



Cite this: *Org. Biomol. Chem.*, 2016, **14**, 5417

Received 15th January 2016,  
Accepted 23rd February 2016

DOI: 10.1039/c6ob00126b

www.rsc.org/obc

## Selective chemical labeling of proteins

Xi Chen<sup>a,b</sup> and Yao-Wen Wu<sup>\*a,b</sup>

Over the years, there have been remarkable efforts in the development of selective protein labeling strategies. In this review, we deliver a comprehensive overview of the currently available bioorthogonal and chemoselective reactions. The ability to introduce bioorthogonal handles to proteins is essential to carry out bioorthogonal reactions for protein labeling in living systems. We therefore summarize the techniques that allow for site-specific "installation" of bioorthogonal handles into proteins. We also highlight the biological applications that have been achieved by selective chemical labeling of proteins.

### 1. Introduction

Selective chemical labeling of proteins is highly useful for probing and controlling protein functions *in vitro* and in living systems.<sup>1–10</sup> Since proteins carry many copies of different functional groups, it is demanding to selectively label a protein at a defined site. Additionally, the labeling conditions have to be mild and reactions should be able to undergo in aqueous solution. Moreover, the labeling reagents should also be orthogonal

to other functionalities in living systems when a protein is to be labeled *in vivo*.<sup>11,12</sup> These restrictions make it really challenging to label proteins in a chemoselective and site-specific manner.

Recent years have seen tremendous progress in chemical protein labeling. There are already some excellent reviews on bioorthogonal reactions and selective chemical labeling of proteins.<sup>2–4,6,12–18</sup> In this review, we compare the features of reported bioorthogonal reactions and chemical tagging approaches, *e.g.* the reaction rate or time, reaction conditions, reagents, *etc.* This could be helpful to identify the most suitable labeling reaction for a particular application. Moreover, we highlight the applications of established chemical labeling techniques to tackle biological problems.

<sup>a</sup>Chemical Genomics Centre of the Max Planck Society, Otto-Hahn-Str. 15, 44227 Dortmund, Germany

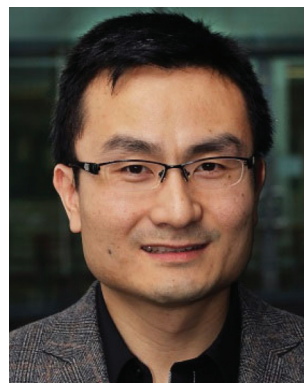
<sup>b</sup>Max-Planck Institute for Molecular Physiology, Otto-Hahn-Str. 11, 44227 Dortmund, Germany. E-mail: yaowen.wu@mpi-dortmund.mpg.de



Xi Chen

Dr. Xi Chen was born in Sicuan, China in 1986. He received his MSc in Chemistry at the National University of Singapore and PhD degree (2012) in Protein Chemistry at Ulm University. Since 2012, he conducted his postdoctoral research under the supervision of Dr. Yao-Wen Wu at the Max-Planck Institute for Molecular Physiology and the Chemical Genomics Centre of the Max-Planck Society. His research focuses on chemical

protein labeling and the development of photochemical approaches for controlling protein function in live cells.



Yao-Wen Wu

Dr. Yao-Wen Wu was born in Jiangxi, China in 1980. He received his BSc in Chemistry from Sun Yat-sen University in 2001 and his MSc in Organic Chemistry from Tsinghua University in 2004. After obtaining Dr rer. nat. (summa cum laude) in 2008 at TU Dortmund working at the Max Planck Institute of Molecular Physiology in Dortmund, he then conducted his postdoctoral research in cell biology at King's College

London. Since 2010 he has been leader of an Otto Hahn group at the Max Planck Institute in Dortmund. Since 2012 he has been group leader of the Chemical Genomics Centre of the Max Planck Society. His research interests include molecular mechanism of membrane trafficking and autophagy, protein chemical modification, chemical probes for visualizing cellular events, chemical and optogenetics.



## 2. The toolbox of bioorthogonal chemistry for protein labeling

Bioorthogonal reactions are robust and invaluable tools for chemical protein labeling.<sup>4,6</sup> Typically, selective protein labeling is accomplished by incorporation of bioorthogonal groups into a protein, followed by chemoselective modifications.<sup>18</sup> This approach is also designated as “tag-and-modify”.<sup>19</sup> A variety of bioorthogonal reactions have been developed, which can be classified into: (1) condensation reactions through carbonyls, (2) “click” reactions through azides, (3) inverse electron-demand Diels–Alder cycloadditions (DA<sub>INV</sub>) and other cycloaddition reactions, (4) transition metal-catalyzed coupling and decaging reactions, and (5) labeling reactions at cysteine residues (Table 1). In parallel, many elegant approaches have been established to selectively equip proteins with bioorthogonal handles (discussed in later sections), fulfilling the requirements for the subsequent bioorthogonal modification.

### 2.1. Condensation through carbonyls

Ketones and aldehydes can react with hydroxylamine and hydrazide compounds under aqueous conditions to form stable oxime and hydrazone linkages, respectively. Oxime ligation<sup>76</sup> is slow under neutral pH conditions and therefore an aniline catalyst is required.<sup>20</sup> Recently, an improved catalyst *p*-phenylenediamine (*p*-PDA) was reported, which displays a higher water solubility and a better catalytic efficacy (10–120 times faster) than aniline.<sup>21</sup> With respect to the condensation using hydrazide (hydrazone ligation), electronic and acid/base effects strongly influence the reaction efficiency at pH 7.4. For instance, carbonyl compounds with neighboring acid/base groups (*e.g.* carboxylate) form hydrazones at accelerated rates of up to 2–20 M<sup>−1</sup> s<sup>−1</sup>.<sup>77</sup> In addition, in the presence of a 5-methoxyanthranilic acid (5MA) catalyst, the condensation rate can be substantially enhanced 84-fold (6.6 M<sup>−1</sup> s<sup>−1</sup>, 1 mM 5MA) compared to the reaction without a catalyst (0.08 M<sup>−1</sup> s<sup>−1</sup>) at pH 6.5 (Table 1A).<sup>22</sup>

Aside from oxime ligation and hydrazone ligation, aldehydes and ketones can undergo a Pictet–Spengler reaction with  $\beta$ -arylethylamines,<sup>78</sup> which has been used for protein labeling at the N-terminus.<sup>23</sup> To date, several modified versions have been introduced, including Pictet–Spengler ligation<sup>24</sup> and hydrazino-Pictet–Spengler ligation.<sup>25</sup> Additionally, proteins engineered with an N-terminal aldehyde tag can be labeled *via* the Mukaiyama–Adol condensation using silyl ketene reagents with the formation of a stable C–C bond.<sup>28</sup> KAHA ( $\alpha$ -ketoacid-hydroxylamine) ligation allows the condensation between an  $\alpha$ -ketoacid and hydroxylamine or 5-oxaproline to form a native amide bond. This ligation has been a valuable alternative to native chemical ligation (NCL)<sup>73</sup> to join two unprotected peptide fragments in peptide synthesis.<sup>29,30</sup> Owing to the rapid association between aldehydes and amines, an aldehyde has been elegantly employed as an amine-capture auxiliary in aldehyde capture ligation (ACL). In ACL, a C-terminal selenobenzaldehyde ester can interact with the N-terminus of a peptide/protein. A native amide bond linkage is formed following a

Se→N acyl shift. The ACL has been used for site-specific N-terminal modification of ubiquitin (Table 1A).<sup>31</sup>

A recently introduced reaction is ABAO (2-aminobenzamidoxime) ligation. ABAO combines an aniline moiety for iminium-based activation of the aldehyde with a nucleophilic group at the *ortho*-position to the amine for intramolecular ring closure. In addition to the rapid condensation reaction kinetics (up to 40 M<sup>−1</sup> s<sup>−1</sup>), the condensation forms a fluorescent dihydroquinazoline derivative, making it possible to develop fluorogenic aldehyde-reactive probes.<sup>26</sup> Alkyl aldehydes can also efficiently couple with aryl diamines under mild conditions (RT, neutral aqueous solution) in the presence of Cu(II) or Zn(II) ions *via* an oxidative condensation process.<sup>27</sup> This reaction forms stable benzimidazole linkages and has been utilized to label the T4 lysozyme protein with an aldehyde dye (Table 1A).

With respect to labeling biomolecules in live cells or organisms, carbonyl compound-related condensations have not been widely used. This is because the catalysts are usually toxic, and endogenous ketones and aldehydes, *e.g.* glucose and pyruvate, would interfere with the labeling reaction. Nevertheless, ketones and aldehydes are generally not present on the cell surface. Therefore, carbonyls serve as useful chemical handles for labeling biomolecules on the cell surface using hydrazide or aminooxy probes.<sup>20,79–83</sup>

### 2.2. “Click” through azides

Azide is a small and stable group, which has a unique dipole for a variety of bioorthogonal reactions.<sup>84</sup> Click reactions using azides include Staudinger ligation,<sup>32</sup> traceless Staudinger ligation,<sup>33,34</sup> Staudinger-phosphite ligation,<sup>35</sup> copper-catalyzed azide alkyne cycloaddition (CuAAC),<sup>36</sup> strain-promoted azide alkyne cycloaddition (SPAAC) and oxanorbornadiene cycloaddition (Table 1B).<sup>38</sup> Among these reactions, CuAAC and SPAAC appear to be the most popular and are discussed in detail in this section.<sup>4</sup>

CuAAC is a hallmark of bioorthogonal chemistry that was reported independently by Sharpless<sup>36</sup> and Meldal<sup>85</sup> in 2002. Its application as a bioorthogonal reaction revolutionized our ability to modify and manipulate proteins.<sup>86,87</sup> CuAAC becomes popular mainly due to the following reasons: (1) the azide and alkyne groups are highly specific toward each other but remain inert to other chemically active molecules in live systems; (2) the reaction produces a regioselective 1,4-triazole product which is stable and inert; (3) CuAAC exhibits fast reaction kinetics ( $\sim 3$  M<sup>−1</sup> s<sup>−1</sup> in the presence of 50  $\mu$ M Cu(I) and 50  $\mu$ M TBTA)<sup>37</sup> and various ligands have been developed to stabilize Cu(I) and further increase the reaction speed.

Cu ions catalyze the production of reactive oxygen species, leading to cytotoxicity.<sup>88</sup> This limits the application of CuAAC in living systems. By choosing an appropriate ligand, CuAAC can be biocompatible with minimal cytotoxicity while showing an increased reaction rate.<sup>89</sup> A panel of these ligands is summarized in Scheme 1A. Copper-chelating azides bring the Cu(I) ion into close proximity and thereby significantly increase the reaction rate (Scheme 1B).<sup>90</sup> The ligand BTTP (3-[4-((bis[1-*tert*-butyl-1*H*-1,2,3-triazol-4-yl)methyl]amino)methyl)-1*H*-1,2,3-triazol-1-yl]propanol) stabilizes the Cu(I) ion while speeding up



Table 1 The toolbox of bioorthogonal chemistry and chemoselective reactions

| Reactant A                               | Reactant B  | Product | $k$ ( $M^{-1} s^{-1}$ ) or $t$   | Features  | Reference(s)  |
|--|-------------|---------|--|---|---|
| <b>A: Condensation through carbonyls</b> |             |         |  |   |   |
|  | $H_2N-O-R'$ |         | 0.006 (pH 7, RT)<br>0.29 (pH 7, RT, 10 mM <i>p</i> -PDA)<br>PBS (pH 6.5, RT)<br>0.0087, or 0.46 (1 mM 5MA)<br>18 h (pH 6.5, 37 °C) | <b>Oxime ligation:</b> <i>p</i> -phenylenediamine ( <i>p</i> -PDA) or aniline, <i>etc.</i> as a catalyst                    | Dirksen (2006) <sup>20</sup><br>Wendeler (2014) <sup>21</sup>     |
| (Carbonyls)                              |             |         |  | <b>Hydrazone ligation:</b> aniline or 5-methoxyanthranilic acid (5MA), <i>etc.</i> as a catalyst; ~85% yield in 5 h         | Crisalli (2013) <sup>22</sup>                                     |
|  |             |         |  | <b>Pictet-Spengler reaction:</b> formation of a stable C-C bond; suitable for N-terminal protein labeling                   | Sasaki (2008) <sup>23</sup>                                       |
|  |             |         | 10 (pD 4.5)<br>2 (pD 6)  | <b>Pictet-Spengler ligation:</b> ligation is faster under lower pH conditions; formation of a stable C-C bond               | Agarwal (2013) <sup>24</sup>                                      |
|  |             |         | 4.17 (pH 6)  | <b>Hydrazino-Pictet-Spengler ligation:</b> ligation proceeds fastest under pH 6; formation of a stable C-C bond             | Agarwal (2013) <sup>25</sup>                                      |
|  |             |         | 40 (pH 4.5)  | <b>ABAO ligation:</b> formation of a fluorescent dihydroquinazoline ( $\lambda_{max}$ 490 nm); quantitative labeling in 1 h | Kitov (2014) <sup>26</sup>  |
|  |             |         | 1.61 (pH 7.4, RT, 10 $\mu$ M $CuSO_4$ , air)   | Under air; requires Cu(II) or Zn(II) catalyst; quantitative labeling in 2 h   | Ji (2014) <sup>27</sup>   |
|  |             |         | 24 h (pH 7, RT)  | <b>Mukaiyama-Adol condensation:</b> 11–55% conversion; stable   | Alam (2010) <sup>28</sup>   |
|  |             |         | 4 h ( $\geq 10\%$ $H_2O$ in DMSO, 60 °C)   | <b>KAHA ligation:</b> formation of a native amide bond; 56–76% yield  | Bode (2006) <sup>29</sup><br>Pattabiraman (2012) <sup>30</sup>    |
|  |             |         | 1.65 (DMF, RT);<br>40 h [10% DMF in PBS (pH 7)]  | <b>ACL:</b> selective N-terminal protein labeling is possible at pH 7; ~70% labeling of ubiquitin                           | Raj (2015) <sup>31</sup>  |
| <b>B: Click reactions through azides</b> |             |         |  |   |   |
| $R-N=N=N$                                |             |         | 0.003 (PBS)  | <b>Staudinger-Bertozzi ligation:</b> phosphine is prone to oxidation  | Saxon (2000) <sup>32</sup>  |
|  |             |         | 0.0074 ( $H_2O$ )  | <b>Traceless Staudinger ligation:</b> needs transient protection of phosphine by $BH_3$ ; 80% yield at pH $\geq 7.5$        | Nilsson (2001) <sup>33</sup><br>Tam (2007) <sup>34</sup>          |
|  |             |         | 6–24 h ( $H_2O$ , RT)  | <b>Staudinger-phosphite ligation:</b> phosphite is stable against air oxidation; up to 90% yield                            | Serwa (2009) <sup>35</sup>  |
|  |             |         | $\sim 3$ [50 $\mu$ M Cu(I) + 50 $\mu$ M TBTA, DMSO : $H_2O$ 1 : 9]<br>up to 0.0024 ( $H_2O$ , 25 °C)                               | <b>CuAAC:</b> ligand for copper catalyst is required; up to 94% yield   | Rostovtsev (2002) <sup>36</sup><br>Presolski (2010) <sup>37</sup> |
|  |             |         | 0.0024–0.076   | <b>Oxanorbornadiene cycloaddition:</b> metal-free, but is slow  | van Berkel (2007) <sup>38</sup>                                   |
|  |             |         | 0.057–0.96   | <b>SPAAC:</b> cyclooctynes are susceptible to thiols  | Agard (2004) <sup>39</sup><br>Baskin (2007) <sup>40</sup>         |
|  |             |         | 0.29; 2–2.9 (with electron-deficient azide)  | <b>SPAAC:</b> cyclooctynes are lipophilic; nonspecifically stick to serum proteins and cellular membranes                   | Ning (2008) <sup>41</sup><br>Jewett (2010) <sup>42</sup>          |
|  |             |         |  | <b>SPAAC:</b> BCN is readily accessible; the reaction rate is accelerated using an electron-deficient azide                 | Dommerholt (2010/2014) <sup>43,44</sup>                           |



