RESEARCH ARTICLE SUMMARY

CHEMICAL BIOLOGY

Posttranslational mutagenesis: A chemical strategy for exploring protein side-chain diversity

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INTRODUCTION: Natural posttranslational modifications (PTMs) to proteins expand the chemical groups available to proteins. The ability to expand posttranslational functional group diversity in an unbounded manner could, in principle, allow exploration and understanding of how these groups modulate biological function. Natural PTMs feature bonds to heteroatoms (non-carbon) made at the γ (Cys Sγ, Thr Oγ, Ser Oγ) or ω (Lys Nω, Tyr Oω) positions of side chains. However, one of the central features of biomolecules is C (sp^3)–C (sp^3) bond formation. Because all amino acid side chains contain this C–C bond, mastering its construction on proteins could allow free-ranging structural alteration of residues in proteins (both natural and unnatural).

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RATIONALE: In principle, C (sp^3)–C (sp^3) disconnections at the β,γ C–C bond would allow the chemical installation of a wide range of amino acid functionalities. Traditional two-electron chemistry (using nucleophiles and electrophiles) requires reagents that are often incompatible with biological substrates and/or water. Free radicals can be tolerant of aqueous conditions and unreactive (and thereby compatible) with the majority of functionality present in biomolecules. We therefore reasoned that mild, carbon-centered free radical chemistry would be enabled by matching free-radical reactivity with a suitable, uniquely reactive functional group partner that possesses a chemical affinity for such singly occupied molecular orbitals. The amino acid residue dehydroalanine (Dha) can be readily introduced in a site-selective manner genetically, biosynthetically, or chemically; upon reaction with a suitable radical, Dha would favorably generate a stabilized Cα radical **1**. Suitable "quenching" of the central Cα radical intermediate **1** generated after formation of the critical C–C bond would thus allow "chemical mutation" of the side chain.

RESULTS: A range of precursor halides (**R**-Hal, Hal = I or Br) allowed the creation of radicals **R•**. These radicals reacted selectively with Dha in peptides and proteins with excellent site selectivity and regioselectivity (>98% β,γ) and typically with a diastereoselectivity of ~1:1. Combined use of R-Hal with $NaBH_4$ under low-oxygen conditions suppressed competing oxidation and disubstitution side reactions of intermediates **1**. This allowed for rapid reactions (typically 30 min) with improved efficiency across a range of representative protein types and scaffolds (all α, α/β folds, all β, receptor, enzyme, antibody). The reactivity of primary, secondary, and tertiary alkyl halides allowed installation of natural, simple hydrophobic residue side chains. Charged or polar protic (e.g., OH, NH) functionality in amino acid side chains was also possible. Even the use of side-chain reagents in unprotected form proved possible, thus highlighting not only exquisite chemoselectivity but also compatibility with common biological functional groups. These transformations enabled the creation of a wide diversity of natural, unnatural, posttranslationally modified (methylated, glycosylated, phosphorylated, hydroxylated) and labeled (fluorinated, isotopically labeled) side chains, as well as difficult-to-access but important residues in proteins (e.g., methyl-Arg, citrulline, ornithine, methyl-Gln, phospho-Ser).

CONCLUSION: This approach to chemical editing of amino acid residues, outside of the rigid constraints of the ribosome and enzymatic processing, may prove to be a general technology for accessing diverse, previously unattainable proteins. ■

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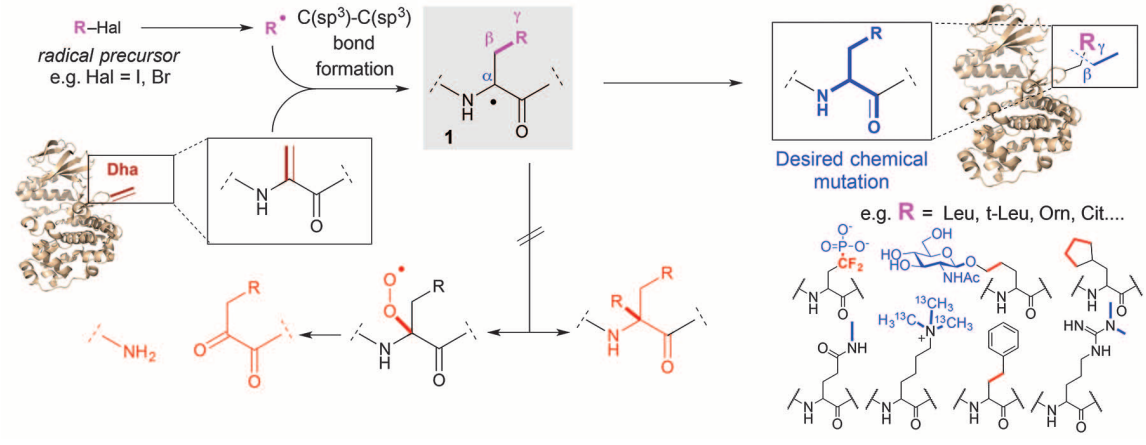

