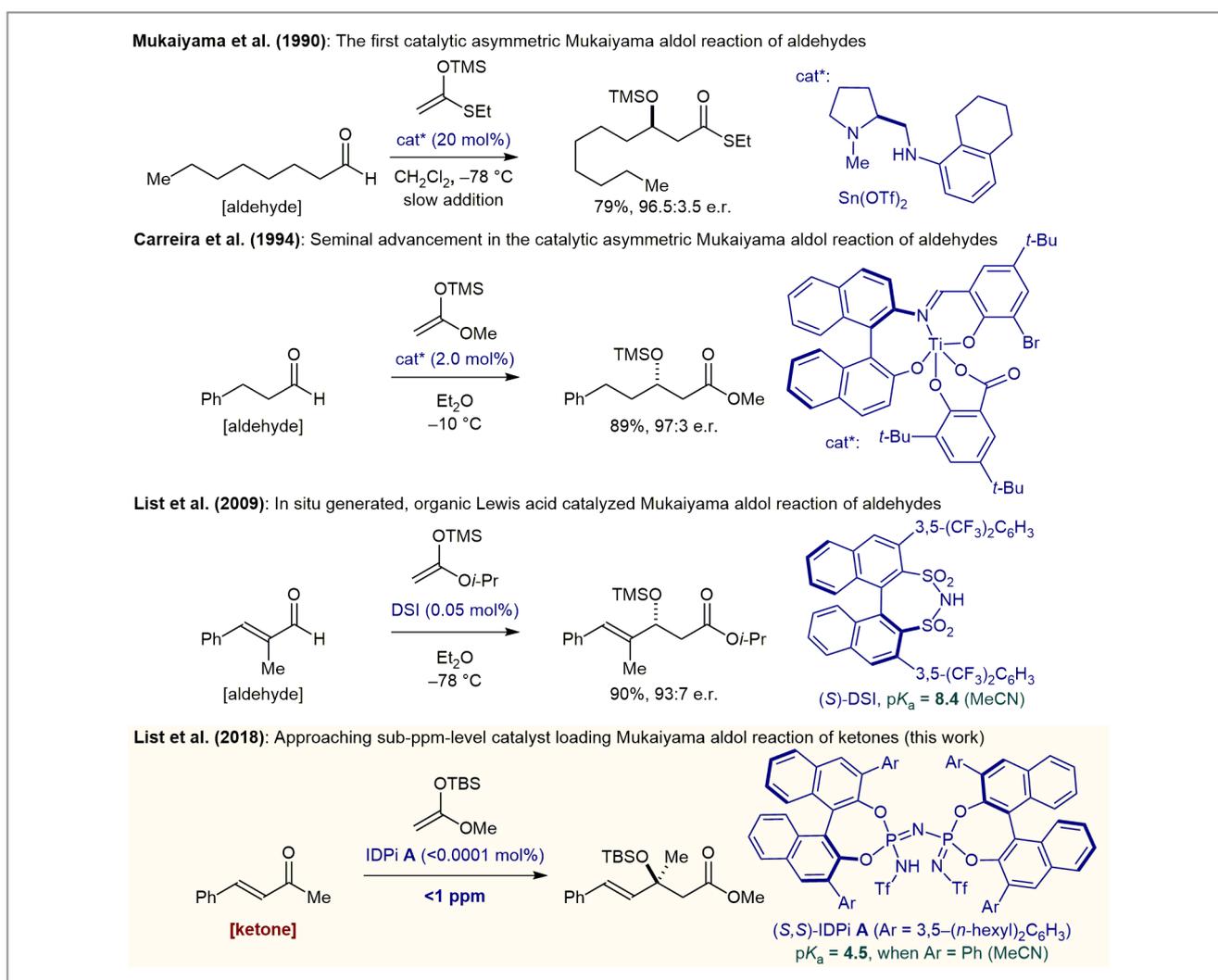
Valentine Ananikov received his Ph.D. in 1999, his Habilitation in 2003, and in 2005 he became Professor and Laboratory Head of the Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences (Russian Federation). In 2008 he was elected a Member of the Russian Academy of Sciences. His research has been supported by grants of the President of Russia for young scientists (2004, 2007). He is recipient of the Russian State Prize for Outstanding Achievements in Science and Technology (2004), an Award of the Science Support Foundation (2005), a Medal of the Russian Academy of Sciences (2000), the Liebig Lectureship from the German Chemical Society (2010), and the Balandin Prize for Outstanding Achievements in Catalysis (2010). In addition, he has been named Actively Cited Researcher – Russia by Thomson Reuters (2015), recipient of the Organometallics Distinguished Author Award Lectureship by the American Chemical Society (2016), and of the Hitachi High-Technologies Award in Appreciation for Novel Approaches and Outstanding Contributions to Setting New Standards for Electron Microscopy Applications in Chemistry (2016). His scientific interests are focused on catalysis, organic synthesis, molecular complexity and transformations.