Table 1 (Contd.)

| Reactant A  | Reactant B | Product | $k$ ( $M^{-1} s^{-1}$ ) or $t$                         | Features   | Reference(s)   |
|---|------------|---------|--|--|--|
| <b>C: Inverse electron-demand Diels–Alder cycloadditions (DA<sub>INV</sub>)</b> |            |         |  |  |  |
|   |            |         | $210 \sim 8.6 \times 10^5$<br>(PBS, 37 °C)             | TCO is lipophilic and isomerizes over time;<br>100% conversion in 5 min  | Blackman (2008) <sup>45</sup>  |
|   |            |         | 437–2672   | BCN is readily accessible; almost quantitative<br>conversion   | Lang (2012) <sup>46</sup>  |
|   |            |         | 0.12–9.46  | Norbornene is stable   | Devaraj (2008) <sup>47</sup>   |
|   |            |         | 0.03–27  | Cyclopropene is small and stable; ED groups<br>increase reactivity; quantitative labeling  | Patterson (2012) <sup>48</sup><br>Elliott (2014) <sup>49</sup>       |
|   |            |         | 0.39 (DMSO : H <sub>2</sub> O<br>12 : 88, 20 °C)       | Used for affinity based protein profiling  | Engelsma (2014) <sup>50</sup>  |
|   |            |         | 0.017–0.041  | Terminal olefin only reacts with highly reactive<br>tetrazines   | Niederwieser<br>(2013) <sup>51</sup>                                 |
|   |            |         | 0.12–0.58<br>(THF : H <sub>2</sub> O 1 : 1)            | Tertiary isonitrile is required; the reaction<br>is slow   | Stöckmann<br>(2011) <sup>52</sup>                                    |
| <b>D: Other dipolar cycloadditions</b>  |            |         |  |  |  |
|   |            |         | 39 (MeCN : H <sub>2</sub> O<br>1 : 9, 25 °C)           | <b>Strain-promoted alkyne-nitrone cycloaddition<br/>(SPAN):</b> some nitrones are prone to hydrolysis;<br>up to 95% yield  | Ning (2010) <sup>53</sup>  |
|   |            |         | 0.043 (CDCl <sub>3</sub> , RT)                         | <b>Diazo-strained alkyne cycloaddition:</b> the reaction<br>rates are similar to the equivalent reactions of<br>azide  | McGrath (2012) <sup>54</sup><br>Josa-Culleré<br>(2014) <sup>55</sup> |
|   |            |         | 0.054 (21 °C, 55%<br>MeOH in H <sub>2</sub> O)         | <b>Strain-promoted sydnone-BCN cycloaddition:</b><br>quantitative reaction in organic solvent and in<br>aqueous buffer   | Wallace (2014) <sup>56</sup>   |
|   |            |         | 0.25 (PBS/EtOH)  | <b>Quadricyclane ligation:</b> quadricyclane is stable;<br>the product is light sensitive  | Sletten (2011) <sup>57</sup>   |
|   |            |         | N.A.   | <b>Nitrile oxide-norbornene cycloaddition:</b> nitrile<br>oxide may cross react with nucleophiles; mostly<br>used for labeling of nucleic acids                      | Gutsmiedl<br>(2009) <sup>58</sup>                                    |
|   |            |         | 0.0015–0.028 (37 °C,<br>1 : 5 MeCN : H <sub>2</sub> O) | <b>TQ ligation:</b> oQQM generated <i>in situ</i> ; EW-groups<br>on oQQM accelerate the reaction   | Li/Dong (2013) <sup>59</sup><br>Zhang (2015) <sup>60</sup>           |
|   |            |         | 0.79 (MeCN : PBS<br>1 : 1)                             | <b>Tetrazole-alkene photo-click reaction:</b> irradiation<br>wavelength is tetrazole dependent; nitrile imine<br>generated <i>in situ</i> ; up to quantitative yield | Wang<br>(2008/2009) <sup>61,62</sup>                                 |
|   |            |         | 2 min (PBS, RT):<br>give 41% labeling<br>of lysozyme   | <b>Azirine ligation:</b> azirine generates a reactive<br>nitrile ylide intermediate <i>in situ</i>   | Lim (2010) <sup>63</sup>   |
| <b>E: Transition metal-catalyzed coupling/decaging reactions</b>                |            |         |  |  |  |
|   |            |         | 30 min (ligand,<br>pH8, 37 °C)                         | <b>Suzuki–Miyaura coupling:</b> boronic acids are<br>moderately toxic; >95% conversion   | Chalker (2009) <sup>64</sup>   |
|   |            |         | 30 min (Cu ion,<br>ligand, RT)                         | <b>Sonogashira coupling:</b> Mg(II) inhibits the<br>binding of Pd(II) to the protein   | Kodama (2007) <sup>65</sup>  |





Table 1 (Contd.)

| Reactant A                                   | Reactant B   | Product                                  | $k$ ( $M^{-1} s^{-1}$ ) or $t$                                | Features   | Reference(s)                     |
|--|--|--|---|--|----------------------------------|
|  | <br>[Ru]   |  | 2–5 h (pH 8, 30% <i>t</i> BuOH/H <sub>2</sub> O, RT to 37 °C) | <b>Olefin cross metathesis:</b> requires ruthenium catalyst; up to 90% yield   | Lin (2008) <sup>66</sup>         |
|  | <br>HO-B(OH) <sub>2</sub> -R'                                |  | 24 h (Pd(OAc) <sub>2</sub> , BIAN, O <sub>2</sub> , pH 7, RT) | <b>Aqueous oxidative Heck reaction:</b> reaction opens to air; up to full conversion if excessive catalyst and boronic acid are used | Ourailidou (2014) <sup>67</sup>  |
| <br>Protein-CH <sub>2</sub> -NH <sub>2</sub> | allyl <sub>2</sub> PdCl <sub>2</sub> or Pd(dba) <sub>2</sub> | Protein-CH <sub>2</sub> -NH <sub>2</sub> | 180 min (10 μM Pd(dba) <sub>2</sub> , 37 °C)                  | Useful for <i>in vivo</i> protein activation   | Li (2014) <sup>68</sup>          |
| <b>F: Labeling at cysteine residue(s)</b>    |  |  |   |  |                                  |
|  |  |  | <30 min (PBS, RT)   | TCEP should be added to maintain cysteine residues in a reduced form   | Kim (2008) <sup>69</sup>         |
|  |  |  | 5 min (pH 7.5, RT, 5 : 95 MeCN : H <sub>2</sub> O)            | X = I, Br, Cl, OTf; quantitative labeling. Cy = cyclohexyl-  | Vinogradova (2015) <sup>70</sup> |
|  | HS-R   |  | 90 min (pH 9.0, 4 °C or RT)                                   | Dha can be derived from cysteine by MSH (pH8.0, 4 °C, 20 min); >95% labeling   | Bernardes (2008) <sup>71</sup>   |
|  |  |  | 9.19 (PBS)  | <b>CBT ligation:</b> side reactions with thiols of CBT   | Ren (2009) <sup>72</sup>         |
|  |  |  | pH 7.0  | <b>NCL:</b> thiol catalysts are used, <i>e.g.</i> , MESNA, MPAA  | Dawson (1994) <sup>73</sup>      |
|  |  |  | After reduction of disulfide: 2 h (pH 7.8, 4 °C)              | <b>S-S intercalation:</b> reaction under mildly basic pH; formation of a stable product  | Shaunak (2006) <sup>74</sup>     |
|  |  |  | TCEP, 1 h; then pH 8, RT, 3 h                                 | <b>Acetone crosslinking:</b> the introduced ketone allows oxime ligation; cross linking also stabilizes helical structures           | Assem (2015) <sup>75</sup>       |

*t*: reaction time. (A) RT: room temperature; ABAO: aminobenzaminoxime; KAHA:  $\alpha$ -ketoacid-hydroxylamine; ACL: aldehyde capture ligation. (B) PBS: phosphate buffered saline; TBTA: tris[(1-benzyl-1*H*-1,2,3-triazol-4-yl)methyl]amine; CuAAC: copper-catalyzed azide alkyne cycloaddition; SPAAC: strain-promoted azide alkyne cycloaddition; BCN: bicyclononyne. (C) TCO: *trans*-cyclooctene; ED: electron-donating. (D) TQ-ligation: thiovinyl ether *o*-quinolinone quinone methide ligation; *o*QQM: *o*-quinolinone quinone methide; EW: electron-withdrawing. (E) BIAN: bis-imine of acenaphthenequinone and mesitylamine; dba: dibenzylidene acetone. (F) TCEP: tris(2-carboxyethyl)phosphine; Dha: dehydroalanine; MSH: *O*-mesitylenesulfonylhydroxylamine; CBT: cyanobenzothiazole; NCL: native chemical ligation; MESNA: 2-mercaptoethanesulfonate; MPAA: 4-mercaptophenylacetic acid.

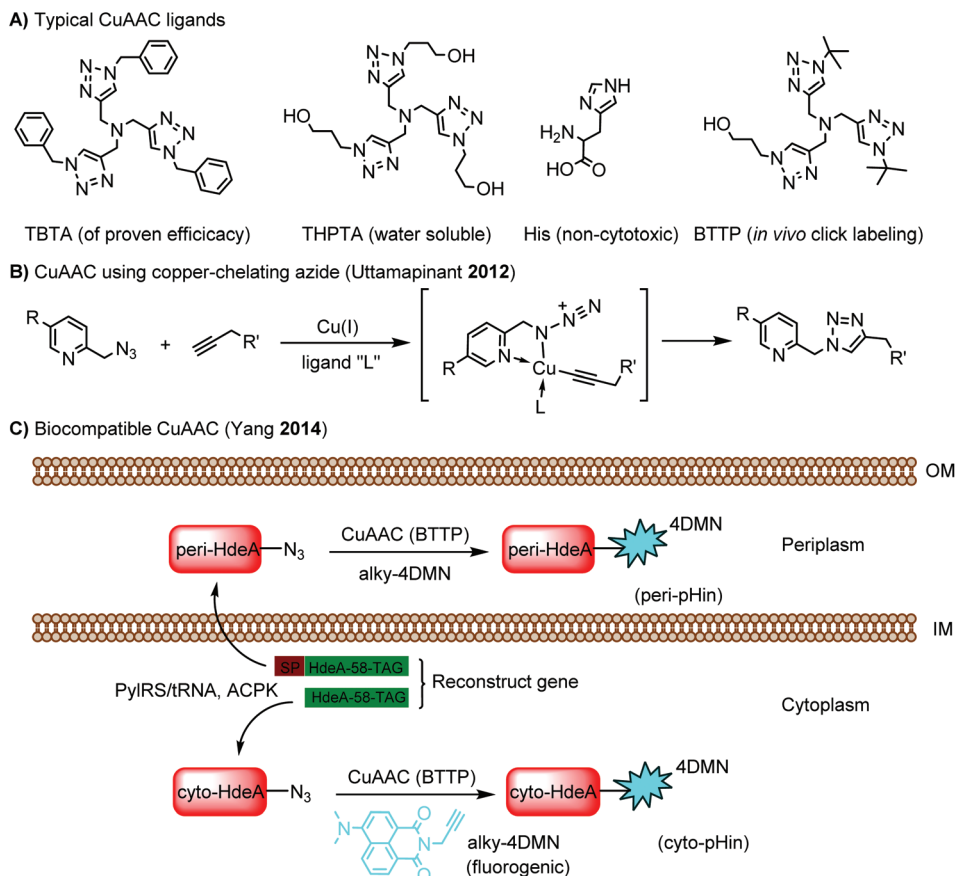
the click reaction (Scheme 1A). In addition, its complex with Cu(I) is cell permeable and non-cytotoxic, facilitating CuAAC in live *E. coli* cells.<sup>91</sup> Using this reaction, an environment-sensitive fluorogenic fluorophore (alky-4DMN) was site-specifically introduced into HdeA in both the periplasm and cytoplasm of *E. coli*. HdeA, an acid-stress chaperone that adopts pH-dependent conformational changes, was genetically encoded with an azide-carrying unnatural amino acid ACPK at residue 58 within its pH-responsive region. The resulting hybrid pH indicator enables compartment-specific pH measurement to determine the pH gradient across the *E. coli* cytoplasmic membrane (Scheme 1C).<sup>91</sup>

Fluorogenic azide probes display substantial fluorescence enhancement upon cycloaddition reaction and therefore confer labeling with minimal background (Fig. 1A). Based on photo-induced electron transfer (PET) mechanism, highly fluorogenic blue-emissive azidomethyl substituted anthracene

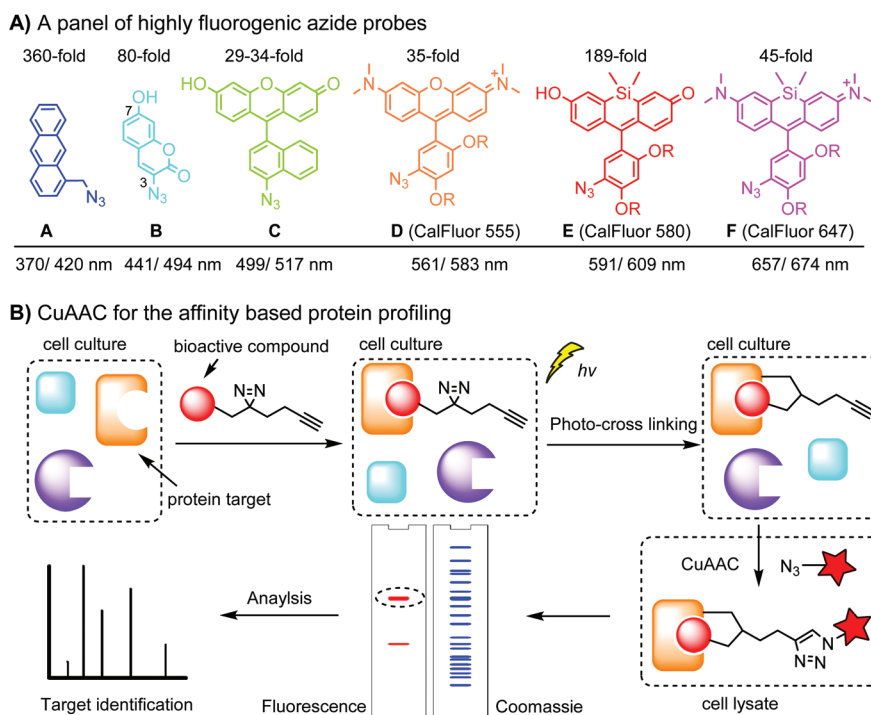
(A) and its analogues have been generated.<sup>92</sup> Substitution at the 3 or 7 position of coumarin has a strong impact on its fluorescence properties. Guided by this principle, 3-azido substituted coumarins (B) show an 80-fold increase in fluorescence intensity upon the cycloaddition reaction.<sup>93</sup> The quantum yield ( $\Phi$ , QY) of a probe after a click reaction can be calculated by density function theory (DPF), allowing rational design of fluorogenic azide probes.<sup>94</sup> Using this approach, the green-emission azido-fluorescein (C) has been designed, which exhibits a fluorescence enhancement of 29 to 34-fold upon cycloaddition with different alkynes.<sup>95</sup> Fluorogenic green- to far red-emitting CalFluors enable sensitive detection of biomolecules under no-wash conditions (D, E, F).<sup>96</sup>

An important application of CuAAC lies in the target identification of biologically active small molecules in biomedical research and drug discovery.<sup>97</sup> A bioactive compound is typically





**Scheme 1** Typical CuAAC ligands (A) and variants of improved CuAAC (B and C).

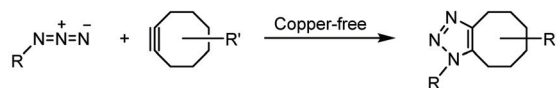


**Fig. 1** (A) A panel of highly fluorogenic azide probes including a selection of CalFluors; the maximal excitation/emission wavelengths refer to the value after the click reaction;  $R = -(\text{CH}_2)_2\text{O}(\text{CH}_2)_2\text{N}^+\text{Me}_2(\text{CH}_2)_3\text{SO}_3^-$ . (B) Target identification using an affinity-based probe (A/BP) by CuAAC.