Posttranslational chemical mutagenesis through C (sp^3)–C (sp^3) bond-forming radical reactions. Modification in a protein after translation using C–C bond formation allows construction of many side chains, not just the modification of existing natural amino acid residues. t-Leu, *tert*-leucine; Orn, ornithine; Cit, citrulline.

RESEARCH ARTICLE

CHEMICAL BIOLOGY

Posttranslational mutagenesis: A chemical strategy for exploring protein side-chain diversity

Tom H. Wright,[1] Ben J. Bower,[1] Justin M. Chalker,[1]* Gonçalo J. L. Bernardes,[1]† Rafal Wiewiora,[1]‡ Wai-Lung Ng,[1] Ritu Raj,[1] Sarah Faulkner,[1] M. Robert J. Vallée,[1] Anuchit Phanumartwiwath,[1] Oliver D. Coleman,[1] Marie-Laëtitia Thézénas,[2] Maola Khan,[1] Sébastien R. G. Galan,[1] Lukas Lercher,[1]§ Matthew W. Schombs,[1] Stefanie Gerstberger,[1] Maria E. Palm-Espling,[1] Andrew J. Baldwin,[1] Benedikt M. Kessler,[2] Timothy D. W. Claridge,[1] Shabaz Mohammed,[1] Benjamin G. Davis[1]||

Posttranslational modification of proteins expands their structural and functional capabilities beyond those directly specified by the genetic code. However, the vast diversity of chemically plausible (including unnatural but functionally relevant) side chains is not readily accessible. We describe C (sp^3)–C (sp^3) bond-forming reactions on proteins under biocompatible conditions, which exploit unusual carbon free-radical chemistry, and use them to form Cβ–Cγ bonds with altered side chains. We demonstrate how these transformations enable a wide diversity of natural, unnatural, posttranslationally modified (methylated, glycosylated, phosphorylated, hydroxylated), and labeled (fluorinated, isotopically labeled) side chains to be added to a common, readily accessible dehydroalanine precursor in a range of representative protein types and scaffolds. This approach, outside of the rigid constraints of the ribosome and enzymatic processing, may be modified more generally for access to diverse proteins.

Natural posttranslational modifications (PTMs) to proteins partially expand the chemical groups available to proteins, modulating both structure and function (Fig. 1A) (*1*). For example, protein glycosylation tunes both physical (e.g., solubility, stability, folding) and biological (e.g., immune response, cell adhesion events, signaling) activity (*2*). Phosphorylation, one of the most frequently occurring posttranslational modifications, is widely used in nature as a powerful functional activation mechanism (as an "on switch") for proteins (*3*). Even relatively small modifications such as methylation have been shown to be critical in a range of pathways with diverse biological effects, such as the transcriptional regulation mediated by histone proteins (*4*). The ability to expand posttranslational functional group diversity in an unbounded manner could therefore, in principle, allow exploration and understanding of even greater and more diverse effects in modulation of biological function.

The vast majority of all known natural PTMs feature bonds to heteroatoms (non-carbon) made at the γ (Cys Sγ, Thr Oγ, Ser Oγ) or ω (Lys Nω, Tyr Oω) positions of side chains (*5*). Yet one of the central features of living "organic" matter is that it exploits carbon's ability as an element to catenate [typically through C (sp^3)–C (sp^3) bond formation], providing one of nature's most important structural motifs. Because all amino acid side chains contain this bond, mastering its construction on proteins could allow free-ranging structural alteration of residues in proteins (both natural and unnatural) and thence functional reprogramming. Such extension of the chemical space accessible to protein engineering could be considered a near-unlimited form of synthetic biology, a form of "chemical mutagenesis" (*6*, *7*).