Approaching Sub-ppm-Level Asymmetric Organocatalysis of a Highly Challenging and Scalable Carbon–Carbon Bond-Forming Reaction

Nat. Chem. **2018**, *10*, 888–894

The Mukaiyama aldol reaction of silyl ketene acetals as pre-formed enolates with carbonyl compounds is a widely applied carbon–carbon bond-forming reaction. “Since Mukaiyama’s initial report on the non-enantioselective aldol reaction of ketone-derived silyl enol ethers with aldehydes in 1973,¹

significant advances of this powerful synthetic tool have been made during the past 45 years,” said Professor Ben List at the Max-Planck-Institut für Kohlenforschung (Germany), who explained that the first catalytic enantioselective version, using silyl ketene thioacetal in the presence of a chiral tin(IV)



Scheme 1 Representative examples of catalytic asymmetric Mukaiyama aldol reactions of silyl ketene (thio)acetals. cat* = chiral catalyst.

complex (20 mol%) was also reported by the same group (Scheme 1, first row).^{2a} “A powerful catalytic system based on titanium(IV), a tridentate Schiff base ligand, and di-*tert*-butylsalicylic acid (2 mol%) was developed by Carreira and co-workers^{2b} and proved to be highly active and enantioselective (Scheme 1, second row),” added Professor List. He also pointed out that despite numerous well-established methods using aldehydes,^{2c} the utilization of ketones as acceptors to afford chiral tertiary β -hydroxy esters is still challenging in terms of substrate scope, enantioselectivity, and scalability (for known catalytic examples, see: Denmark et al.^{3a} using 10 mol% of a chiral bis-*N*-oxide Lewis base; Shibasaki et al.^{3b} using 4 mol% of a chiral copper(I) fluoride–phosphine complex and stoichiometric additives).

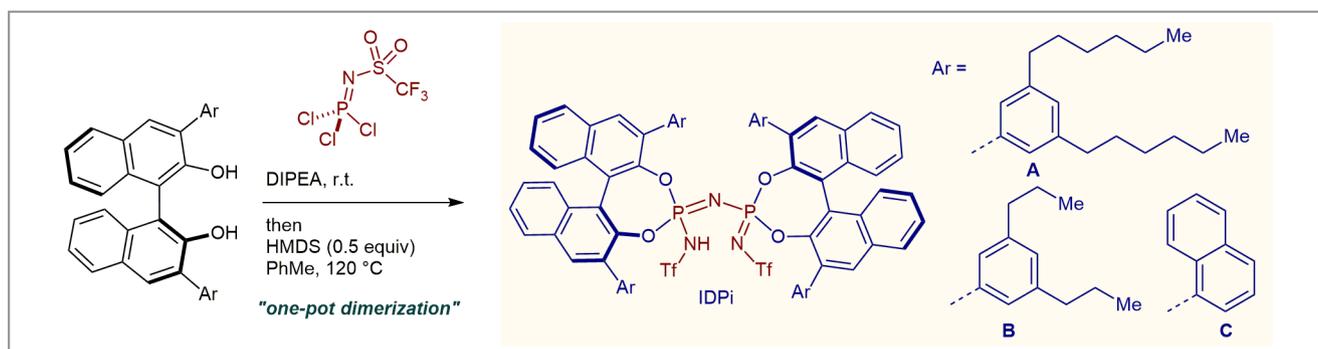
Recently, Professor List's group reported a new class of chiral organocatalysts, which enable the challenging enantioselective Mukaiyama aldol reaction of ketones in the presence of extremely low catalyst loading (Scheme 1, fourth row). In their article, the newly developed highly acidic ($pK_a = 4.5$ in acetonitrile) imidodiphosphorimidate (IDPi)⁴ compounds were employed as potent catalysts for the Mukaiyama aldol reaction of commercially available silyl ketene acetals with ketones. “Previously developed chiral disulfonimides⁵ (DSI, $pK_a = 8.4$ in acetonitrile), which proved to be efficient catalysts of the Mukaiyama aldol reaction of aldehydes, failed to achieve the desired transformation (Scheme 1, third row),” explained Professor List.