Table 2 Variants of strained alkynes for SPAAC

## A) Strain-promoted azide-alkyne cycloaddition



## B) Variants of strained alkynes

| Prototype                                       | Hydrophilic        | Electronic activation               |                      | Activated by ring strain                                |  |                                |  |
|---|--------------------|-------------------------------------|----------------------|---|--|--------------------------------|--|
|   |                    |                                     |                      |   |  |                                |  |
| Agard<br>2004                                   | Sletten<br>2008    | Agard<br>2006                       | Baskin<br>2007       | Ning<br>2008  | Debets<br>2010                                       | Varga<br>2012                  | Jewett<br>2010   |
| $2.4 \times 10^{-3}$                            | $3 \times 10^{-3}$ | $4.3 \times 10^{-3}$                | $7.6 \times 10^{-2}$ | $5.7 \times 10^{-2}$                                    | 0.31   | 0.8                            | 0.96 ( $\text{M}^{-1} \text{s}^{-1}$ )   |
| Electronic + Ring strain                        |                    | Fused with cyclopropane             |                      | Reduced Ring Size                                       |  |                                | <div> <div>Cyan</div> <div>Green</div> <div>Orange</div> <div>Red</div> </div> <div> <div><math>&lt; 10^{-2} \text{ M}^{-1} \text{s}^{-1}</math></div> <div><math>0.01\text{--}0.1 \text{ M}^{-1} \text{s}^{-1}</math></div> <div><math>0.1\text{--}1.0 \text{ M}^{-1} \text{s}^{-1}</math></div> <div><math>&gt; 1.0 \text{ M}^{-1} \text{s}^{-1}</math></div> </div> |
|   |                    |                                     |                      |   |  |                                |  |
| Sletten<br>2010                                 |                    | Dommerholt<br>2010                  |                      | (7-membered)<br>de Almeida<br>2012                      | (6-membered)<br>Medina<br>2014                       | (5-membered)<br>Medina<br>2014 |  |
| $0.22 \text{ M}^{-1} \text{s}^{-1}$<br>unstable |                    | $0.29 \text{ M}^{-1} \text{s}^{-1}$ |                      | up to $4 \text{ M}^{-1} \text{s}^{-1}$<br>stable in PBS | rapid<br>not isolable/ can be tracked <i>in situ</i> | rapid                          |  |
|   |                    |                                     |                      |   |  |                                |  |

derivatized with a photo-crosslinking moiety (e.g. diazirine) and a terminal alkyne, which is denoted as an affinity-based probe (A/BP) (Fig. 1B). By photo-crosslinking, the A/BP probe *in situ* captures the protein target and forms a stable protein–ligand complex in the cell. Subsequent labeling of the target proteins using azide probes is followed by separation *via* gel-electrophoresis and determination *via* mass spectroscopy.<sup>97</sup> Among many bioorthogonal groups, a terminal alkyne is a well suited tag as it is small with minimal interference of protein–ligand interactions, chemically inert, and can be easily modified *via* CuAAC.

Although the cytotoxicity of Cu(i) can be reduced by using ligands, copper-free click chemistry is more straightforward. Strain-promoted azide–alkyne cycloaddition (SPAAC) and other copper-free click reactions<sup>38</sup> without the requirement for a metal catalyst have been developed (Table 2A). The first SPAAC reaction for protein labeling was reported by Bertozzi and co-workers in 2004 using a strained cyclooctyne.<sup>39</sup> However, the reaction rate is slow ( $k = 2.4 \times 10^{-3} \text{ M}^{-1} \text{s}^{-1}$ ), which is comparable to Staudinger ligation ( $k = 3 \times 10^{-3} \text{ M}^{-1} \text{s}^{-1}$ ). To date, new variants of strained alkynes have been developed with improved properties, such as enhanced specificity, reduced lipophilicity<sup>98</sup> and increased reaction rates (Table 2B).

There are several ways to improve strained alkynes.<sup>99</sup> The first strategy is to modulate the electronic properties by introducing electron-withdrawing (EW) groups, e.g. fluorine, near the triple bond.<sup>100</sup> Examples include MOFO<sup>101</sup> and DIFO.<sup>40</sup> The second approach is to fuse the cyclooctynes with rigid aromatic rings, leading to an enhancement of reactivity by

increasing ring strain. The ring-fused cyclooctynes, including DIBO,<sup>41,102</sup> DIBAC,<sup>103</sup> COMBO<sup>104</sup> and BARAC,<sup>42</sup> show a 25–400-fold increase in the reaction rate.<sup>105</sup> However, synthesis of these cyclooctynes is usually laborious. Bicyclononyne (BCN), a cyclopropane-fused cyclooctyne, shows relatively fast reaction kinetics ( $0.3\text{--}1 \text{ M}^{-1} \text{s}^{-1}$ ) toward azides and can be readily prepared in only three steps.<sup>43</sup> Using an electron-deficient azide, e.g. 4-azido-1-methylpyridinium iodide, the cycloaddition reaction rate with BCN can be further increased to  $2\text{--}2.9 \text{ M}^{-1} \text{s}^{-1}$ .<sup>44</sup> By introducing both EW groups and ring strain, difluorobenzocyclooctyne (DIFBO) shows only a moderate increase of reactivity ( $0.22 \text{ M}^{-1} \text{s}^{-1}$ ) with a significant reduction in stability.<sup>106</sup> The third strategy is to shorten the ring size as exemplified by the 7-membered tetramethylthiazacycloheptyne (TMTH),<sup>107</sup> cyclohexyne and cyclopentyne.<sup>108</sup> However, these compounds have poor stability (Table 2B). The copper-free click reactions have been used for antibody-free western blot analysis,<sup>109</sup> visualization of glycosylation on cell surfaces<sup>110</sup> and protein labeling inside live cells.<sup>111</sup>

### 2.3. Inverse electron-demand Diels–Alder cycloaddition ( $\text{DA}_{\text{INV}}$ ) and other cycloadditions

The inverse electron-demand Diels–Alder cycloaddition ( $\text{DA}_{\text{INV}}$ ) occurs between an electron-rich dienophile (e.g. strained alkene/alkyne) and an electron-poor diene, typically 1,2,4,5-tetrazine (Table 3A).  $\text{DA}_{\text{INV}}$  represents so far the most rapid bioorthogonal reaction (up to  $8.6 \times 10^5 \text{ M}^{-1} \text{s}^{-1}$ ).<sup>45,112</sup> In contrast, the reaction rate of SPAAC is only up to  $1 \text{ M}^{-1} \text{s}^{-1}$ .



Table 3 Reactivity of strained alkenes and tetrazines

**A) Inverse electron-demand Diel-Alder cycloaddition (DA<sub>INV</sub>)**

**B) Reactivity of strained alkenes**

| Strained Alkene | Rough Relative Reactivity with Tz | $k$ (M <sup>-1</sup> s <sup>-1</sup> ) | Reaction Conditions                     |
|-----------------|-----------------------------------|--|---|
| sTCO            | 1600                              | 160-fold Faster than TCO               |   |
| TCO             | 10                                | 21000 (Tz2)                            | (aq., 20 °C)                            |
| TCO*            | ~6                                | 13000 (Tz2)                            | (aq., 20 °C)                            |
| TCO#            | ~5                                | 10000 (Tz2)                            | (aq., 20 °C)                            |
| BCN             | 0.7                               | 1245 (Tz3)                             | (MeOH: H <sub>2</sub> O (55:45, 25 °C)) |
| SCO             | 0.3                               | 670 (Tz2)                              | (aq., 20 °C)                            |
| Cpp             | 0.03                              | 27 (Tz5)                               | (pH 7.4)                                |
| Norbornene      | 0.001                             | 0.94 (Tz5)                             | (pH 7.4, 21 °C)                         |
| Acylazetine     | 0.00019                           | 0.39 (Tz2)                             | (aq., 20 °C)                            |
| Terminal alkene | ~0.00002                          | 0.041 (Tz4')                           | (pH 4.8)                                |

**C) Reaction kinetics (with TCO) and stability of tetrazines**

| Tetrazine | $k$ (M <sup>-1</sup> s <sup>-1</sup> ) | Stability (%)  |
|-----------|--|----------------|
| Tz1       | 30000                                  | 70             |
| Tz2       | 26000                                  | 40             |
| Tz3       | 17248 <sup>a</sup>                     | N.A.           |
| Tz3'      | 2672 <sup>b</sup>                      | N.A.           |
| Tz4       | 22000                                  | 23             |
| Tz4'      | —                                      | N.A.           |
| Tz5       | 5235 <sup>a</sup>                      | N.A.           |
| Tz6       | 5300                                   | precipitate    |
| Tz7       | 4900                                   | 75             |
| Tz8       | 4400                                   | 40             |
| Tz9       | 2300                                   | 85             |
| Tz10      | 80 <sup>b</sup>                        | N.A.           |
| Tz11      | 820                                    | 96             |
| Tz12      | 380 <sup>a</sup>                       | N.A.           |
| Tz13      | 210                                    | 96             |
| Tz14      | 880 <sup>c</sup>                       | stable in cell |

<sup>a</sup> Protein labeling reaction. <sup>b</sup> The reaction kinetics values with BCN which is roughly 10–15 times smaller than with TCO<sup>46</sup>. <sup>c</sup> Reaction with sTCO; stability (%) refers to the intact tetrazine in fetal bovine serum (FBS) at 37 °C after 10 h.<sup>115</sup>

Theoretical calculation suggests that the rapid reaction rate can be attributed to the much higher interaction energy between tetrazine and *trans*-cyclooctene (TCO) in comparison to the interaction energy between an azide and a strained alkyne.<sup>113</sup>

Tetrazines are highly reactive so that they can also readily react with strained alkynes, isonitriles<sup>52</sup> and even terminal alkenes. Among these reactions, the reaction between tetrazine and BCN or cyclopropene has proven to be the most useful. Tetrazine reacts with BCN in a rapid fashion with a reaction rate constant of 3000 M<sup>-1</sup> s<sup>-1</sup>.<sup>46</sup> In comparison to TCO that requires complicated synthetic procedures, BCN is readily available through organic synthesis. Compared to BCN and TCO groups, cyclopropene (Cpp) is much smaller, and therefore has been employed as a “minimalist” tag for live-cell imaging and affinity-based protein labeling.<sup>114</sup>

Alkenes and alkynes display different reactivity toward tetrazine (Table 3B).<sup>116</sup> sTCO features a cyclopropane ring, which brings additional strain and increases the reaction rate of the cycloaddition up to 160-fold in comparison to TCO.<sup>116</sup> The carbamate bond near the *trans*-double bond in TCO\* reduces the chance of nucleophilic attack. Thus, TCO\* shows better stability than TCO with only 2-fold reduction in reactivity toward tetrazine.<sup>117</sup> The reaction rate of BCN with tetrazine is about 10 times slower than that of TCO.<sup>46</sup> Norbornene is *ca.* 10 000 times less reactive than TCO, as it is more bulky and exhibits less ring strain than TCO.<sup>46,47</sup> Other alkenes, including Cpp,<sup>48,49,114</sup> acyl-

azetine<sup>50</sup> and terminal alkene,<sup>51</sup> are less reactive, and therefore can react only with highly reactive tetrazines.

Different tetrazines show varied reactivity toward strained alkenes (Table 3C). Studies have been conducted to evaluate the reactivity and stability of tetrazines.<sup>115</sup> The introduction of EW substituents can substantially increase the reaction rate. However, it is a double-edged sword. Increase in the reactivity of tetrazine often results in the reduction of stability and lifetime in the serum. ED substituents on the other hand decrease the reactivity of tetrazine.<sup>115</sup> Besides electronic effects, steric effects also play a crucial role. In general, there is a trade-off between reactivity and stability. The rate constants of tetrazine reactions with TCO as well as their stability are summarized in Table 3C.

Green- and red-emitting fluorophores display electronic interactions with tetrazine chromophores that have absorption maxima at 500–525 nm. As a consequence, tetrazine-conjugated fluorophores often show reduced fluorescence. After a cycloaddition reaction, tetrazine is deconjugated and loses its quenching capability. Hence, many tetrazine-fluorophores feature fluorogenic properties, such as BODIPY-FL, Oregon Green 488, BODIPY-TMR, VT680,<sup>118</sup> TAMRA, and fluorescein.<sup>119</sup> These probes show a moderate turn-on ratio (up to 20-fold) (Fig. 2A). By adapting through-bond energy transfer (TBET) for fluorescence quenching, Weissleder and coworkers developed green-emitting BODIPY-tetrazine probes with up to 1600-fold turn-on ratio<sup>120</sup> and blue-emitting coumarin-tetrazine





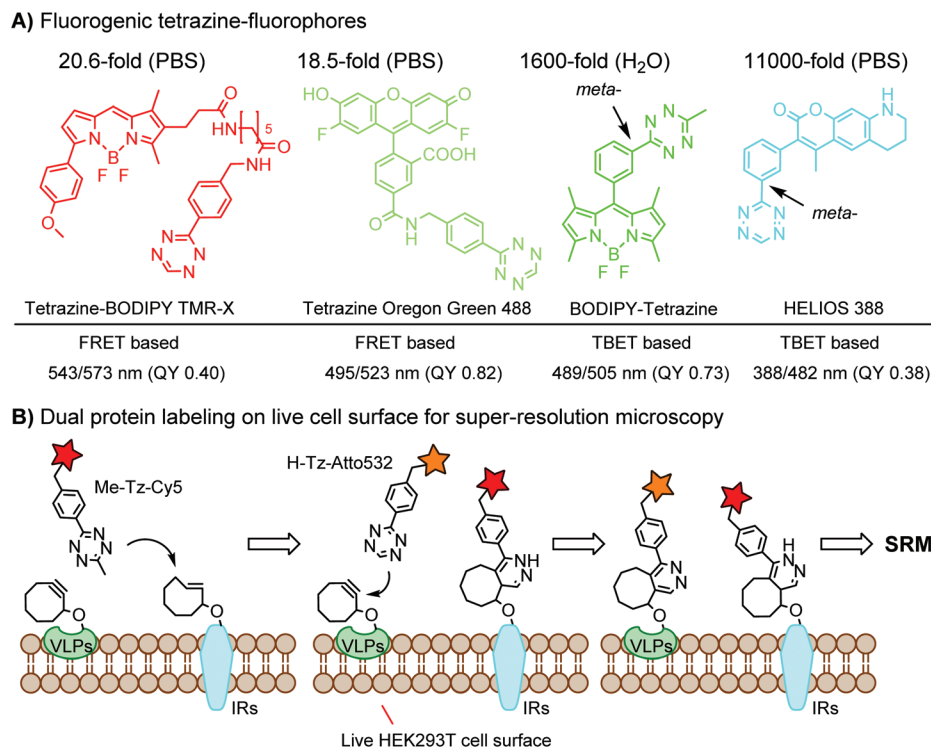


Fig. 2 (A) Fluorogenic tetrazine-fluorophores; (B) dual protein labeling using orthogonal DA<sub>INV</sub> pairs for super-resolution microscopy (SRM).

probes with up to 11 000-fold fluorescence enhancement.<sup>121</sup> The tetrazine moiety is attached at the *meta*-position to the fluorophore on a rigid phenyl ring (Fig. 2A). Under these conditions, the tetrazine group is perpendicular to the fluorophore moiety, leading to the collinear alignment of two dipoles.<sup>121</sup>

To achieve dual- or multi-labeling of proteins, mutually orthogonal reactions are desirable.<sup>122</sup> By fine-tuning the DA<sub>INV</sub> reactions, “selectivity enhanced” DA<sub>INV</sub> reactions have been applied to sequential dual-color labeling of insulin receptors (IRs) and virus-like particles (VLPs) on the cell surface of HEK293T cells, facilitating dual-color super-resolution microscopy (Fig. 2B).<sup>117</sup>