Site-directed mutagenesis has revolutionized the study and understanding of proteins (*8*, *9*). This now long-standing technique, however, is generally restricted to the 20 natural amino acid building blocks by the high selectivity of natural aminoacyl tRNA synthetases and the limited plasticity of the ribosome (*10*), which creates an effective "filter" to translation. The incorporation of unnatural amino acids expands a protein's functional capacity and can provide insight into biochemical mechanisms (*11*–*13*). Some strategies for the incorporation of noncanonical residues have emerged as a powerful route to unnatural mutant proteins. Biological techniques such as amber codon suppression (*14*), while useful, remain limited in scope of structural variation (*13*) by the tolerance of the translational machinery and hence must be optimized on a case-by-case basis (*12*). The total or partial synthesis of proteins has been made possible by powerful native chemical ligation techniques (*15*). However, there remain restrictions on the size of the proteins that can be readily synthesized; such syntheses typically require many steps followed by correct refolding, and hence expertise is required for all but the simplest protein targets (*16*).

An alternative, divergent, and potentially unlimited approach would be to incorporate a single amino acid that can act as a general chemical precursor for any desired side chain, whether natural or unnatural (*17*). The introduction of various chemical "tags" (*18*) that allow selective protein modification via reactivity compatible with that of natural biomolecules (*19*) has been an important step toward this goal. However, current protein modification approaches rely on unnatural carbon-heteroatom linkages (*20*) that do not construct the C–C framework found in biology and thus cannot be used for the site-selective introduction of natural posttranslational modifications and their modified variants (*19*). Thus far, the formation of carbon (sp3)–carbon (sp3) bonds for protein modification has remained out of reach, despite the ubiquity of the C–C bond in amino acid side chains. Access to such reactivity would enable the rapid and divergent exploration of both natural and unnatural "side chain" space from a readily accessible precursor.

Here, we demonstrate that such C (sp^3)–C (sp^3) bond formation is possible in a protein-compatible manner by exploiting the selectivity of carbon-centered radicals to allow a form of general posttranslational mutagenesis (*7*, *17*, *21*).

Design of a biocompatible C (sp^3)–C (sp^3) bond-forming reaction

We envisaged a unique strategy through retrosynthetic analysis (Fig. 1B). In principle, C (sp^3)–C (sp^3) disconnections at the β,γ C–C bond would allow the chemical installation of not only natural amino acid residues but also their posttranslationally modified variants and a wide range of unnatural amino acids. Traditional two-electron chemistry (using nucleophiles and electrophiles; Fig. 1B) results in consideration of reagents likely incompatible with biological substrates by virtue of their reactivity with water and/or the functional groups found in natural biomolecules. We considered that single-electron chemistry might prove more compatible with proteins, because suitable free radicals are tolerant of aqueous conditions (*22*) and are unreactive (and thereby compatible) with the majority of existing functionality present in biomolecules ["bio-orthogonal" (*19*)]. We reasoned that use of such mild, carbon-centered free-radical chemistry (Fig. 1, B and C) would be enabled by matching free-radical reactivity with a suitable, uniquely reactive functional group

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partner that possesses a chemical affinity for such singly occupied molecular orbitals (SOMOs). The amino acid residue dehydroalanine (Dha) can be readily introduced in a site-selective manner genetically (*23*, *24*), biosynthetically (*25*), or chemically (*26*, *27*) and is a potent "SOMOphile" (*28*), which, upon reaction with a suitable radical, would favorably generate a capto-dative stabilized Cα radical (Fig. 1C and Fig. 2).

Development of a peptide-compatible C (sp^3)–C (sp^3) bond-forming reaction

Our attention focused on methods for the ready generation of suitable carbon-centered free radicals and the suitable productive "quenching" of the central Cα radical intermediate **1** generated after formation of the critical C–C bond (Fig. 2B). We considered that alkyl radicals might be derived from the corresponding alkyl halides (R-Hal) through processes that would generate single electron species either through direct homolytic bond fission (e.g., of the C–Hal bond) or through single-electron transfer from metals with suitable redox potentials in their low valence states (*29*, *30*) [e.g., zinc (*31*, *32*) Zn^0 or indium (*33*) In^0] followed by halide anion loss.