“The preparation of our IDPi catalysts is simple. A one-pot condensating dimerization of readily accessible 3,3'-disubstituted binols in the presence of [(trifluoromethyl)sulfonyl]phosphorimidoyl trichloride and hexamethyldisilazane provides the catalysts. In our laboratory, we have set up a convenient and routine synthesis protocol, which enables the facile preparation of structurally diverse IDPi catalysts,” Professor List emphasized (Scheme 2).

The scope of the developed method is extensive, as presented in the original paper, and summarized by a few selected examples shown in Scheme 3a. “Besides (hetero)aryl-alkyl ketones, alkyl-alkyl ketones were also converted with good to excellent enantiomeric ratios (e.r.). An alkynyl ketone also gave an excellent e.r. Interestingly, benzylideneacetone-type α,β -unsaturated ketones were highly reactive and generally gave good 1,2- versus 1,4-regioselectivity ($\sim 10:1$) and excellent enantioselectivity. In particular, loadings of 2.8–500 ppm (0.00028–0.05 mol%) with the IDPi catalysts **A**, **B** or **C** proved to be sufficient to provide the desired enantioenriched products, even on a preparative scale (grams to decagrams),” explained Professor List.

“Interestingly, in sharp contrast to the formidable catalytic activity of the IDPi catalysts, our DSIs unexpectedly led to a completely different outcome under identical reaction conditions,” said Dr. Han Yong Bae. He continued: “In the case of using 2-acetonaphthone as the starting material, instead of the desired tertiary aldol product, quantitative silyl-deprotonation of the ketone was observed (Scheme 3b, top). In the case of benzylideneacetone, both transfer-silylation and 1,2-/1,4-reactions competitively occurred (Scheme 3b, bottom).”

“The significance of this method was further demonstrated by conducting large-scale, extremely low catalyst loading experiments. We could readily reduce the catalyst loading to a ppm level, ultimately even approaching parts-per-billion (ppb) levels. This surprisingly high reactivity can probably be attributed to the extreme Lewis acidity of the in situ generated silylium ion Lewis pair, which is formed in a reaction of the IDPi catalyst with the silyl ketene acetal. While the reactions under these extreme conditions require purified reagents and rather long reaction times, to our knowledge, the catalyst loadings reported are unprecedented in asymmetric carbon–carbon bond-forming reactions,” added Professor List.