In addition to CuAAC, SPAAC and DA<sub>INV</sub>, which are popularly used for protein labeling, other dipolar cycloaddition reactions are summarized in Table 1D, including strain-promoted alkyne-nitrone cycloaddition (SPANC),<sup>53</sup> diazo-strained alkyne cycloaddition,<sup>54,55</sup> nitrile oxide-norbornene cycloaddition,<sup>58</sup> quadricyclane ligation,<sup>57</sup> TQ-ligation,<sup>59,60</sup> strain-promoted sydnone-BCN cycloaddition,<sup>56</sup> and plenty of photo-triggered cycloaddition reactions, such as the tetrazole-alkene photo-click reaction<sup>61,62</sup> and azirine ligation.<sup>63</sup>

#### 2.4. Transition metal-catalyzed couplings and decaging reactions

Biocompatible transition metal-catalyzed couplings include the Suzuki–Miyaura coupling,<sup>64</sup> Sonogashira coupling, and olefin metathesis. These reactions can be performed under mild and aqueous conditions, despite the necessity to use a transition metal catalyst (Table 1E).<sup>15</sup> Suzuki–Miyaura coupling requires an iodophenyl group, a water soluble palladium (0) catalyst and an

appropriate ligand. Recently, an improved ligand, 1,1-dimethylguanidine, has been employed for aqueous Suzuki–Miyaura coupling.<sup>123</sup> Suzuki–Miyaura coupling has been successfully used for protein glycosylation and labeling at the cell surface.<sup>124</sup> Sonogashira coupling is another Pd-catalyzed coupling reaction.<sup>65</sup> An alkyne group is incorporated into the protein and subsequently reacts with an iodophenyl probe. Sonogashira coupling has been used for the modification of ubiquitin in live cells.<sup>11,15,125</sup>

Terminal olefins can undergo an oxidative Heck reaction with boronic acid in the presence of Pd(OAc)<sub>2</sub>/BIAN catalysts. This reaction has been used for the site-specific labeling of 4-oxalocrotonate tautomerase (4-OT).<sup>67</sup> Olefin metathesis is the redistribution of fragments of alkenes by scission and regeneration of carbon–carbon double bonds.<sup>117,118</sup> Hence, in order to avoid undesired cross coupling products, a terminal olefin and a more reactive thiovinyl ether are required.<sup>126</sup> Water soluble ruthenium catalysts have been developed to mediate the reaction in aqueous solution.<sup>126,127</sup>

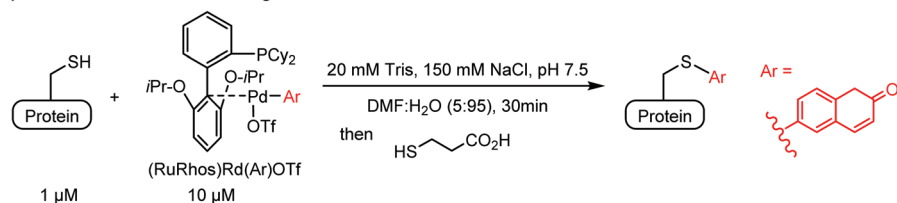
Chemical protein labeling not only makes proteins visible but also renders them controllable. Recently, palladium catalysts have been used to manipulate protein function in cells. Pd-mediated cleavage of the propargyl carbamate group leads to the generation of a free lysine residue. The protected lysine analogue can be genetically and site-specifically incorporated into a protein using an unnatural amino acid (UAA) mutagenesis technique (discussed in the later section). This strategy enables protein activation in living cells by decaging the lysine residue located at the active site of a protein, and has been utilized to elucidate the virulence mechanism of a bacterial type III effector protein in its host cells



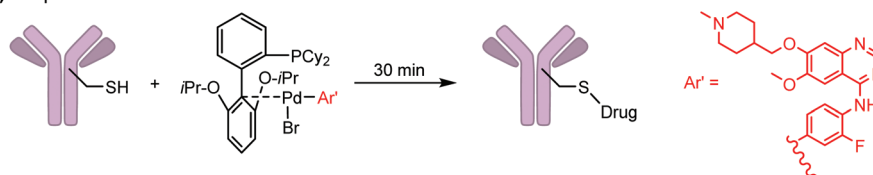


The N-terminus of a protein shows unique reactivity and can be site-specifically labeled or converted to a bioorthogonal handle. The N-terminal  $\alpha$ -amino group features a lower  $pK_a$  value (*ca.* 8) than that of the  $\epsilon$ -amino group of lysine (*ca.* 10). Transamination methods have been used to convert the N-terminal  $\alpha$ -amino group to an aldehyde or a ketone using glyoxylate in the presence of a divalent metal ion and a base<sup>136</sup> or using pyridoxal-5-phosphate (PLP).<sup>137</sup> N-terminal glycine shows the highest reactivity in the transamination reaction.<sup>137</sup> A ketene compound has been reported to selectively react with an N-terminal  $\alpha$ -amino group at pH 6.3.<sup>138</sup> Another approach is the oxidation of an N-terminal serine or threonine to an aldehyde or ketone by sodium *m*-periodate at neutral pH.<sup>139</sup> Afterwards, the N-terminal aldehyde or ketone tag is ready for

## A) Protein fluorescent labeling



## B) Preparation of ADCs

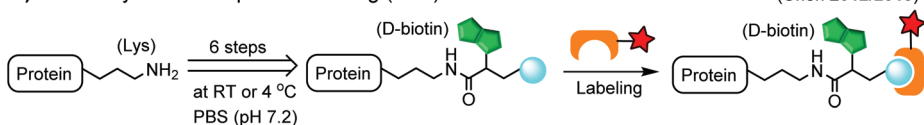


Scheme 2 Organometallic palladium reagents for cysteine bioconjugation on proteins.

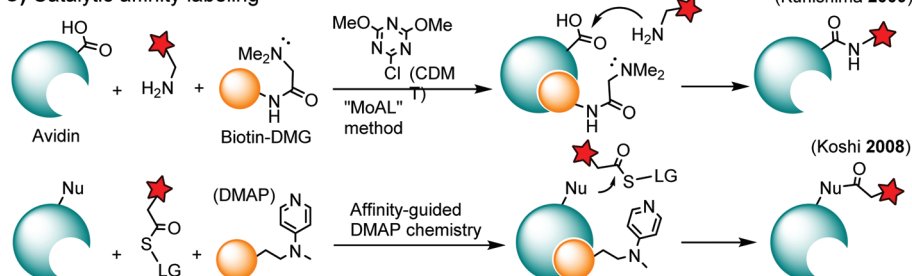
## A) N-terminal engineering



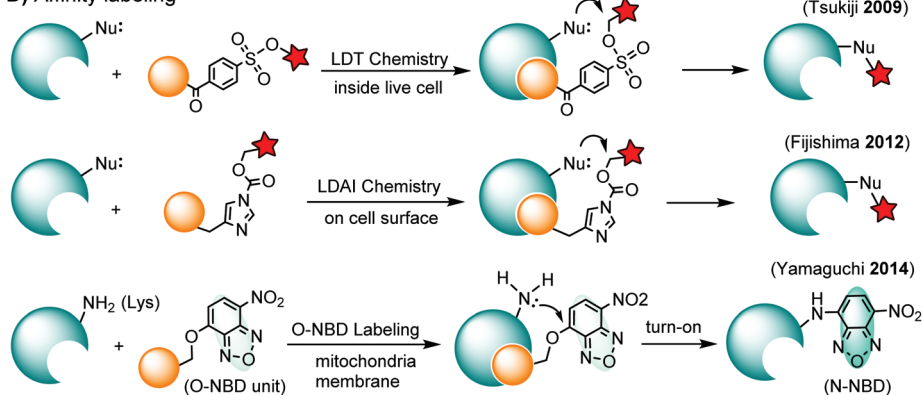
## B) Kinetically controlled protein labeling (KPL)



## C) Catalytic affinity labeling



## D) Affinity labeling



Scheme 3 Methods for chemoselective labeling of native proteins. LG: leaving group.



oxime ligation, Mukaiyama-Adol condensation, Pictet-Spengler reaction, *etc.*, as discussed in previous sections (Scheme 3A).

### 3.2. Kinetically-controlled protein labeling (KPL)

Under normal bioconjugation conditions for protein labeling at lysine side chains, it is usually difficult to achieve site-specificity using regular amine-reactive reagents, such as an *N*-hydroxysuccinimidyl (NHS) ester. Nonetheless, lysine residues on a protein's surface display subtle differences regarding their individual reactivity. This difference may originate from the different solvent accessibility of lysine, or the interaction of lysine with neighboring residues, or the combination of both.<sup>140</sup> Through kinetically-controlled protein labeling (KPL), proteins can be mono-modified at a specific lysine side chain.<sup>140</sup> This approach enables the site-selective introduction of a terminal alkyne, or azide into native proteins for a click reaction<sup>140</sup> or Staudinger ligation (Scheme 3B).<sup>141</sup> KPL has been utilized for site-specific biotinylation of pharmaceutically relevant proteins for delivery into macrophages<sup>142</sup> and dual labeling of the peptide hormone, somatostatin, for the visualization of targeted drug delivery in tumor cells.<sup>143</sup>

### 3.3. Catalytic affinity labeling

Catalytic modules tethered with a ligand can be targeted to the binding pocket of a protein to locally catalyze the labeling reaction on the protein. For instance, a biotin-conjugated dimethylglycine (DMG) group is brought to the proximity of the avidin binding pocket, where it specifically catalyzes the acylation of amine probes with Asp108.<sup>144</sup> In the so-called modular affinity labeling (MoAL) approach, three modules are required: (1) the catalytic ligand module (biotin-DMG), (2) the labeling module (amine probe) and (3) the reactive module (CDMT). Another catalytic affinity labeling method is termed affinity-guided DMAP (4-dimethylaminopyridine) chemistry. DMAP is an effective acyl transfer catalyst, which can activate an acyl ester for its transfer to a nucleophilic residue. Therefore, a ligand tethered with DMAP allows specific labeling of native proteins by acyl ester probes (Scheme 3C).<sup>145</sup>

### 3.4. Affinity labeling of endogenous proteins

In ligand-directed tosyl (LDT) chemistry, ligand-tethered tosyl ester probes are used to label endogenous proteins in cells. Upon labeling, the ligand is cleaved off at the tosyl ester linkage. Therefore, the protein is still active after labeling because the active center is no longer occupied by its ligand.<sup>146</sup> The concept was employed to construct a turn-on probe based on the release of the quencher upon labeling.<sup>147</sup> The LDT chemistry has been applied to the labeling of cell surface receptors<sup>148</sup> and native FKBP12 in live cells.<sup>149</sup> LDT chemistry is slow and typically requires over 12 hours of incubation time. Recently, a faster affinity labeling approach, known as ligand-directed acyl imidazole (LDAI) chemistry, was used to selectively modify the endogenous folate receptor at the cell surface (Scheme 3D). The experiments showed that LDAI labeling is 12-fold more efficient than LDT labeling.<sup>150</sup> New emerging affinity labeling reagents include chemical

probes bearing an O-nitrobenzoxadiazole (O-NBD) unit. Upon the ligand-directed reaction with a lysine side chain, the non-fluorescent O-NBD is converted to fluorescent N-NBD. Translocator protein (TSPO) ligands carrying an O-NBD unit enabled proteomic identification of a partner protein of TSPO, a voltage-dependent anion channel (VDAC). The affinity labeling reaction using O-NBD is quite efficient with yields of 41% and 76% after 1 h and 12 h, respectively.<sup>151</sup>

## 4. Chemical labeling of proteins in living cells

Proteins function in signaling pathways and interacting networks in the complicated surroundings of cells and organisms. Fluorescent proteins (FPs) have revolutionized our ability to visualize and investigate protein function directly in living cells and organisms by fusion of individual proteins with FPs. Chemical probes, including organic dyes, are able to achieve properties that are not readily possible when using FPs. For instance, many organic dyes are superior to FPs in terms of brightness, photostability, far red-emission, environmental sensitivity, pulse-chase labeling and the flexibility for modifications to their spectral and biochemical properties. In the chemical tagging approach, a protein of interest (POI) is fused with a polypeptide tag, which is subsequently labeled with chemical probes. In general, these tags can be classified in the following categories: (1) metal chelation based peptide tags; (2) self-labeling peptide tags; (3) ligand binding domains (LBDs); (4) self-labeling enzymatic domains; (5) peptide sequences for enzymatic modifications; and (6) genetically encoded unnatural amino acids (UAAs) as "minimalist" tags (Table 4).

### 4.1. Metal chelation based peptide tags

Metal chelation methods have been adopted for affinity chromatography in protein purification. The principle has also been utilized for protein labeling, either by non-covalent complex formation or by chelation-driven affinity conjugation.<sup>152,185</sup> Examples include the poly-histidine tag (His-tag, HHHHHH) and the tetra-aspartate tag [D4 tag, (DDDD)<sub>n</sub>, *n* = 1–3], which can be labeled using Ni-NTA probes and zinc complexes, respectively.<sup>152,154,155,186–189</sup> Specific intracellular labeling of His-tagged proteins was achieved using cell-penetrating multivalent *N*-nitrilotriacetic acid (NTA) carrier complexes.<sup>153</sup> The advantages of metal chelation based labeling can be attributed to the small size of the tag which confers minimal disturbance to protein function, the high labeling efficiency, selectivity and accessibility of various functional probes (Table 4A).<sup>190</sup>

### 4.2. Self-labeling peptide tags

Tsien and coworkers reported the biarsenical FLaSH (fluorescein arsenical hairpin) as the first chemical surrogate to FPs for labeling proteins in live cells.<sup>156</sup> A red version of FLaSH, a resorufin-based biarsenical (ReAsH), was developed later. FLaSH and ReAsH probes allow specific and fluorogenic labeling of proteins fused to a tetracysteine motif (CCXXCC).<sup>191–193</sup>





Table 4 Representative chemical tags for the labeling of proteins in cells

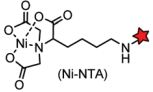
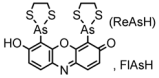
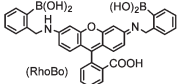
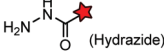
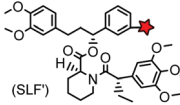
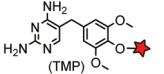
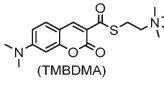
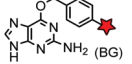
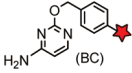
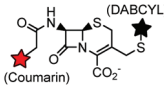
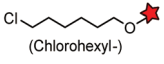
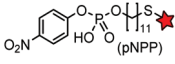
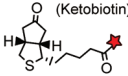
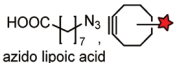
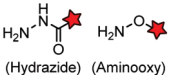