We chose leucine (Leu), an amino acid residue that has a widespread occurrence in proteins, as an initial test side-chain system, which we could potentially generate from the readily available simple organic compound isopropyl iodide as a precursor (Fig. 2A, R = iPr). Pleasingly, reaction of Dha-containing derivatives and peptides as small-molecule models under Zn^0-mediated conditions in aqueous buffer [pH 5 to 6, NH_4Cl (aq)] afforded the corresponding Leu derivatives directly (fig. S1 and supplementary materials). Generation of Dha from cysteine (Cys) followed by conversion to Leu thus allowed the overall "chemical mutation" of a residue (Cys → Leu) inside an intact peptide backbone; under optimized conditions (see supplementary materials), this could be achieved in >90% yield and in less than 30 min.

Extension of this methodology to a range of alkyl halides (R-Hal) enabled the synthesis of a variety of natural and unnatural amino acid residues, including unnatural aliphatic and cyclic structures (fig. S2). Notably, not only were primary, secondary, and tertiary alkyl halides all tolerated, allowing installation of the natural simple and hydrophobic residue side chains, so too was the presence of polar protic (e.g., hydroxyl and amine) functionality common in amino acid side chains. The use of these side-chain reagents proved possible even without protection, thus highlighting not only exquisite chemoselectivity but also compatibility with common biological functional groups and hence biological compatibility (orthogonality). Full characterization of the adducts (see fig. S1 and supplementary materials) confirmed absolute regioselectivity (>98% with diastereomeric ratio 55:45) for the radical addition, consistent with the designed, matched polarities of the radicals and the corresponding radical acceptor Dha, respectively (*34*).