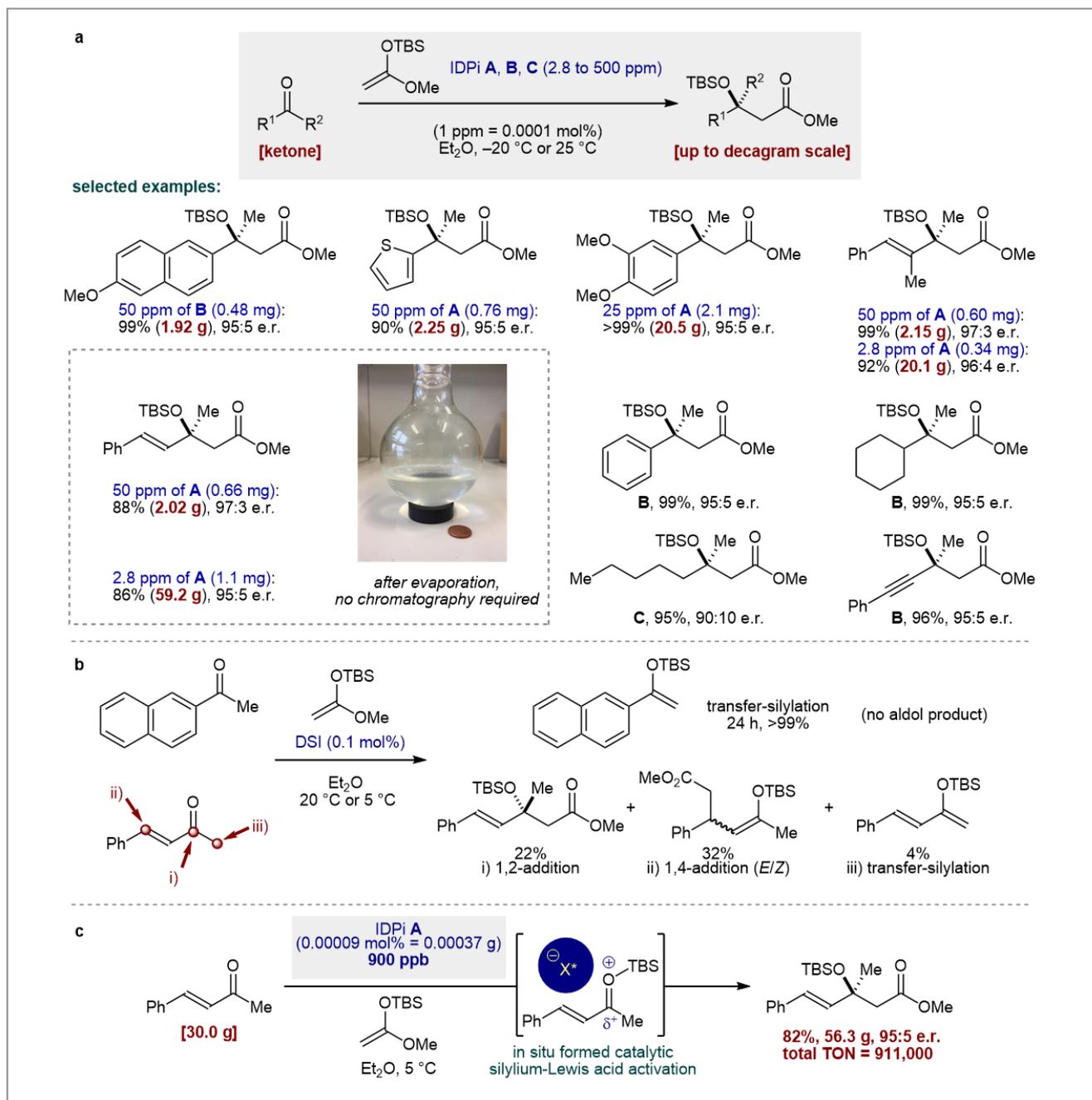


Scheme 2 Preparation of representative chiral IDPi **A**, **B**, and **C** catalysts used in this study.

He concluded: "The developed method is operationally simple, scalable, and the obtained products are highly valuable and can be readily derivatized. Generally, only ppm level loadings of the catalyst, in one case even less than 1 ppm, is required. We think that our discovery represents a major mile-

stone, not only in the field of organocatalysis but in chemical synthesis as a whole."

Matthew Fenske



Scheme 3 IDPi-catalyzed Mukaiyama aldol reactions of ketones. a) Substrate scope. b) Results of using DSI as catalyst instead of IDPis. c) Experiment of approaching ppb-level (0.00009 mol%) catalyst loading.

REFERENCES

- (1) T. Mukaiyama, K. Narasaka, K. Banno *Chem. Lett.* **1973**, *2*, 1011–1014.
- (2) (a) S. Kobayashi, M. Furuya, A. Ohtsubo, T. Mukaiyama *Tetrahedron: Asymmetry* **1991**, *2*, 635–638. (b) E. M. Carreira, R. A. Singer, W. Lee, *J. Am. Chem. Soc.* **1994**, *116*, 8837–8838.
- (c) For a recent comprehensive book, see: *Modern Methods in Stereoselective Aldol Reactions*; R. Mahrwald, Ed.; Wiley-VCH: Weinheim, **2013**.

- (3) (a) S. E. Denmark, Y. Fan *J. Am. Chem. Soc.* **2002**, *124*, 4233–4235. (b) K. Oisaki, D. Zhao, M. Kanai, M. Shibasaki *J. Am. Chem. Soc.* **2006**, *128*, 7164–7165.
- (4) P. S. J. Kaib, L. Schreyer, S. Lee, R. Properzi, B. List *Angew. Chem. Int. Ed.* **2016**, *55*, 13200–13203.
- (5) P. García-García, F. Lay, P. García-García, C. Rabalakos, B. List *Angew. Chem. Int. Ed.* **2009**, *48*, 4363–4366.