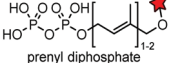
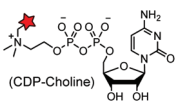
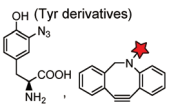
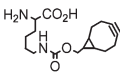
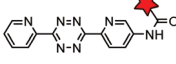
| Tag name (size in AA)                        | Probe   | Enzyme  | Cellular labeling              | Features   | Reference(s)   |
|--|---|---|--------------------------------|--|--|
| <b>A. Metal chelation based peptide tags</b> |   |   |                                |  |  |
| His-tag (6): HHHHHH                          | <br>(Ni-NTA)         | No  | Cell surface/<br>intracellular | Ni(II) is toxic to cells and quenches fluorescence; intracellular labeling is possible using cell-penetrating multivalent chelator carrier complexes                             | Guignet (2004) <sup>152</sup><br>Wieneke (2014) <sup>153</sup> |
| His-tag (6): HHHHHH                          | Zn(II) complex: HisZiFit  | No  | Cell surface                   | Zn(II) is non-toxic; the zinc complex is membrane-impermeant   | Hauser (2007) <sup>154</sup>                                   |
| D4 tag (4): (DDDD) <sub>n</sub> , n = 1–3    | Multinuclear Zn(II) complexes: Zn(II)-DpaTyrs probe   | No  | Cell surface                   | Spectroscopic change upon chelation; D4 tag/Zn(II)-DpaTyrs pair is orthogonal to the His tag/Ni(II)-NTA pair   | Ojida (2006) <sup>155</sup>                                    |
| <b>B. Self-labeling peptide tags</b>         |   |   |                                |  |  |
| CCXXCC (6) (tetracysteine)                   | <br>(ReAsH), FIAsh   | No  | Intracellular                  | Fluorogenic; non-specific reactions and interactions to endogenous thiols; biarsenical probes may be cytotoxic   | Griffin (1998) <sup>156</sup><br>Gaietta (2002) <sup>157</sup> |
| SSPGSS (6) (tetraserine)                     | <br>(RhoBo)          | No  | Cell surface                   | Fluorogenic; reduced background staining; cytotoxic; off-target labeling of endogenous tetraserine motif; RhoBo is cell permeable  | Halo (2009) <sup>158</sup>                                     |
| HyRe tag (11): HKSNHSSKNRE                   | <br>(Hydrazide)      | No  | Cell surface                   | Neutral pH; imine byproduct formation at pH < 6  | Eldridge (2011) <sup>159</sup>                                 |
| SpyTag (13)                                  | SpyCatcher protein domain (138 AA)  | No  | Cell surface                   | $k = 1.4 \times 10^3 \text{ M}^{-1} \text{ s}^{-1}$ ; high yield under diverse conditions of pH, temperature and buffer; formation of a stable amide bond linkage; not traceless | Zakeri (2012) <sup>160</sup>                                   |
| E3 tag (21): (EIAALEK) <sub>3</sub>          | K3 peptide (21 AA): (KIAALKE) <sub>3</sub>  | No  | Cell surface                   | E3/K3 coiled-coil template induces proximity-driven rhodium(II)-catalyzed modification or acyl transfer reaction ( $t_{1/2} = 10 \text{ min}$ )                                  | Chen (2011) <sup>161</sup><br>Reinhardt (2014) <sup>162</sup>  |
| <b>C. Ligand binding domains (LBDs)</b>      |   |   |                                |  |  |
| FKBP' (108) (FKBP12_F36 V)                   | <br>(SLF')         | No  | Intracellular                  | Specific binding between FKBP' and SLF'; non-covalent  | Clackson (1998) <sup>163</sup><br>Marks (2004) <sup>164</sup>  |
| eDHFR (159)                                  | <br>(TMP)          | No  | Intracellular                  | Tight and specific binding between eDHFR and TMP; non-covalent/covalent; non-cytotoxic; affinity conjugation is rapid ( $t_{1/2} = 1.8 \text{ min}$ )                            | Miller (2005) <sup>165</sup><br>Liu (2014) <sup>166</sup>      |
| PYP-tag (125)                                | <br>(TMBDMA)       | No; PYP tag is derived from a purple bacteria                                 | Intracellular                  | PYP-tag covalently binds to the thioester derivative of cinnamic acid/coumarin; fluorogenic; up to $k = 3950 \text{ M}^{-1} \text{ s}^{-1}$                                      | Hori (2009/2013) <sup>167,168</sup>                            |
| <b>D. Self-labeling enzymatic domains</b>    |   |   |                                |  |  |
| SNAP tag (182)                               | <br>(BG)           | hAGT (mutated human <i>O</i> <sup>6</sup> -alkylguanine-DNA alkyltransferase) | Intracellular                  | BG: $k = 0.3 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$ ; BG-FL: $k = 2.8 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$ ; removal of guanine after labeling                         | Keppler (2003) <sup>169</sup>                                  |
| CLIP tag (182)                               | <br>(BC)           |   | Intracellular                  | BC-FL: $k = 0.1 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$ . SNAP-tag and CLIP-tag possess orthogonal substrate specificities; removal of cytosine after labeling                | Gautier (2008) <sup>157</sup>                                  |
| BL-tag (263)                                 | <br>(Coumarin)     | Non-catalytic $\beta$ -lactamase variant                                      | Cell surface                   | $k = 7.8 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$ , E166N mutant of $\beta$ -lactamase; fluorogenic labeling   | Mizukami (2009) <sup>170</sup>                                 |
| Halo tag (290)                               | <br>(Chlorohexyl-) | Dha (mutated haloalkane dehalogenase)   | Intracellular                  | $k = 2.7 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ ; covalent; probe easily accessible by synthesis   | Los (2008) <sup>171</sup>                                      |



Table 4 (Contd.)

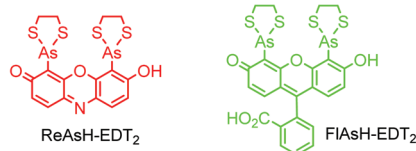
| Tag name (size in AA)   | Probe  | Enzyme                                     | Cellular labeling          | Features   | Reference(s)   |
|---|--|--|----------------------------|--|--|
| Cutinase (197)  |                   | A small globular serine esterase of 22 kDa | Cell surface               | Cutinase is labeled by the covalent inhibitor, <i>p</i> -nitrophenyl phosphonate (pNPP)  | Bonasio (2007) <sup>172</sup>  |
| <b>E. Enzymatic modifications</b>   |  |  |                            |  |  |
| ACP (77)/S6(12)/A1 (12)/PCP(80)/ybbR tag(11)  | Coenzyme A (CoA) derivatives   | PPTase (AcpS or Sfp)                       | Cell surface               | AcpS/Sfp catalyzes the transfer of a CoA-activated probe to the Ser residue of the tag. $k_{\text{cat}} = 5.5 \times 10^{-4} - 0.32 \text{ s}^{-1}$ , $k_{\text{cat}}/K_{\text{m}} = 5.3 - 4550 \text{ M}^{-1} \text{ s}^{-1}$   | George (2004) <sup>173</sup><br>Yin (2005) <sup>174</sup><br>Zhou (2007) <sup>175</sup><br>Chen (2005) <sup>83</sup> |
| AP tag (15): GLNDIFEAQKIEWHE  |                   | Biotin ligase (BirA)                       | Cell surface               | Ketobiotin is a substrate for BirA and is incorporated into the Lys residue of the peptide tag; labeling time >20 min  |  |
| Q-tag (7): PKPQQFM  | Cadaverine derivatives   | Transglutaminase (TGase)                   | Cell surface               | TGase mediates the formation of an amide bond between the amine of cadaverine and the Glu residue of the Q-tag   | Sato (1996) <sup>176</sup><br>Lin (2006) <sup>177</sup>  |
| LAP tag (13–22)   |                   | Lipoic acid ligase (LplA)/LplA mutant      | Cell surface/intracellular | $k_{\text{cat}} = 0.048 \text{ s}^{-1}$ for the conjugation of azido lipoic acid; coumarin addition by <sup>W37V</sup> LplA: $k_{\text{cat}} = 0.019 \text{ s}^{-1}$ , $k_{\text{cat}}/K_{\text{m}} = 3.8 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$ ; <sup>W37I</sup> LplA: $k_{\text{cat}} = 0.016 \text{ s}^{-1}$ , $k_{\text{cat}}/K_{\text{m}} = 0.6 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$ | Fernandez-Suarez (2007) <sup>178</sup>   |
| LCXPXR (6)  |                   | Formylglycine generating enzyme (FGE)      | Cell surface               | FGE catalyzes the transformation of a Cys of the peptide tag to a formylglycine  | Carrico (2007) <sup>79</sup>   |
| LPXTG (5)   | G <sub>n</sub> —  | Sortase A (SrtA)                           | Cell surface               | SrtA cleaves the peptide at the Thr-Gly site, and attaches a labeled polyglycine peptide   | Popp (2007) <sup>179</sup>   |
| CAAX (4)  |                  | Protein farnesyltransferase (PTFase)       | Cell surface               | CAAX is also present in endogenous proteins; an alkyne group is introduced for click labeling  | Wollack (2009) <sup>180</sup>  |
| Split intein [Int <sup>C</sup> (35) or Int <sup>N</sup> (25)]                       | Another half of split intein [Int <sup>N</sup> (100) or Int <sup>C</sup> (104)]                    | Reconstituted split inteins                | Cell surface/intracellular | Intein-mediated protein <i>trans</i> splicing removes intein after reaction (traceless); yield 55–90% and $k = 0.9 - 4.7 \text{ s}^{-1}$ using Npu DnaE intein and AceL-TerL intein  | Giriat (2003) <sup>181</sup><br>Schütz (2014) <sup>182</sup>   |
| TITSSYYR (8)  |                 | AnkX from <i>Legionella pneumophila</i>    | <i>In vitro</i>            | $k_{\text{cat}}/K_{\text{m}} = 0.9 - 5 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$ , covalent labeling can be removed by Lem1   | Heller (2015) <sup>183</sup>   |
| Tub-tag (14): VDSVEGEGEEGEE   |                 | Recombinant tubulin tyrosine ligase (TTL)  | In fixed cell              | Yield up to 99% with moderate enzyme concentrations and short reaction times   | Schumacher (2015) <sup>184</sup>   |
| <b>F. Incorporation of UAA as a “minimalist” tag</b>                                |  |  |                            |  |  |
|  |                 | BCN-RS/trNA <sub>CUA</sub>                 | Cell surface/intracellular | UAA bearing BCN or TCO can be site-specifically incorporated to proteins in live cells for labeling with tetrazine dyes  | Lang (2012) <sup>46</sup>  |

AA: amino acids. (A) BG: *O*<sup>6</sup>-benzylguanine; BC: *O*<sup>2</sup>-benzylcytosine; BG-FL: BG-fluorescein conjugate; BC-FL: BC-fluorescein conjugate. (E) ACP: acyl carrier protein; PPTase: 4'-phosphopantetheinyl transferase; CoA: coenzyme A; PCP: peptide carrier proteins.

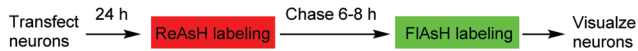
However, this labeling technology suffers practically from non-specific labeling of thiol-rich biomolecules in the cell and the toxicity of the biarsenical ligands.<sup>194</sup> Nevertheless, the tetra-cysteine motif (CCXXCC) is much smaller than FPs. Other self-labeling peptide tags include the bisboronic RhoBo-tetraserine tagging system,<sup>158</sup> hydrazide-reactive (HyRe) tag,<sup>159</sup> SpyTag<sup>160</sup> and E3 tag<sup>161,162</sup> (Table 4B).

Prominent applications of self-labeling peptide tag approaches involve visualization of newly synthesized proteins and tracking of protein trafficking in live cells. This is readily achieved *via* the “pulse-chase” technique. The old populations of proteins were pulse-labeled by green-emitting FAsH, while the newly synthesized proteins were chased by red-emitting ReAsH. Consequently, old and new copies of an individual



A) The chemical structure of ReAsH-EDT<sub>2</sub> and FIAsh-EDT<sub>2</sub>

## B) The "pulse-chase" labeling scheme



**Scheme 4** Dual-color "pulse-chase" labeling of neurons using ReAsH and FIAsh for the visualization of the synthesis and trafficking of AMPA receptors.

protein were labeled using two colors. In one example, this approach was used to elucidate the mechanism of connexin assembly and turnover in HeLa cells.<sup>191</sup> In another example, the approach was employed to study AMPA receptor (AMPA) trafficking. Regulation of AMPA receptor (AMPA) trafficking is important for neural plasticity. GluR1 and GluR2 are two AMPAR subunits that play a key role in the activity-dependent trafficking of the AMPARs during long-term potentiation (LTP) and depression (LTD). In order to examine the trafficking and synthesis of GluR1 and GluR2, a tetracysteine motif (EAAAR-EACCRECCARA) was attached at the C-termini. ReAsH-EDT<sub>2</sub> was first applied and after 6–8 h, FIAsh-EDT<sub>2</sub> was applied to cells expressing tetracysteine-tagged GluR1 or GluR2 (Scheme 4B). In this case, the red ReAsH-EDT<sub>2</sub> labels all pre-existing GluR1/2 subunits, while the green FIAsh-EDT<sub>2</sub> labels those AMPAR subunits synthesized during the 6–8 h chase period. The measurements suggested that both GluR1 and GluR2 are synthesized in dendrites and that an activity blockade enhances the dendritic synthesis of GluR1 but not GluR2.<sup>195</sup>

### 4.3. Ligand binding domains (LBDs)

The specific interaction between the ligand binding domain (LBD) and its small-molecule ligand confers specificity of labeling in cells. SLF', a derivative of the synthetic ligand of FKBP12 (FK506 binding protein), binds to FKBP' (FKBP12\_F36 V mutant) with more than 1000-fold selectivity over the wild type FKBP12 protein.<sup>163</sup> Based on this specific binding, proteins fused with FKBP' have been selectively labeled by SLF'-conjugated probes in live cells.<sup>164</sup> The antibiotic trimethoprim (TMP) is a specific inhibitor of *E. coli* dihydrofolate reductase (eDHFR). TMP binds to eDHFR with nanomolar affinity, which is over 1000-fold higher than the interaction with mammalian DHFR. As a result, the off-target labeling by TMP probes is minimal under certain conditions.<sup>165</sup>

Because of the non-covalent binding, the labeling *via* the FKBP' or eDHFR tag is reversible. In order to achieve a stable labeling, the affinity conjugation approach has been introduced. A cysteine mutation is introduced in the proximity of the TMP binding site on eDHFR, which can be specifically labeled by TMP-acryloyl probes due to a proximity-induced

effect.<sup>196</sup> The reaction of a mildly reactive acryloyl group with other thiols in the cell is minimal under certain conditions.<sup>197</sup> Based on the affinity conjugation principle, a rapid and fluorogenic TMP-AcBOPDIPY probe is developed with a half-life of less than 2 min for covalent labeling (Fig. 4A).<sup>166</sup> Intracellular proteins fused with eDHFR\_N23C were rapidly labeled by the TMP-AcBOPDIPY probe under no-wash conditions (Fig. 4B). In addition, the chemical probe displays a superior dynamic range in fluorescence lifetime imaging microscopy (FLIM) for intracellular FRET studies.

Recently, a more versatile "tagging-then-labeling" approach has been realized, enabling efficient introduction of bioorthogonal groups into proteins for bioorthogonal labeling in live cells. The TMP-AcAz ligand incorporates an azido group to proteins fused with the eDHFR tag (Fig. 4C). Subsequently, strain promoted cycloaddition reactions using DBCO- or BCN-conjugates facilitate protein labeling with various probes inside live cells (Fig. 4D).<sup>111</sup>

The eDHFR tag has been used for live-cell imaging of protein-protein interactions (PPIs) between the first PDZ domain of ZO-1 (fused with eDHFR) and the C-terminal YV motif of claudin-1 (fused with GFP) using time resolved luminescence resonance energy transfer (LRET) technique (Fig. 5).<sup>198</sup> Conventional FRET imaging suffers from fluorescence bleed-through, leading to high background. In the LRET approach, background signals from cellular auto-fluorescence and direct excitation of GFP were effectively eliminated by imposing a time delay of 10  $\mu$ s between excitation and detection.

Photoactive yellow protein (PYP) is a small (14 kDa) soluble protein found in several purple bacteria. It binds to a natural cofactor, the CoA thioester of 4-hydroxycinnamic acid through transthioesterification with Cys69. It also binds to the thioester derivative of coumarin-3-carboxylic acid. Since PYP and its ligands do not exist in animal cells, they can therefore be employed for bioorthogonal labeling of proteins ( $k = 1.1$ – $124 \text{ M}^{-1} \text{ s}^{-1}$ ).<sup>167,168</sup>

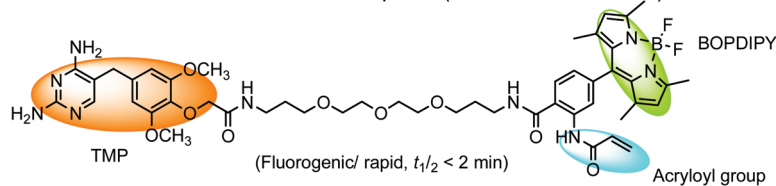
### 4.4. Self-labeling enzymatic domains

Enzyme-catalyzed reactions that proceed *via* irreversible conjugation with "suicide substrates" have been used for protein labeling in live cells. A variety of enzyme-substrate pairs are available. Many of these enzymes are able to tolerate modifications to their substrates. By generating fusion constructs with a protein, it is possible to covalently link the modified substrate to the protein. Generally, these reactions are specific, rapid and irreversible.