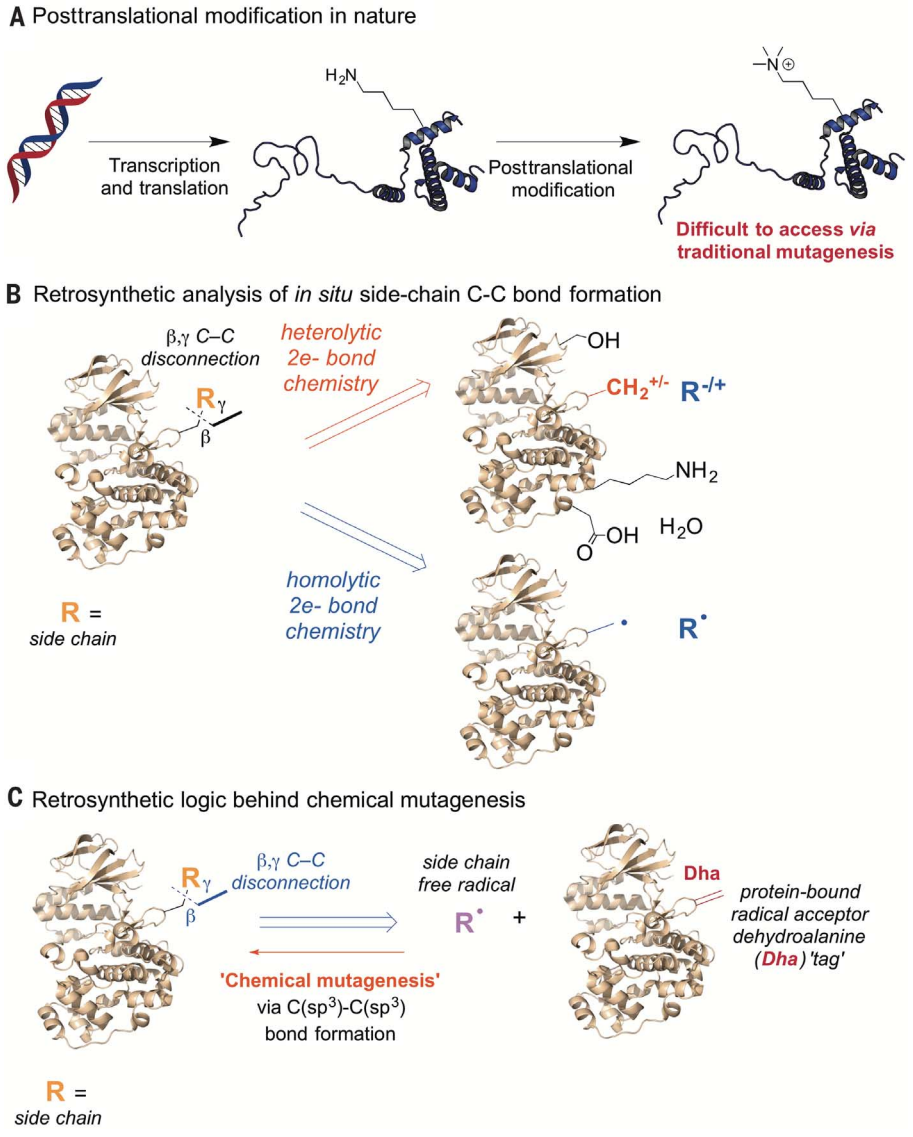

Fig. 1. Design of a biocompatible C (sp^3)–C (sp^3) bond-forming reaction as part of a general strategy for chemical mutagenesis. (**A**) Natural posttranslational modification exploits C-heteroatom bond formation, such as C–N bond formation in Lys methylation, to diversify protein structure and hence modulate function. (**B**) Modification in a protein after translation, akin to PTM formation, but using C–C bond formation would allow construction of many side chains, not just the modification of existing natural amino acid residues. Retrosynthetic analysis (blue arrow) suggests a C–C β,γ bond disconnection and reveals several possible "synthons." For heterolytic two-electron reactions (shown in red), the resulting disconnection yields "synthetic equivalents" $\mathbf{R^+}$ or $\mathbf{R^-}$ or reagents that would react and/or quench with the water in the necessary aqueous solvent or with example protein side chains shown. However, for the homolytic one-electron reaction (shown in blue), the resulting disconnection yields a free-radical "synthon" that would allow an equivalent $\mathbf{R^\bullet}$ for which compatibility can be envisaged. (**C**) A functional group with affinity for carbon-centered free radicals that was suitably polarized could act as the "synthetic equivalent" corresponding to the other protein-based "synthon" arising from this homolytic disconnection. The residue dehydroalanine (Dha) is the functional group proposed as a radical reactive "synthetic equivalent" that would allow corresponding C–C β,γ bond formation.

We observed that the predicted Cα radical intermediate **1** (Fig. 2B), as well as displaying advantageous stability that would favor initial reaction, was sufficiently long-lived to allow further reaction with other radicals in unproductive and unwanted termination reactions (fig. S3). For example, reaction with a second alkyl radical afforded disubstituted ("dialkylated") products, whereas reaction with molecular oxygen (which in its natively abundant state is the triplet form $^3O_2$ that may react with radicals) led to apparent oxidative protein cleavage (*35*). Notably, additional amounts of reagents were seemingly needed for full conversion because of such