About the authors



Dr. H. Y. Bae

Han Yong Bae was born in Daegu, Republic of Korea (1983). He received his B.Sc. (2010) and Ph.D. (2015) degrees from Sungkyunkwan University (SKKU, Korea), conducting studies on biomimetic Brønsted base catalyzed asymmetric catalysis under the supervision of Professor Choong Eui Song. During his graduate studies, Han Yong developed a polyketide biosynthesis mimic, the first organocatalytic decarboxylative aldol reaction

of malonic acid half-thioester with aldehyde in collaboration with Professor Benjamin List's laboratory. He then moved to Germany and is currently pursuing postdoctoral research with Professor List at the Max-Planck-Institut für Kohlenforschung. His research mainly focuses on the development of new methodologies for challenging organic Lewis acid catalyzed asymmetric reactions and, ultimately, finding useful applications of the developed methods. He has received prizes such as the Global Ph.D. Fellowship (2012, Ministry of Education of Korea), the DOW Chemical Scholarship (2015), the Chancellor's Award/Valedictorian (2015, SKKU), the Award for Best Ph.D. Thesis (2015, Korean Chemical Society), and a RESOLV Post-doctoral Fellowship (2016, German Research Foundation).



Professor B. List

Benjamin List was born in 1968 in Frankfurt, Germany. He graduated from Freie University Berlin (Germany) in 1993 and received his Ph.D. (1997) from the University of Frankfurt. After postdoctoral studies (1997–1998) as a Feodor Lynen Fellow of the Alexander von Humboldt foundation at The Scripps Research Institute (USA), he became a Tenure Track Assistant Professor there in January 1999. Subsequently, he developed the first proline-catalyzed asymmetric intermolecular aldol-, Mannich-, Michael-, and α -Amination reactions. In 2003 he moved to the Max-Planck-Institut für Kohlenforschung (Germany), where he has been a director since 2005. From 2012 until 2014 he was the managing director of the institute. Since 2004 he also serves as an honorary professor at the University of Cologne (Germany). His research interests are new catalysis concepts and chemical synthesis in general. He has pioneered and contributed several concepts including aminocatalysis, enamine catalysis, and asymmetric counteranion-directed catalysis (ACDC). His accomplishments have been recognized by several awards including the Otto Bayer Prize (2012), the Mukaiyama Award (2013), the Cope-Scholar Award (2014), the Gottfried Wilhelm Leibniz Prize (2016), and admission as a member of the German National Academy of Sciences Leopoldina (2018).

of malonic acid half-thioester with aldehyde in collaboration with Professor Benjamin List's laboratory. He then moved to Germany and is currently pursuing postdoctoral research with Professor List at the Max-Planck-Institut für Kohlenforschung. His research mainly focuses on the development of new methodologies for challenging organic Lewis acid catalyzed asymmetric reactions and, ultimately, finding useful applications of the developed methods. He has received prizes such as the Global Ph.D. Fellowship (2012, Ministry of Education of Korea), the DOW Chemical Scholarship (2015), the Chancellor's Award/Valedictorian (2015, SKKU), the Award for Best Ph.D. Thesis (2015, Korean Chemical Society), and a RESOLV Post-doctoral Fellowship (2016, German Research Foundation).

Acceptorless Dehydrogenative Coupling Using Ammonia: Direct Synthesis of N-Heteroaromatics from Diols Catalyzed by Ruthenium