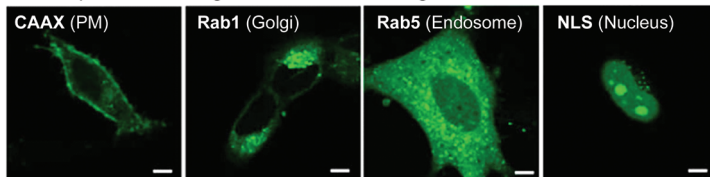
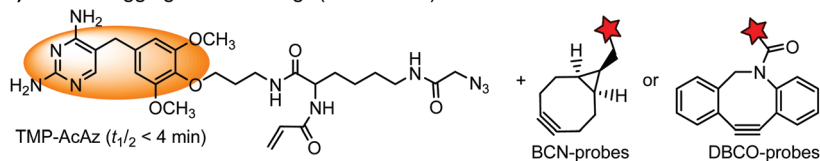
O<sup>6</sup>-Alkylguanine transferase (AGT), a human DNA repair protein, has been used as a self-labeling tag.<sup>169,199</sup> The reaction involves the irreversible transfer of the alkyl group of O<sup>6</sup>-benzylguanine (BG) derivatives to the reactive cysteine residue within the enzyme to generate a covalently modified protein. More efficient AGT mutants, termed SNAP-tags (19 kDa), have been developed.<sup>169</sup> An orthogonal AGT-based tag, termed a CLIP-tag, reacts specifically with O<sup>2</sup>-benzylcytosine derivatives.<sup>157</sup>



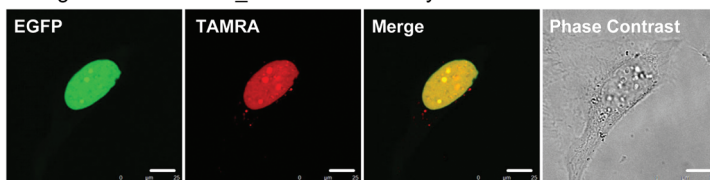
## A) Chemical structure of TMP-AcBOPDIPY probe (Liu/Li/Chen/Hou 2014)



## B) No-wash protein labeling inside live cells using TMP-AcBOPDIPY

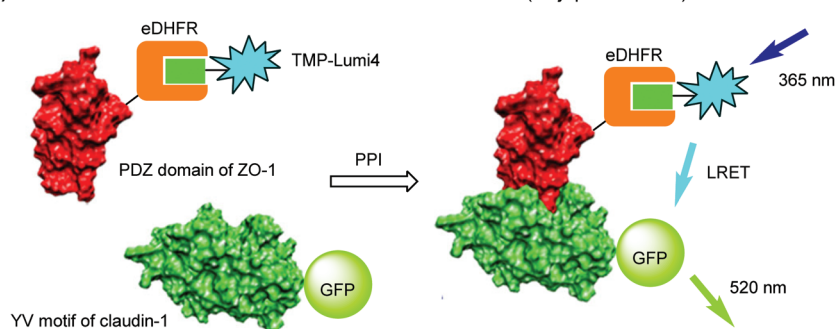
C) *In vivo* "tagging-then-labeling" (Chen 2015)

## D) Labeling of EGFP-eDHFR\_N23C/L28C-NLS by BCN-TAMRA

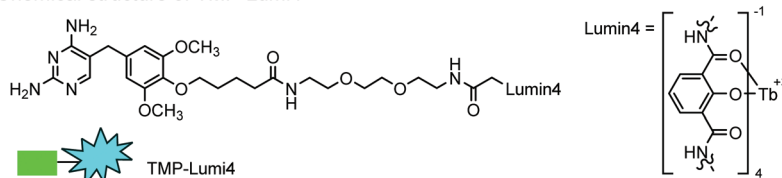


**Fig. 4** (A) The chemical structure of the TMP-AcBOPDIPY probe (BOPDIPY: boron phenyldipyrrolemethene). (B) Cellular labeling of eDHFR\_N23C fused with a K-Ras C-terminal sequence (CAAX), Rab1, Rab5, and nucleus localizing sequence (NLS) at the plasma membrane (PM), the Golgi body, the endosomes, and the nucleus, respectively, using the TMP-AcBOPDIPY probe under no-wash conditions. (C) The "tagging-then-labeling" approach using the TMP-AcAz ligand and BCN or DBCO probes for labeling intracellular proteins in live cells. (D) Specific labeling of EGFP-eDHFR\_N23C/L28C-NLS at the nucleus in living HeLa cells by the BCN-TAMRA probe. Scale bar: 10  $\mu$ m.

## A) Schematic view of intermolecular terbium-to-GFP LRET (Rajapakse 2010)



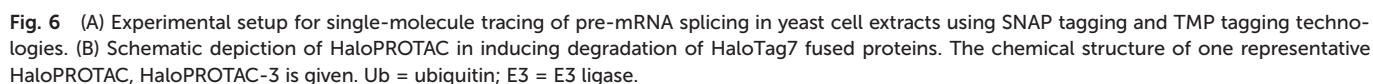
## B) Chemical structure of TMP-Lumi4



**Fig. 5** Time resolved LRET for live-cell imaging of protein-protein interactions using the eDHFR tag.

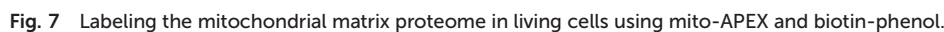






$\beta$ -Lactamase is a small bacterial enzyme (29 kDa) that hydrolyzes  $\beta$ -lactam antibiotics. The E166N mutation of  $\beta$ -lactamase leads to the accumulation of acyl-enzyme intermediates due to the dramatic suppression of deacylation. The mutant  $\beta$ -lactamase, termed BL-tag, and  $\beta$ -lactam probes have been used for

A number of post-translational modifications have been harnessed to specifically incorporate chemical probes or bioorthogonal handles into proteins (Table 4E). The first example is the modification of cell surface proteins using *E. coli* biotin ligase (BirA). The enzyme recognizes and biotinylates a 15-mer acceptor peptide (AP) sequence. Using a synthetic ketone-containing biotin isostere (keto-biotin) as a substrate, BirA can be used as a “ketone ligase” to introduce a ketone handle for oxime ligation.<sup>83</sup> Another example is *E. coli* lipoic acid ligase, which is able to transfer a lipoic acid derivative carrying an azide<sup>178</sup> or a TCO moiety to proteins.<sup>119</sup> The introduced azide and TCO moieties facilitate subsequent labeling using strained cyclooctyne and tetrazine probes, respectively.<sup>119,178</sup> The formylglycine-generating enzyme (FGE) specifically oxidizes the cysteine in the consensus LCXPXR motif to the formyl glycine. Subsequently, the aldehyde tag generated by the FGE on the target protein can selectively react with aminoxy and hydrazide probes.<sup>79</sup> Reconstitution of the split inteins mediates protein *trans* splicing (PTS). After ligation of the N- and C-peptide fragments, the intein is eventually removed.<sup>181</sup> By choosing appropriate naturally split inteins, PTS reactions can proceed efficiently in live cells.<sup>182,207</sup> The bacterial enzyme AnkX from *Legionella pneumophila* has been used to transfer phosphocholine moieties from synthetically produced CDP-choline derivatives to a consensus sequence, TITSSYYR, at the termini or internal loop regions of a POI. The covalent labeling can be removed by another *Legionella* dephosphocholineation enzyme Lem3.<sup>183</sup>



This journal is © The Royal Society of Chemistry 2016

Since there are few “perfect” bioorthogonal reactions available, one has to carefully consider both the pros and cons of each reaction in order to identify the most suited ones for a particular application.

Chemical tagging approaches allow for the incorporation of probes or bioorthogonal handles into proteins in cells and organisms. However, most of these approaches rely on exogenous expression of the POI with tags or UAAs. Although the investigation of exogenous proteins is useful for unraveling biological processes, the advance in selective labeling of endogenous proteins should facilitate the proteomic analysis of cellular organelles and protein complexes, target identification and diagnosis. An advantage of chemical probes over FPs lies in the flexibility of modifications on organic dyes. Therefore, the development of new organic dyes with special properties, *e.g.* photo-switchable, activatable, highly fluorogenic, bright, far-red emissive, *etc.*, should substantially help to understand the biological mechanisms of proteins in the context of living systems.

## Acknowledgements

This work was supported by DFG grants (grant no. SPP 1623 and SFB 642 to Y. W. W.).

## References

- 1 L. Spasser and A. Brik, *Angew. Chem., Int. Ed.*, 2012, **51**, 6840–6862.
- 2 C. D. Spicer and B. G. Davis, *Nat. Commun.*, 2014, **5**, 4740.
- 3 K. Lang and J. W. Chin, *Chem. Rev.*, 2014, **114**, 4764–4806.
- 4 D. M. Patterson, L. A. Nazarova and J. A. Prescher, *ACS Chem. Biol.*, 2014, **9**, 592–605.
- 5 K. M. Marks and G. P. Nolan, *Nat. Methods*, 2006, **3**, 591–596.
- 6 E. M. Sletten and C. R. Bertozzi, *Angew. Chem., Int. Ed.*, 2009, **48**, 6974–6998.
- 7 M. Vila-Perello and T. W. Muir, *Cell*, 2010, **143**, 191–200.
- 8 C. P. R. Hackenberger and D. Schwarzer, *Angew. Chem., Int. Ed.*, 2008, **47**, 10030–10074.
- 9 C. R. Jing and V. W. Cornish, *Acc. Chem. Res.*, 2011, **44**, 784–792.
- 10 Y. W. Wu and R. S. Goody, *J. Pept. Sci.*, 2010, **16**, 514–523.
- 11 J. Li and P. R. Chen, *ChemBioChem*, 2012, **13**, 1728–1731.
- 12 H. W. Shih, D. N. Kamber and J. A. Prescher, *Curr. Opin. Chem. Biol.*, 2014, **21**, 103–111.
- 13 M. F. Debets, J. C. M. van Hest and F. P. J. T. Rutjes, *Org. Biomol. Chem.*, 2013, **11**, 6439–6455.
- 14 C. S. McKay and M. G. Finn, *Chem. Biol.*, 2014, **21**, 1075–1101.
- 15 M. Yang, J. Li and P. R. Chen, *Chem. Soc. Rev.*, 2014, **43**, 6511–6526.
- 16 M. A. Tasdelen and Y. Yagci, *Angew. Chem., Int. Ed.*, 2013, **52**, 5930–5938.
- 17 Y. K. Gong and L. F. Pan, *Tetrahedron Lett.*, 2015, **56**, 2123–2132.
- 18 R. K. Lim and Q. Lin, *Chem. Commun.*, 2010, **46**, 1589–1600.
- 19 J. M. Chalker, G. J. Bernardes and B. G. Davis, *Acc. Chem. Res.*, 2011, **44**, 730–741.
- 20 A. Dirksen, T. M. Hackeng and P. E. Dawson, *Angew. Chem., Int. Ed.*, 2006, **45**, 7581–7584.
- 21 M. Wendeler, L. Grinberg, X. Wang, P. E. Dawson and M. Baca, *Bioconjugate Chem.*, 2014, **25**, 93–101.
- 22 P. Crisalli and E. T. Kool, *J. Org. Chem.*, 2013, **78**, 1184–1189.
- 23 T. Sasaki, K. Kodama, H. Suzuki, S. Fukuzawa and K. Tachibana, *Bioorg. Med. Chem. Lett.*, 2008, **18**, 4550–4553.
- 24 P. Agarwal, J. van der Weijden, E. M. Sletten, D. Rabuka and C. R. Bertozzi, *Proc. Natl. Acad. Sci. U. S. A.*, 2013, **110**, 46–51.
- 25 P. Agarwal, R. Kudirka, A. E. Albers, R. M. Barfield, G. W. de Hart, P. M. Drake, L. C. Jones and D. Rabuka, *Bioconjugate Chem.*, 2013, **24**, 846–851.
- 26 P. I. Kitov, D. F. Vinals, S. Ng, K. F. Tjhung and R. Derda, *J. Am. Chem. Soc.*, 2014, **136**, 8149–8152.
- 27 A. Ji, W. Ren and H. W. Ai, *Chem. Commun.*, 2014, **50**, 7469–7472.
- 28 J. Alam, T. H. Keller and T. P. Loh, *J. Am. Chem. Soc.*, 2010, **132**, 9546–9548.
- 29 J. W. Bode, R. M. Fox and K. D. Baucom, *Angew. Chem., Int. Ed.*, 2006, **45**, 1248–1252.
- 30 V. R. Pattabiraman, A. O. Ogunkoya and J. W. Bode, *Angew. Chem., Int. Ed.*, 2012, **51**, 5114–5118.
- 31 M. Raj, H. B. Wu, S. L. Blosser, M. A. Vittoria and P. S. Arora, *J. Am. Chem. Soc.*, 2015, **137**, 6932–6940.
- 32 E. Saxon and C. R. Bertozzi, *Science*, 2000, **287**, 2007–2010.
- 33 B. L. Nilsson, L. L. Kiessling and R. T. Raines, *Org. Lett.*, 2001, **3**, 9–12.
- 34 A. Tam, M. B. Soellner and R. T. Raines, *J. Am. Chem. Soc.*, 2007, **129**, 11421–11430.
- 35 R. Serwa, I. Wilkening, G. Del Signore, M. Muhlberg, I. Claussnitzer, C. Weise, M. Gerrits and C. P. Hackenberger, *Angew. Chem., Int. Ed.*, 2009, **48**, 8234–8239.
- 36 V. V. Rostovtsev, L. G. Green, V. V. Fokin and K. B. Sharpless, *Angew. Chem., Int. Ed.*, 2002, **41**, 2596–2599.
- 37 S. I. Presolski, V. Hong, S. H. Cho and M. G. Finn, *J. Am. Chem. Soc.*, 2010, **132**, 14570–14576.
- 38 S. S. van Berkel, A. T. J. Dirks, M. F. Debets, F. L. van Delft, J. J. L. M. Cornelissen, R. J. M. Nolte and F. P. J. T. Rutjes, *ChemBioChem*, 2007, **8**, 1504–1508.
- 39 N. J. Agard, J. A. Prescher and C. R. Bertozzi, *J. Am. Chem. Soc.*, 2004, **126**, 15046–15047.
- 40 J. M. Baskin, J. A. Prescher, S. T. Laughlin, N. J. Agard, P. V. Chang, I. A. Miller, A. Lo, J. A. Codelli and C. R. Bertozzi, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 16793–16797.
- 41 X. H. Ning, J. Guo, M. A. Wolfert and G. J. Boons, *Angew. Chem., Int. Ed.*, 2008, **47**, 2253–2255.