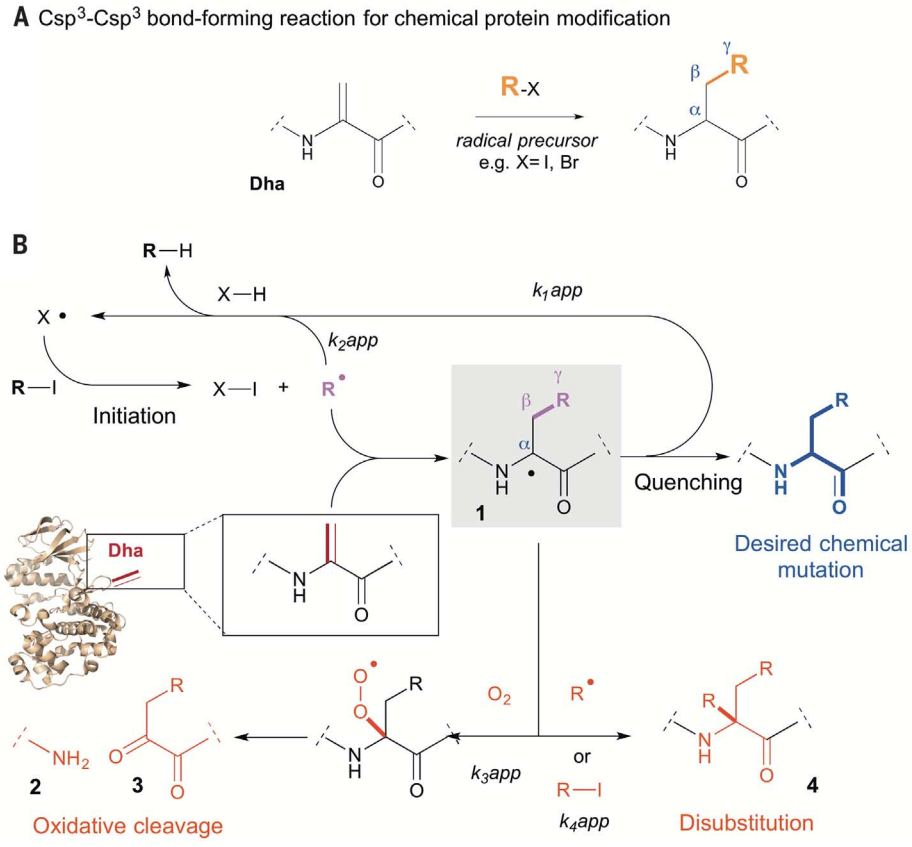

Fig. 2. Proposed radical reaction to allow posttranslational mutagenesis and suggested mechanism. (**A**) The required "side-chain free-radical" synthetic equivalent could be generated from a suitable radical precursor R–X and then reacted with the radical-reactive SOMOphile residue dehydroalanine (Dha) as a privileged unnatural amino acid "tag" to allow site-selective "chemical mutagenesis." (**B**) This would generate the capto-dative stabilized intermediates **1**. The proposed mechanism of free-radical R• generation illustrates the paths to efficient C–C bond-forming chain reaction and desired product (in blue) and competing side reactions and unwanted products (in red).

observed competing processes (reduction of alkyl halide to alkane as well as disubstitution and oxidative degradation). The successful development of a radical reaction for protein modification (Fig. 2A) therefore necessitated a means of eliminating and controlling these undesired pathways.

Mechanism-guided reaction development allowed optimization of protein-compatible C (sp^3)–C (sp^3) bond formation

Next, two initial model proteins were selected to test radical reactivity on more complex extended polypeptides: a highly ordered three-layer α/β Rossman-fold serine protease [subtilisin from *Bacillus lentus* (SBL)] and a three-α-helix protein representative of the histone fold that contains both ordered and disordered motifs (histone H3). Dha was installed (*27*, *36*) site-selectively from corresponding single cysteine variants (see supplementary materials) to generate radical acceptor sites at position 156 in SBL (SBL-Dha^{156}) and at three separate sites (9, 27, and 64) in histone H3 (H3-Dha^{9}, H3-Dha^{27}, H3-Dha^{64}). These allowed us to test alterations of the protein scaffold as well as variation of the reaction site within the same protein scaffold.

Under essentially identical conditions to those used on small-molecule systems (isopropyl iodide, Zn^0 aqueous ammonium acetate buffer, pH 6), we observed direct Dha → Leu "chemical mutation" (fig. S4) in both SBL and histone H3. However, additional side products were also detected. Careful isolation, trapping, and characterization of these side products (figs. S5 to S8) revealed that they were the product of two competing pathways, both of which are consistent with the long-lived intermediacy of the Cα capto-dative radical formed after addition of **R•** to Dha. The observed oxidative cleavage products, C-terminal amide **2** and dicarbonyl **3** (figs. S5 to S7), would arise from the termination reaction of the Cα radical with triplet oxygen (Fig. 2B) (*37*). Disubstituted ("dialkylated") products **4** were observed to arise from the termination reaction of the Cα radical with **R•**. Consistent with these analyses, "peptide mapping" [tryptic tandem mass spectrometry (MSMS)] confirmed clean site selectivity of both the desired mutations and these side reactions: No residues other than that determined by the Dha "tag" site were identified (fig. S8). Notably, these results were also wholly consistent with the corresponding Cγ- and Cα-disubstituted products observed under comparable conditions from small-molecule models (see above) (fig. S3). These observations in proteins therefore were also consistent with radical addition at Cγ followed by termination of the Cα radical intermediate thus generated (Fig. 2B).

The generality of these parallel processes—chemical mutation with competing oxidative cleavage and disubstitution—was confirmed by its observation in both of the scaffolds (SBL and histone H3) and at several sites (e.g., Lys^{9}, Lys^{27}, and Lys^{64} within histone H3). These results not only highlight the need for an improved reaction with better control of radical addition, they also provide compelling chemical evidence for the intermediacy of the proposed Cα radical intermediate (Fig. 2B) and hence the (partial and initial) success of our designed C–C radical-forming reaction in proteins.