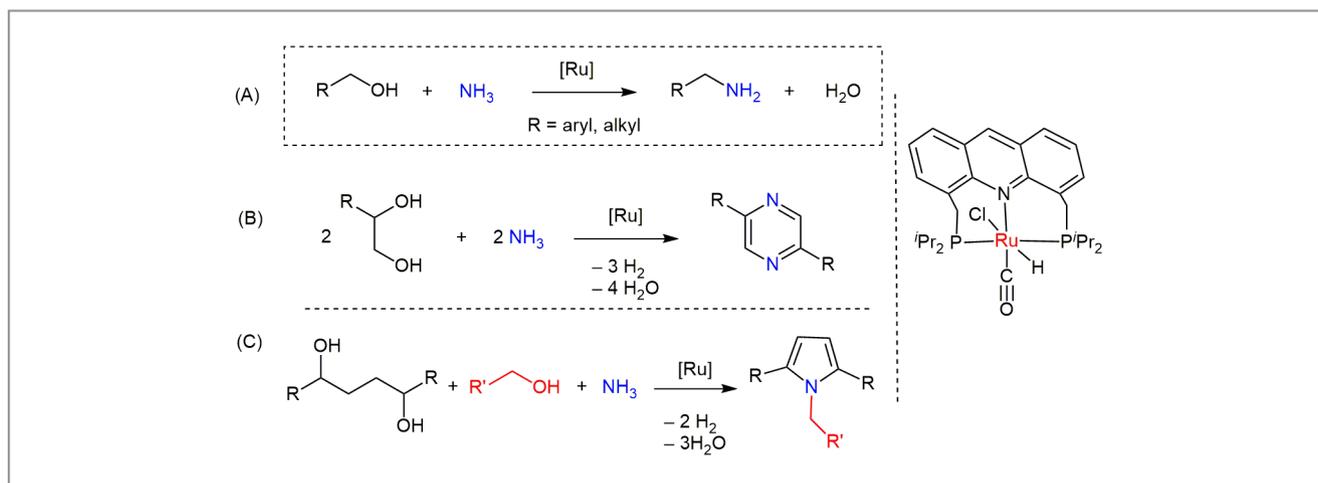
J. Am. Chem. Soc. **2018**, *140*, 11931–11934

Acceptorless dehydrogenative coupling (ADC) reactions involve dehydrogenation, with generation of hydrogen gas, of various substrates, followed by coupling of the dehydrogenated intermediate with another substrate to form a value-added product. Many of these reactions form the basis for efficient, sustainable and environmentally benign ('green') synthetic methodologies.

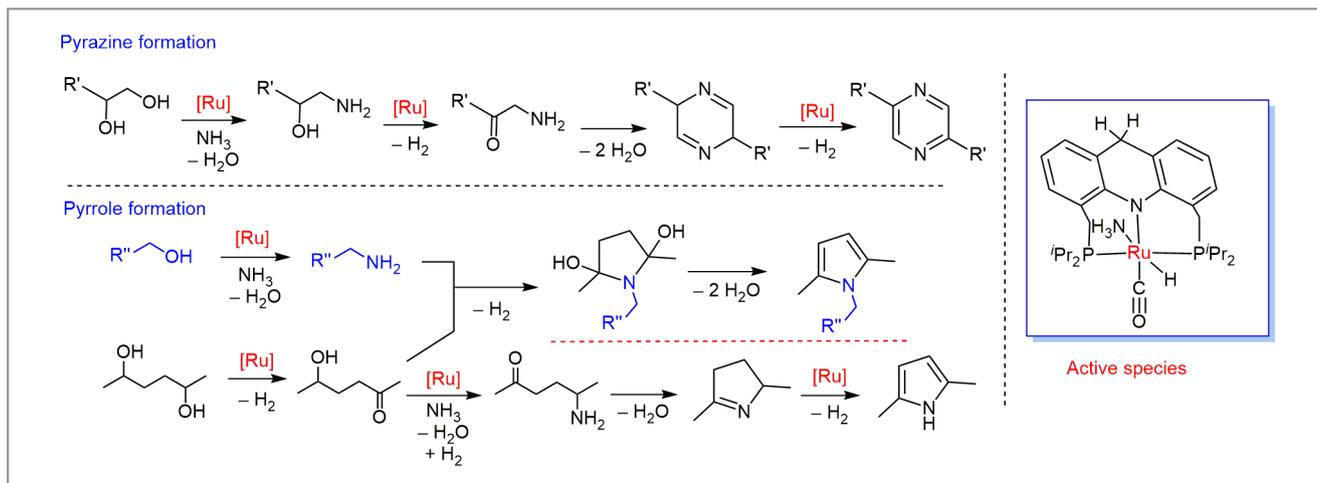
The group of Professor David Milstein at the Weizman Institute of Science (Rehovot, Israel) focuses on the design and development of ADC reactions for green organic transformations catalyzed by special pincer-based metal complexes. These complexes can activate chemical bonds by metal–ligand cooperation, in which both the metal and the ligand attached to it undergo bond-making and bond-breaking. The development of practical, green, and atom-economical processes for the synthesis of value-added products using cheaper, greener and sustainable methodologies is highly desirable. "Ammonia is the simplest, reactive molecule employed as a nitrogen source in the synthesis of organo-nitrogen compounds," said Prof. Milstein, continuing: "However, the direct use of ammonia in acceptorless dehydrogenative coupling reactions is challenging, due to several issues; ammonia is an excellent ligand for many metals and can coordinatively saturate the metal complex catalyst, retarding binding of the organic reac-