- 42 J. C. Jewett, E. M. Sletten and C. R. Bertozzi, *J. Am. Chem. Soc.*, 2010, **132**, 3688–3690.
- 43 J. Dommerholt, S. Schmidt, R. Temming, L. J. Hendriks, F. P. Rutjes, J. C. van Hest, D. J. Lefeber, P. Friedl and F. L. van Delft, *Angew. Chem., Int. Ed.*, 2010, **49**, 9422–9425.
- 44 J. Dommerholt, O. van Rooijen, A. Borrmann, C. F. Guerra, F. M. Bickelhaupt and F. L. van Delft, *Nat. Commun.*, 2014, **5**, 5378–5384.
- 45 M. L. Blackman, M. Royzen and J. M. Fox, *J. Am. Chem. Soc.*, 2008, **130**, 13518–13519.
- 46 K. Lang, L. Davis, S. Wallace, M. Mahesh, D. J. Cox, M. L. Blackman, J. M. Fox and J. W. Chin, *J. Am. Chem. Soc.*, 2012, **134**, 10317–10320.
- 47 N. K. Devaraj, R. Weissleder and S. A. Hilderbrand, *Bioconjugate Chem.*, 2008, **19**, 2297–2299.
- 48 D. M. Patterson, L. A. Nazarova, B. Xie, D. N. Kamber and J. A. Prescher, *J. Am. Chem. Soc.*, 2012, **134**, 18638–18643.
- 49 T. S. Elliott, F. M. Townsley, A. Bianco, R. J. Ernst, A. Sachdeva, S. J. Elsasser, L. Davis, K. Lang, R. Pisa, S. Greiss, K. S. Lilley and J. W. Chin, *Nat. Biotechnol.*, 2014, **32**, 465–472.
- 50 S. B. Engelsma, L. I. Willems, C. E. van Paaschen, S. I. van Kasteren, G. A. van der Marel, H. S. Overkleeft and D. V. Filippov, *Org. Lett.*, 2014, **16**, 2744–2747.
- 51 A. Niederwieser, A. K. Spate, L. D. Nguyen, C. Jungst, W. Reutter and V. Wittmann, *Angew. Chem., Int. Ed.*, 2013, **52**, 4265–4268.
- 52 H. Stockmann, A. A. Neves, S. Stairs, K. M. Brindle and F. J. Leeper, *Org. Biomol. Chem.*, 2011, **9**, 7303–7305.
- 53 X. H. Ning, R. P. Temming, J. Dommerholt, J. Guo, D. B. Ania, M. F. Debets, M. A. Wolfert, G. J. Boons and F. L. van Delft, *Angew. Chem., Int. Ed.*, 2010, **49**, 3065–3068.
- 54 N. A. McGrath and R. T. Raines, *Chem. Sci.*, 2012, **3**, 3237–3240.
- 55 L. Josa-Cullere, Y. A. Wainman, K. M. Brindle and F. J. Leeper, *RSC Adv.*, 2014, **4**, 52241–52244.
- 56 S. Wallace and J. W. Chin, *Chem. Sci.*, 2014, **5**, 1742–1744.
- 57 E. M. Sletten and C. R. Bertozzi, *J. Am. Chem. Soc.*, 2011, **133**, 17570–17573.
- 58 K. Gutmiedl, C. T. Wirges, V. Ehmke and T. Carell, *Org. Lett.*, 2009, **11**, 2405–2408.
- 59 Q. Li, T. Dong, X. H. Liu and X. G. Lei, *J. Am. Chem. Soc.*, 2013, **135**, 4996–4999.
- 60 X. Y. Zhang, T. Dong, Q. Li, X. H. Liu, L. Li, S. Chen and X. G. Lei, *ACS Chem. Biol.*, 2015, **10**, 1676–1683.
- 61 Y. Z. Wang, W. J. Hu, W. J. Song, R. K. V. Lint and Q. Lin, *Org. Lett.*, 2008, **10**, 3725–3728.
- 62 Y. Z. Wang, W. J. Song, W. J. Hu and Q. Lin, *Angew. Chem., Int. Ed.*, 2009, **48**, 5330–5333.
- 63 R. K. V. Lim and Q. Lin, *Chem. Commun.*, 2010, **46**, 7993–7995.
- 64 J. M. Chalker, C. S. C. Wood and B. G. Davis, *J. Am. Chem. Soc.*, 2009, **131**, 16346–16347.
- 65 K. Kodama, S. Fukuzawa, H. Nakayama, K. Sakamoto, T. Kigawa, T. Yabuki, N. Matsuda, M. Shirouzu, K. Takio, S. Yokoyama and K. Tachibana, *ChemBioChem*, 2007, **8**, 232–238.
- 66 Y. A. Lin, J. M. Chalker, N. Floyd, G. J. L. Bernardes and B. G. Davis, *J. Am. Chem. Soc.*, 2008, **130**, 9642–9643.
- 67 M. E. Ourailidou, J. Y. van der Meer, B. J. Baas, M. Jeronimus-Stratingh, A. L. Gottumukkala, G. J. Poelarends, A. J. Minnaard and F. J. Dekker, *ChemBioChem*, 2014, **15**, 209–212.
- 68 J. Li, J. T. Yu, J. Y. Zhao, J. Wang, S. Q. Zheng, S. X. Lin, L. Chen, M. Y. Yang, S. Jia, X. Y. Zhang and P. R. Chen, *Nat. Chem.*, 2014, **6**, 352–361.
- 69 Y. G. Kim, S. O. Ho, N. R. Gassman, Y. Korlann, E. V. Landorf, F. R. Collart and S. Weiss, *Bioconjugate Chem.*, 2008, **19**, 786–791.
- 70 E. V. Vinogradova, C. Zhang, A. M. Spokoyny, B. L. Pentelute and S. L. Buchwald, *Nature*, 2015, **526**, 687–691.
- 71 G. J. L. Bernardes, J. M. Chalker, J. C. Errey and B. G. Davis, *J. Am. Chem. Soc.*, 2008, **130**, 5052–5053.
- 72 H. J. Ren, F. Xiao, K. Zhan, Y. P. Kim, H. X. Xie, Z. Y. Xia and J. Rao, *Angew. Chem., Int. Ed.*, 2009, **48**, 9658–9662.
- 73 P. E. Dawson, T. W. Muir, I. Clarklewis and S. B. H. Kent, *Science*, 1994, **266**, 776–779.
- 74 S. Shaunak, A. Godwin, J. W. Choi, S. Balan, E. Pedone, D. Vijayarangam, S. Heidelberger, I. Teo, M. Zloh and S. Brocchini, *Nat. Chem. Biol.*, 2006, **2**, 312–313.
- 75 N. Assem, D. J. Ferreira, D. W. Wolan and P. E. Dawson, *Angew. Chem., Int. Ed.*, 2015, **54**, 8665–8668.
- 76 S. Ulrich, D. Boturyn, A. Marra, O. Renaudet and P. Dumy, *Chem. – Eur. J.*, 2014, **20**, 34–41.
- 77 E. T. Kool, D. H. Park and P. Crisalli, *J. Am. Chem. Soc.*, 2013, **135**, 17663–17666.
- 78 J. Stockigt, A. P. Antonchick, F. Wu and H. Waldmann, *Angew. Chem., Int. Ed.*, 2011, **50**, 8538–8564.
- 79 I. S. Carrico, B. L. Carlson and C. R. Bertozzi, *Nat. Chem. Biol.*, 2007, **3**, 321–322.
- 80 L. K. Mahal, K. J. Yarema and C. R. Bertozzi, *Science*, 1997, **276**, 1125–1128.
- 81 H. C. Hang and C. R. Bertozzi, *J. Am. Chem. Soc.*, 2001, **123**, 1242–1243.
- 82 Y. Zeng, T. N. Ramya, A. Dirksen, P. E. Dawson and J. C. Paulson, *Nat. Methods*, 2009, **6**, 207–209.
- 83 I. Chen, M. Howarth, W. Y. Lin and A. Y. Ting, *Nat. Methods*, 2005, **2**, 99–104.
- 84 M. F. Debets, C. W. van der Doelen, F. P. Rutjes and F. L. van Delft, *ChemBioChem*, 2010, **11**, 1168–1184.
- 85 C. W. Tornoe, C. Christensen and M. Meldal, *J. Org. Chem.*, 2002, **67**, 3057–3064.
- 86 M. Grammel and H. C. Hang, *Nat. Chem. Biol.*, 2013, **9**, 475–484.
- 87 M. D. Best, *Biochemistry*, 2009, **48**, 6571–6584.
- 88 V. Hong, N. F. Steinmetz, M. Manchester and M. G. Finn, *Bioconjugate Chem.*, 2010, **21**, 1912–1916.
- 89 D. C. Kennedy, C. S. McKay, M. C. Legault, D. C. Danielson, J. A. Blake, A. F. Pegoraro, A. Stolor, S. Yokoyama and K. Tachibana, *ChemBioChem*, 2007, **8**, 232–238.





- Z. Mester and J. P. Pezacki, *J. Am. Chem. Soc.*, 2011, **133**, 17993–18001.
- 90 C. Uttamapinant, A. Tangpeerachaikul, S. Grecian, S. Clarke, U. Singh, P. Slade, K. R. Gee and A. Y. Ting, *Angew. Chem., Int. Ed.*, 2012, **51**, 5852–5856.
- 91 M. Y. Yang, A. S. Jalloh, W. Wei, J. Zhao, P. Wu and P. R. Chen, *Nat. Commun.*, 2014, **5**, 4981.
- 92 F. Xie, K. Sivakumar, Q. B. Zeng, M. A. Bruckman, B. Hodges and Q. Wang, *Tetrahedron*, 2008, **64**, 2906–2914.
- 93 K. Sivakumar, F. Xie, B. M. Cash, S. Long, H. N. Barnhill and Q. Wang, *Org. Lett.*, 2004, **6**, 4603–4606.
- 94 Y. Urano, M. Kamiya, K. Kanda, T. Ueno, K. Hirose and T. Nagano, *J. Am. Chem. Soc.*, 2005, **127**, 4888–4894.
- 95 P. Shieh, M. J. Hangauer and C. R. Bertozzi, *J. Am. Chem. Soc.*, 2012, **134**, 17428–17431.
- 96 P. Shieh, V. T. Dien, B. J. Beahm, J. M. Castellano, T. Wyss-Coray and C. R. Bertozzi, *J. Am. Chem. Soc.*, 2015, **137**, 7145–7151.
- 97 Y. Su, J. Y. Ge, B. W. Zhu, Y. G. Zheng, Q. Zhu and S. Q. Yao, *Curr. Opin. Chem. Biol.*, 2013, **17**, 768–775.
- 98 E. M. Sletten and C. R. Bertozzi, *Org. Lett.*, 2008, **10**, 3097–3099.
- 99 B. Gold, N. E. Shevchenko, N. Bonus, G. B. Dudley and I. V. Alabugin, *J. Org. Chem.*, 2012, **77**, 75–89.
- 100 M. F. Debets, S. S. van Berkel, J. Dommerholt, A. T. Dirks, F. P. Rutjes and F. L. van Delft, *Acc. Chem. Res.*, 2011, **44**, 805–815.
- 101 N. J. Agard, J. M. Baskin, J. A. Prescher, A. Lo and C. R. Bertozzi, *ACS Chem. Biol.*, 2006, **1**, 644–648.
- 102 A. A. Poloukhine, N. E. Mbua, M. A. Wolfert, G. J. Boons and V. V. Popik, *J. Am. Chem. Soc.*, 2009, **131**, 15769–15776.
- 103 M. F. Debets, S. S. van Berkel, S. Schoffelen, F. P. Rutjes, J. C. van Hest and F. L. van Delft, *Chem. Commun.*, 2010, **46**, 97–99.
- 104 B. R. Varga, M. Kallay, K. Hegyi, S. Beni and P. Kele, *Chem. – Eur. J.*, 2012, **18**, 822–828.
- 105 C. G. Gordon, J. L. Mackey, J. C. Jewett, E. M. Sletten, K. N. Houk and C. R. Bertozzi, *J. Am. Chem. Soc.*, 2012, **134**, 9199–9208.
- 106 E. M. Sletten, H. Nakamura, J. C. Jewett and C. R. Bertozzi, *J. Am. Chem. Soc.*, 2010, **132**, 11799–11805.
- 107 G. de Almeida, E. M. Sletten, H. Nakamura, K. K. Palaniappan and C. R. Bertozzi, *Angew. Chem., Int. Ed.*, 2012, **51**, 2443–2447.
- 108 J. M. Medina, T. C. McMahon, G. Jimenez-Oses, K. N. Houk and N. K. Garg, *J. Am. Chem. Soc.*, 2014, **136**, 14706–14709.
- 109 S. Jang, K. Sachin, H. J. Lee, D. W. Kim and H. S. Lee, *Bioconjugate Chem.*, 2012, **23**, 2256–2261.
- 110 B. Belardi, A. de la Zerda, D. R. Spicariach, S. L. Maund, D. M. Peehl and C. R. Bertozzi, *Angew. Chem., Int. Ed.*, 2013, **52**, 14045–14049.
- 111 X. Chen, F. Li and Y. W. Wu, *Chem. Commun.*, 2015, **51**, 16537–16540.
- 112 N. K. Devaraj and R. Weissleder, *Acc. Chem. Res.*, 2011, **44**, 816–827.
- 113 Y. Liang, J. L. Mackey, S. A. Lopez, F. Liu and K. N. Houk, *J. Am. Chem. Soc.*, 2012, **134**, 17904–17907.
- 114 Z. Li, D. Wang, L. Li, S. Pan, Z. Na, C. Y. Tan and S. Q. Yao, *J. Am. Chem. Soc.*, 2014, **136**, 9990–9998.
- 115 M. R. Karver, R. Weissleder and S. A. Hilderbrand, *Bioconjugate Chem.*, 2011, **22**, 2263–2270.
- 116 M. T. Taylor, M. L. Blackman, O. Dmitrenko and J. M. Fox, *J. Am. Chem. Soc.*, 2011, **133**, 9646–9649.
- 117 I. Nikic, T. Plass, O. Schraidt, J. Szymanski, J. A. Briggs, C. Schultz and E. A. Lemke, *Angew. Chem., Int. Ed.*, 2014, **53**, 2245–2249.
- 118 N. K. Devaraj, S. Hilderbrand, R. Upadhyay, R. Mazitschek and R. Weissleder, *Angew. Chem., Int. Ed.*, 2010, **49**, 2869–2872.
- 119 D. S. Liu, A. Tangpeerachaikul, R. Selvaraj, M. T. Taylor, J. M. Fox and A. Y. Ting, *J. Am. Chem. Soc.*, 2012, **134**, 792–795.
- 120 J. C. Carlson, L. G. Meimetis, S. A. Hilderbrand and R. Weissleder, *Angew. Chem., Int. Ed.*, 2013, **52**, 6917–6920.
- 121 L. G. Meimetis, J. C. Carlson, R. J. Giedt, R. H. Kohler and R. Weissleder, *Angew. Chem., Int. Ed.*, 2014, **53**, 7531–7534.
- 122 M. R. Karver, R. Weissleder and S. A. Hilderbrand, *Angew. Chem., Int. Ed.*, 2012, **51**, 920–922.
- 123 Z. Gao, V. Gouverneur and B. G. Davis, *J. Am. Chem. Soc.*, 2013, **135**, 13612–13615.
- 124 C. D. Spicer, T. Triemer and B. G. Davis, *J. Am. Chem. Soc.*, 2012, **134**, 800–803.
- 125 N. Li, R. K. Lim, S. Edwardraja and Q. Lin, *J. Am. Chem. Soc.*, 2011, **133**, 15316–15319.
- 126 Y. A. Lin and B. G. Davis, *Beilstein J. Org. Chem.*, 2010, **6**, 1219–1228.
- 127 Y. A. Lin, J. M. Chalker and B. G. Davis, *J. Am. Chem. Soc.*, 2010, **132**, 16805–16811.
- 128 C. Streu and E. Meggers, *Angew. Chem., Int. Ed.*, 2006, **45**, 5645–5648.
- 129 S. Sechi and B. T. Chait, *Anal. Chem.*, 1998, **70**, 5150–5158.
- 130 J. M. Chalker, S. B. Gunnoo, O. Boutureira, S. C. Gerstberger, M. Fernandez-Gonzalez, G. J. L. Bernardes, L. Griffin, H. Hailu, C. J. Schofield and B. G. Davis, *Chem. Sci.*, 2011, **2**, 1666–1676.
- 131 J. M. Chalker, L. Lercher, N. R. Rose, C. J. Schofield and B. G. Davis, *Angew. Chem., Int. Ed.*, 2012, **51**, 1835–1839.
- 132 T. J. Tolbert and C. H. Wong, *Angew. Chem., Int. Ed.*, 2002, **41**, 2171–2174.
- 133 A. Godinat, H. M. Park, S. C. Miller, K. Cheng, D. Hanahan, L. E. Sanman, M. Boggyo, A. Yu, G. F. Nikitin, A. Stahl and E. A. Dubikovskaya, *ACS Chem. Biol.*, 2013, **8**, 987–999.
- 134 P. M. Drake and D. Rabuka, *Curr. Opin. Chem. Biol.*, 2015, **28**, 174–180.
- 135 Y. Takaoka, A. Ojida and I. Hamachi, *Angew. Chem., Int. Ed.*, 2013, **52**, 4088–4106.
- 136 H. B. F. Dixon, *J. Protein Chem.*, 1984, **3**, 99–108.
- 137 J. M. Gilmore, R. A. Scheck, A. P. Esser-Kahn, N. S. Joshi and M. B. Francis, *Angew. Chem., Int. Ed.*, 2006, **45**, 5307–5311.