These methodological observations and mechanistic rationalization allowed us in turn to optimize the balance between the desired radical side-chain addition and the unwanted competing side reactions (oxidative cleavage and disubstitution). In our initial reaction systems, our use of metal-mediated single-electron transfer exploited a system that relies on the redox potentials of the metals that were used not only in the initiation step but also in the subsequent second-electron transfer, which creates an enolate that is quenched by protonation (likely from solvent) (see fig. S9). In principle, more effective second-electron transfer to enhance enolate formation would allow more rapid formation of desired product at the expense of side reactions (quenching of the intermediate Cα radical before side reaction). Survey of redox potentials (*38*, *39*) suggested various metal potentials that might prove useful; of those that are compatible with water, indium suggested itself as a strong alternative candidate to zinc standard reduction potentials $E°/V$, $Zn^{(2/0)}$ –0.76; $In^{(1/0)}$ –0.14; $In^{(2/1)}$ –0.40; $In^{(3/2)}$ –0.49). This tuning of the single-electron donor, through the use of In^0 instead of Zn^0, proved partially successful, yielding cleaner and more effective chemical mutation through radical addition (see fig. S10 and supplementary materials) on several but not all substrates. In particular, certain primary iodides (e.g., the side chains of MeArg and MeLys, where Me = methyl) were so reactive that unwanted disubstitution side products remained.

Next, we considered alternative methods for "quenching" of the intermediate Cα radical. In principle, direct hydrogen atom ("radical hydride") transfer (Fig. 2B) would not only enhance desired product formation but, by building a suitable chain reaction, could prove more efficient and sustainable. However, analysis of the putative chain cycle (Fig. 2B) highlighted that this would require selective increase of the rate of this step (encompassed by k_{1app}) to a greater extent than that of not only the oxidative and disubstitution side reactions (k_{3app} and k_{4app}, respectively) but also over that of the direct reduction of alkyl