tant. Also, ADC reactions are often driven by the efficient removal of the generated H₂ using an open system, which poses an obvious problem when ammonia gas has to be used under pressure."

In 2008, the direct homogeneous catalytic selective amination of primary alcohols to form primary amines using ammonia, catalyzed by an acridine-based Ru pincer complex, was reported by the Milstein group (Scheme 1, A). This finding, along with the subsequent discoveries of more catalysts, has established this particular reaction as a valuable synthetic method. Professor Milstein added: "However, we wanted to see if it was possible to synthesize N-heteroaromatic molecules by direct use of ammonia as the only nitrogen source in a dehydrogenative coupling reaction." Indeed, using diols, this goal was accomplished: several pyrazine derivatives were efficiently and selectively synthesized from 1,2-diols and ammonia (Scheme 1, B). Moreover, N-substituted pyrroles were synthesized by a three-component reaction involving the dehydrogenative coupling of 1,4-diols with primary alcohols and ammonia (Scheme 1, C). "In both reactions, gaseous ammonia is the source of nitrogen, and the catalyst is an acridine-based ruthenium pincer complex, with no additives, such as base or oxidant, being required," explained Professor Milstein. He continued: "Analysis of the gas phase of both reactions by



Scheme 1 Acceptorless dehydrogenative coupling reactions using ammonia



Scheme 2 Proposed mechanism for N-heteroaromatic compound formation from diols and ammonia

gas chromatography shows formation of H_2 . It was observed that linear primary alcohols such as 1-hexanol and 1-pentanol are more efficient than benzyl alcohol derivatives in the synthesis of the N-substituted pyrroles. Mechanistically, it is proposed that both reactions involve a sequence of alcohol amination, alcohol dehydrogenation, and keto-amine condensation, yielding the N-heteroaromatic product (Scheme 2). The acridine-based PNP-pincer ligand plays a vital role in these transformations, generating the active complex bearing an anionic dearomatized PNP-pincer ligand framework.”

Professor Milstein concluded: “We believe that these discoveries provide a new approach towards the green synthesis of heteroaromatics in one step via acceptorless dehydrogenative coupling by direct use of ammonia. In addition, we would like to expand the direct use of ammonia to other transformations involving dehydrogenative coupling reactions.”

Mattias Sundberg

About the authors



Dr. P. Daw

Prosenjit Daw obtained his B.Sc. in chemistry from the University of Calcutta (India). He completed his M.Sc. and Ph.D. at the Indian Institute of Technology Kanpur (IIT Kanpur, India) where he worked on N-heterocyclic carbene based organometallic catalysts and their application in organic transformations in the group of Prof. Jitendra K. Bera under a Shyama Prasad Mukherjee Fellowship (SPMF). After completing his Ph.D. he moved

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Dr. Y. Ben-David

Yehoshua Ben-David obtained his B.Sc. in chemistry and botany from the University of Khartoum (Sudan) in 1967. In the same year he moved to Israel and joined the Department of Organic Chemistry in the Weizmann Institute of Science as a research assistant. He worked with many senior scientists at that time in the same department. In 1988 he joined Prof. David Milstein's group as a research assistant and he has been there since.

After his retirement in 2010, he returned as a part-time research assistant in the same group.



Prof. D. Milstein

David Milstein is the Israel Matz Professorial Chair of Organic Chemistry at the Weizmann Institute of Science (Israel). He received his Ph.D. at the Hebrew University (Israel) in 1976 with Prof. Blum, and performed post-doctoral research at Colorado State University (USA) with Prof. Stille. In 1979 he joined DuPont Company's Central Research & Development Department in Wilmington (Delaware, USA) as a Group Leader, and in 1986

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