- 138 A. O. Y. Chan, C. M. Ho, H. C. Chong, Y. C. Leung, J. S. Huang, M. K. Wong and C. M. Che, *J. Am. Chem. Soc.*, 2012, **134**, 2589–2598.
- 139 K. F. Geoghegan and J. G. Stroh, *Bioconjugate Chem.*, 1992, **3**, 138–146.
- 140 X. Chen, K. Muthoosamy, A. Pfisterer, B. Neumann and T. Weil, *Bioconjugate Chem.*, 2012, **23**, 500–508.
- 141 X. Chen, L. Henschke, Q. Wu, K. Muthoosamy, B. Neumann and T. Weil, *Org. Biomol. Chem.*, 2013, **11**, 353–361.
- 142 M. Lillich, X. Chen, T. Weil, H. Barth and J. Fahrner, *Bioconjugate Chem.*, 2012, **23**, 1426–1436.
- 143 T. Wang, D. Y. W. Ng, Y. Z. Wu, J. Thomas, T. TamTran and T. Weil, *Chem. Commun.*, 2014, **50**, 1116–1118.
- 144 M. Kunishima, S. Nakanishi, J. Nishida, H. Tanaka, D. Morisaki, K. Hioki and H. Nomoto, *Chem. Commun.*, 2009, 5597–5599.
- 145 Y. Koshi, E. Nakata, M. Miyagawa, S. Tsukiji, T. Ogawa and I. Hamachi, *J. Am. Chem. Soc.*, 2008, **130**, 245–251.
- 146 S. Tsukiji, M. Miyagawa, Y. Takaoka, T. Tamura and I. Hamachi, *Nat. Chem. Biol.*, 2009, **5**, 341–343.
- 147 S. Tsukiji, H. X. Wang, M. Miyagawa, T. Tamura, Y. Takaoka and I. Hamachi, *J. Am. Chem. Soc.*, 2009, **131**, 9046–9054.
- 148 H. X. Wang, Y. Koshi, D. Minato, H. Nonaka, S. Kiyonaka, Y. Mori, S. Tsukiji and I. Hamachi, *J. Am. Chem. Soc.*, 2011, **133**, 12220–12228.
- 149 T. Tamura, Y. Kioi, T. Miki, S. Tsukiji and I. Hamachi, *J. Am. Chem. Soc.*, 2013, **135**, 6782–6785.
- 150 S. H. Fujishima, R. Yasui, T. Miki, A. Ojida and I. Hamachi, *J. Am. Chem. Soc.*, 2012, **134**, 3961–3964.
- 151 T. Yamaguchi, M. Asanuma, S. Nakanishi, Y. Saito, M. Okazaki, K. Dodo and M. Sodeoka, *Chem. Sci.*, 2014, **5**, 1021–1029.
- 152 E. G. Guignet, R. Hovius and H. Vogel, *Nat. Biotechnol.*, 2004, **22**, 440–444.
- 153 R. Wieneke, N. Latoria, M. Rajan, A. Kollmannsperger, F. Natale, M. C. Cardoso and R. Tampe, *J. Am. Chem. Soc.*, 2014, **136**, 13975–13978.
- 154 C. T. Hauser and R. Y. Tsien, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 3693–3697.
- 155 A. Ojida, K. Honda, D. Shinmi, S. Kiyonaka, Y. Mori and I. Hamachi, *J. Am. Chem. Soc.*, 2006, **128**, 10452–10459.
- 156 B. A. Griffin, S. R. Adams and R. Y. Tsien, *Science*, 1998, **281**, 269–272.
- 157 A. Gautier, A. Juillerat, C. Heinis, I. R. Correa Jr., M. Kindermann, F. Beaufils and K. Johnsson, *Chem. Biol.*, 2008, **15**, 128–136.
- 158 T. L. Halo, J. Appelbaum, E. M. Hobert, D. M. Balkin and A. Schepartz, *J. Am. Chem. Soc.*, 2009, **131**, 438–439.
- 159 G. M. Eldridge and G. A. Weiss, *Bioconjugate Chem.*, 2011, **22**, 2143–2153.
- 160 B. Zakeri, J. O. Fierer, E. Celik, E. C. Chittock, U. Schwarz-Linek, V. T. Moy and M. Howarth, *Proc. Natl. Acad. Sci. U. S. A.*, 2012, **109**, E690–E697.
- 161 Z. Chen, B. V. Popp, C. L. Bovet and Z. T. Ball, *ACS Chem. Biol.*, 2011, **6**, 920–925.
- 162 U. Reinhardt, J. Lotze, S. Zernia, K. Morl, A. G. Beck-Sickinger and O. Seitz, *Angew. Chem., Int. Ed.*, 2014, **53**, 10237–10241.
- 163 T. Clackson, W. Yang, L. W. Rozamus, M. Hatada, J. F. Amara, C. T. Rollins, L. F. Stevenson, S. R. Magari, S. A. Wood, N. L. Courage, X. Lu, F. Cerasoli Jr., M. Gilman and D. A. Holt, *Proc. Natl. Acad. Sci. U. S. A.*, 1998, **95**, 10437–10442.
- 164 K. M. Marks, P. D. Braun and G. P. Nolan, *Proc. Natl. Acad. Sci. U. S. A.*, 2004, **101**, 9982–9987.
- 165 L. W. Miller, Y. Cai, M. P. Sheetz and V. W. Cornish, *Nat. Methods*, 2005, **2**, 255–257.
- 166 W. Liu, F. Li, X. Chen, J. Hou, L. Yi and Y. W. Wu, *J. Am. Chem. Soc.*, 2014, **136**, 4468–4471.
- 167 Y. Hori, H. Ueno, S. Mizukami and K. Kikuchi, *J. Am. Chem. Soc.*, 2009, **131**, 16610–16611.
- 168 Y. Hori, T. Norinobu, M. Sato, K. Arita, M. Shirakawa and K. Kikuchi, *J. Am. Chem. Soc.*, 2013, **135**, 12360–12365.
- 169 A. Keppler, S. Gendreizig, T. Gronemeyer, H. Pick, H. Vogel and K. Johnsson, *Nat. Biotechnol.*, 2003, **21**, 86–89.
- 170 S. Mizukami, S. Watanabe, Y. Hori and K. Kikuchi, *J. Am. Chem. Soc.*, 2009, **131**, 5016–5017.
- 171 G. V. Los, L. P. Encell, M. G. McDougall, D. D. Hartzell, N. Karassina, C. Zimprich, M. G. Wood, R. Learish, R. F. Ohana, M. Urh, D. Simpson, J. Mendez, K. Zimmerman, P. Otto, G. Vidugiris, J. Zhu, A. Darzins, D. H. Klaubert, R. F. Bulleit and K. V. Wood, *ACS Chem. Biol.*, 2008, **3**, 373–382.
- 172 R. Bonasio, C. V. Carman, E. Kim, P. T. Sage, K. R. Love, T. R. Mempel, T. A. Springer and U. H. von Andrian, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 14753–14758.
- 173 N. George, H. Pick, H. Vogel, N. Johnsson and K. Johnsson, *J. Am. Chem. Soc.*, 2004, **126**, 8896–8897.
- 174 J. Yin, P. D. Straight, S. M. McLoughlin, Z. Zhou, A. J. Lin, D. E. Golan, N. L. Kelleher, R. Kolter and C. T. Walsh, *Proc. Natl. Acad. Sci. U. S. A.*, 2005, **102**, 15815–15820.
- 175 Z. Zhou, P. Cironi, A. J. Lin, Y. Q. Xu, S. Hrvatin, D. E. Golan, P. A. Silver, C. T. Walsh and J. Yin, *ACS Chem. Biol.*, 2007, **2**, 337–346.
- 176 H. Sato, M. Ikeda, K. Suzuki and K. Hirayama, *Biochemistry*, 1996, **35**, 13072–13080.
- 177 C. W. Lin and A. Y. Ting, *J. Am. Chem. Soc.*, 2006, **128**, 4542–4543.
- 178 M. Fernandez-Suarez, H. Baruah, L. Martinez-Hernandez, K. T. Xie, J. M. Baskin, C. R. Bertozzi and A. Y. Ting, *Nat. Biotechnol.*, 2007, **25**, 1483–1487.
- 179 M. W. Popp, J. M. Antos, G. M. Grotenbreg, E. Spooner and H. L. Ploegh, *Nat. Chem. Biol.*, 2007, **3**, 707–708.
- 180 J. W. Wollack, J. M. Silverman, C. J. Petzold, J. D. Mougous and M. D. Distefano, *ChemBioChem*, 2009, **10**, 2934–2943.
- 181 I. Gariat and T. W. Muir, *J. Am. Chem. Soc.*, 2003, **125**, 7180–7181.
- 182 V. Schutz and H. D. Mootz, *Angew. Chem., Int. Ed.*, 2014, **53**, 4113–4117.



- 183 K. Heller, P. Ochtrop, M. F. Albers, F. B. Zauner, A. Itzen and C. Hedberg, *Angew. Chem., Int. Ed.*, 2015, **54**, 10327–10330.
- 184 D. Schumacher, J. Helma, F. A. Mann, G. Pichler, F. Natale, E. Krause, M. C. Cardoso, C. P. R. Hackenberger and H. Leonhardt, *Angew. Chem., Int. Ed.*, 2015, **54**, 13787–13791.
- 185 S. H. Uchinomiya, H. Nonaka, S. H. Fujishima, S. Tsukiji, A. Ojida and I. Hamachi, *Chem. Commun.*, 2009, 5880–5882.
- 186 K. Honda, S. H. Fujishima, A. Ojida and I. Hamachi, *ChemBioChem*, 2007, **8**, 1370–1372.
- 187 K. Honda, E. Nakata, A. Ojida and I. Hamachi, *Chem. Commun.*, 2006, 4024–4026.
- 188 H. Nonaka, S. Tsukiji, A. Ojida and I. Hamachi, *J. Am. Chem. Soc.*, 2007, **129**, 15777–15779.
- 189 C. R. Goldsmith, J. Jaworski, M. Sheng and S. J. Lippard, *J. Am. Chem. Soc.*, 2006, **128**, 418–419.
- 190 S. Uchinomiya, H. Nonaka, S. Wakayama, A. Ojida and I. Hamachi, *Chem. Commun.*, 2013, **49**, 5022–5024.
- 191 G. Gaietta, T. J. Deerinck, S. R. Adams, J. Bouwer, O. Tour, D. W. Laird, G. E. Sosinsky, R. Y. Tsien and M. H. Ellisman, *Science*, 2002, **296**, 503–507.
- 192 B. R. Martin, B. N. Giepmans, S. R. Adams and R. Y. Tsien, *Nat. Biotechnol.*, 2005, **23**, 1308–1314.
- 193 M. Andresen, R. Schmitz-Salue and S. Jakobs, *Mol. Biol. Cell*, 2004, **15**, 5616–5622.
- 194 C. Hoffmann, G. Gaietta, A. Zurn, S. R. Adams, S. Terrillon, M. H. Ellisman, R. Y. Tsien and M. J. Lohse, *Nat. Protoc.*, 2010, **5**, 1666–1677.
- 195 W. Ju, W. Morishita, J. Tsui, G. Gaietta, T. J. Deerinck, S. R. Adams, C. C. Garner, R. Y. Tsien, M. H. Ellisman and R. C. Malenka, *Nat. Neurosci.*, 2004, **7**, 244–253.
- 196 S. S. Gallagher, J. E. Sable, M. P. Sheetz and V. W. Cornish, *ACS Chem. Biol.*, 2009, **4**, 547–556.
- 197 Z. X. Chen, C. R. Jing, S. S. Gallagher, M. P. Sheetz and V. W. Cornish, *J. Am. Chem. Soc.*, 2012, **134**, 13692–13699.
- 198 H. E. Rajapakse, N. Gahlaut, S. Mohandessi, D. Yu, J. R. Turner and L. W. Miller, *Proc. Natl. Acad. Sci. U. S. A.*, 2010, **107**, 13582–13587.
- 199 A. Juillerat, T. Gronemeyer, A. Keppler, S. Gendreizig, H. Pick, H. Vogel and K. Johnsson, *Chem. Biol.*, 2003, **10**, 313–317.
- 200 A. A. Hoskins, L. J. Friedman, S. S. Gallagher, D. J. Crawford, E. G. Anderson, R. Wombacher, N. Ramirez, V. W. Cornish, J. Gelles and M. J. Moore, *Science*, 2011, **331**, 1289–1295.
- 201 Y. Zhang, M. K. So, A. M. Loening, H. Yao, S. S. Gambhir and J. Rao, *Angew. Chem., Int. Ed.*, 2006, **45**, 4936–4940.
- 202 K. M. Sakamoto, K. B. Kim, A. Kumagai, F. Mercurio, C. M. Crews and R. J. Deshaies, *Proc. Natl. Acad. Sci. U. S. A.*, 2001, **98**, 8554–8559.
- 203 D. L. Buckley, K. Raina, N. Darricarrere, J. Hines, J. L. Gustafson, I. E. Smith, A. H. Miah, J. D. Harling and C. M. Crews, *ACS Chem. Biol.*, 2015, **10**, 1831–1837.
- 204 S. Mizukami, Y. Hori and K. Kikuchi, *Acc. Chem. Res.*, 2014, **47**, 247–256.
- 205 S. Mizukami, S. Watanabe, Y. Akimoto and K. Kikuchi, *J. Am. Chem. Soc.*, 2012, **134**, 1623–1629.
- 206 R. K. Goswami, Z. Z. Huang, J. S. Forsyth, B. Felding-Habermann and S. C. Sinha, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 3821–3824.
- 207 I. V. Thiel, G. Volkmann, S. Pietrokovski and H. D. Mootz, *Angew. Chem., Int. Ed.*, 2014, **53**, 1306–1310.
- 208 J. Yin, F. Liu, X. H. Li and C. T. Walsh, *J. Am. Chem. Soc.*, 2004, **126**, 7754–7755.
- 209 S. DeFrees, Z. G. Wang, R. Xing, A. E. Scott, J. Wang, D. Zopf, D. L. Gouty, E. R. Sjöberg, K. Panneerselvam, E. C. Brinkman-Van der Linden, R. J. Bayer, M. A. Tarp and H. Clausen, *Glycobiology*, 2006, **16**, 833–843.
- 210 H. C. Hang, E. J. Geutjes, G. Grotenbreg, A. M. Pollington, M. J. Bijlmakers and H. L. Ploegh, *J. Am. Chem. Soc.*, 2007, **129**, 2744–2745.
- 211 H. W. Rhee, P. Zou, N. D. Udeshi, J. D. Martell, V. K. Mootha, S. A. Carr and A. Y. Ting, *Science*, 2013, **339**, 1328–1331.
- 212 L. Wang, A. Brock, B. Herberich and P. G. Schultz, *Science*, 2001, **292**, 498–500.
- 213 H. Xiao, A. Chatterjee, S. H. Choi, K. M. Bajjuri, S. C. Sinha and P. G. Schultz, *Angew. Chem., Int. Ed.*, 2013, **52**, 14080–14083.
- 214 D. T. Rogerson, A. Sachdeva, K. H. Wang, T. Haq, A. Kazlauskaitė, S. M. Hancock, N. Huguenin-Dezot, M. M. K. Muqit, A. M. Fry, R. Bayliss and J. W. Chin, *Nat. Chem. Biol.*, 2015, **11**, 496–503.
- 215 Y. H. Tsai, S. Essig, J. R. James, K. Lang and J. W. Chin, *Nat. Chem.*, 2015, **7**, 554–561.
- 216 G. Lukinavicius, K. Umezawa, N. Olivier, A. Honigsmann, G. Yang, T. Plass, V. Mueller, L. Reymond, I. R. Correa Jr., Z. G. Luo, C. Schultz, E. A. Lemke, P. Heppenstall, C. Eggeling, S. Manley and K. Johnsson, *Nat. Chem.*, 2013, **5**, 132–139.