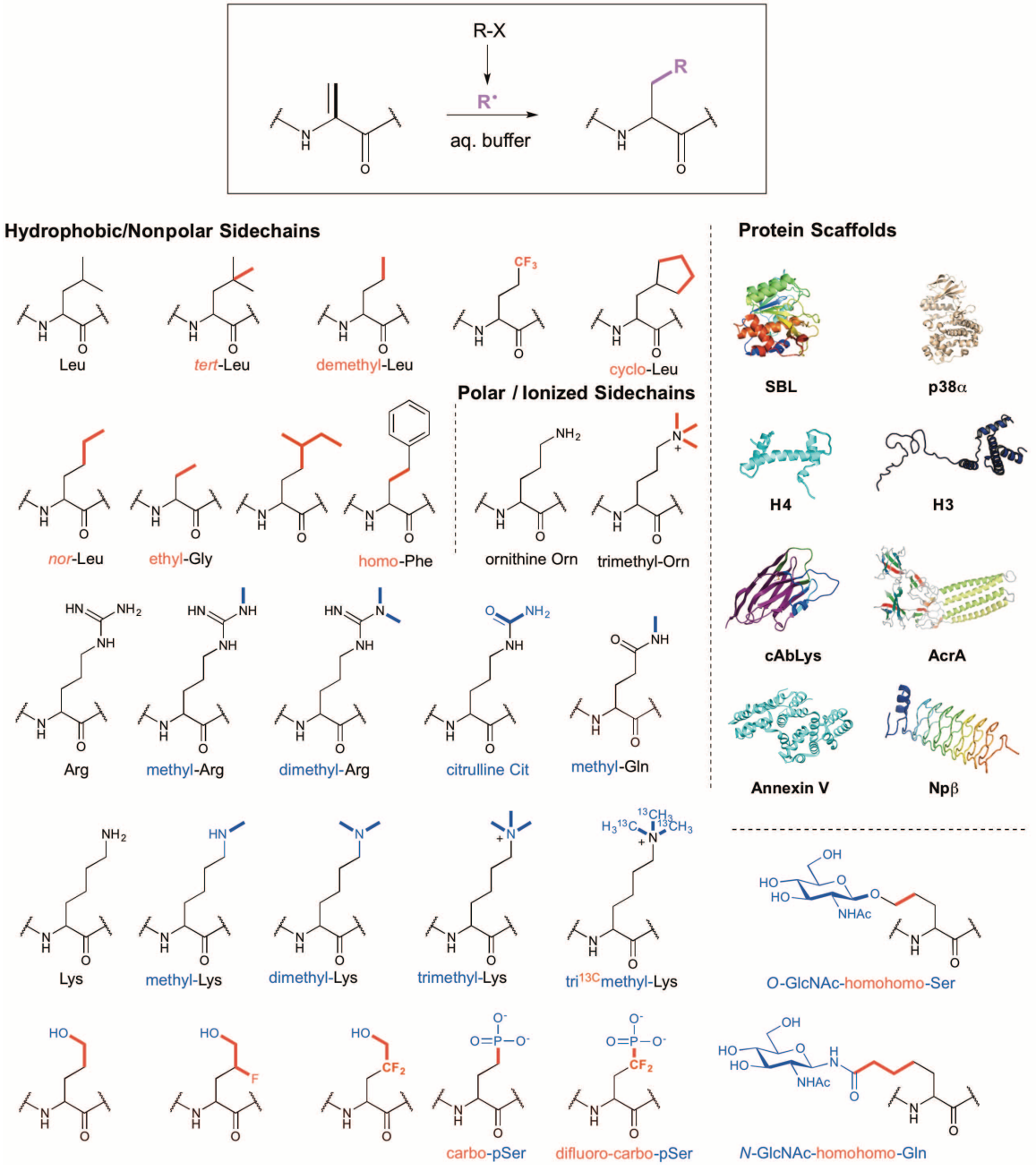

Fig. 3. Biocompatible C (sp^3)–C (sp^3) bond-formation allows wide-ranging chemical mutagenesis. Application of the optimized bond-forming reaction allows direct installation of side chains onto Dha tags found in multiple, representative protein scaffolds and at different sites within the same scaffolds. Attachment of polar, hydrophobic, nonpolar, ionized, and modified side chains with natural motifs (black), with natural modifications (blue) or with unnatural motifs (red) were all possible allowing the construction of >50 individual protein examples representative of >25 side chains on eight varied, representative protein scaffolds.

iodide (R–I → R–H, k_{2app}) (Fig. 2B). A range of traditional "radical hydride" sources were screened (e.g., R_3SnH, R_3SiH, RSH), yet none proved useful and all appeared to favor k_{2app} over k_{1app}. We reasoned that these bulkier hydride sources preferentially transfer hydride H• to less bulky radicals (such as direct transfer to **R•**, thereby favoring k_{2app}), and so we next tested less hindered hydride sources (which might be able to access the more hindered intermediate Cα radical **1**, as desired). Although borohydrides RBH_3^- are traditionally viewed as nucleophilic hydride sources, rare studies on these (*40*–*42*) and related aluminum hydrides (*43*) have previously suggested possible radical behavior under certain circumstances (*44*). Strikingly, we found that $NaBH_4$ in aqueous solution proved to be a highly effective reagent, allowing improved efficiency (as judged by the need for reduced equivalents of iodides) and by the quality of protein chemical mutation products (fig. S11). The radical nature of this controlled, clean, and efficient reaction was confirmed not only by direct observation of radicals by electron paramagnetic resonance (EPR) (fig. S12) but also through the use of radical trapping; the reaction was fully inhibited by substoichiometric 4-hydroxy-TEMPO (4-hydroxy-2,2,6,6-tetramethylpiperidin-1-oxyl) or acrylamide (fig. S13 and supplementary materials).

Finally, having suppressed competing disubstitution, we were able to efficiently suppress competing oxidative cleavage simply through the removal of molecular oxygen from the buffer solutions in which we conducted "chemical mutagenesis" reactions; controlled equilibration experiments at a variety of oxygen partial pressures (figs. S14 and S15) revealed that incubation at <6 ppm O_2 for 6 hours prior to reaction proved generally sufficient. Application of the combined optimized conditions led directly to clean "chemically mutated" proteins without side reactions that, when sequenced by MSMS, were interpreted directly as the intended mutation (fig. S16). Both whole-protein liquid chromatography–MS and post-digestion MSMS (figs. S17 and S18) confirmed that there was no nonselective alkylation or overalkylation by the halide reagents on other residues in proteins substrates. Additionally,

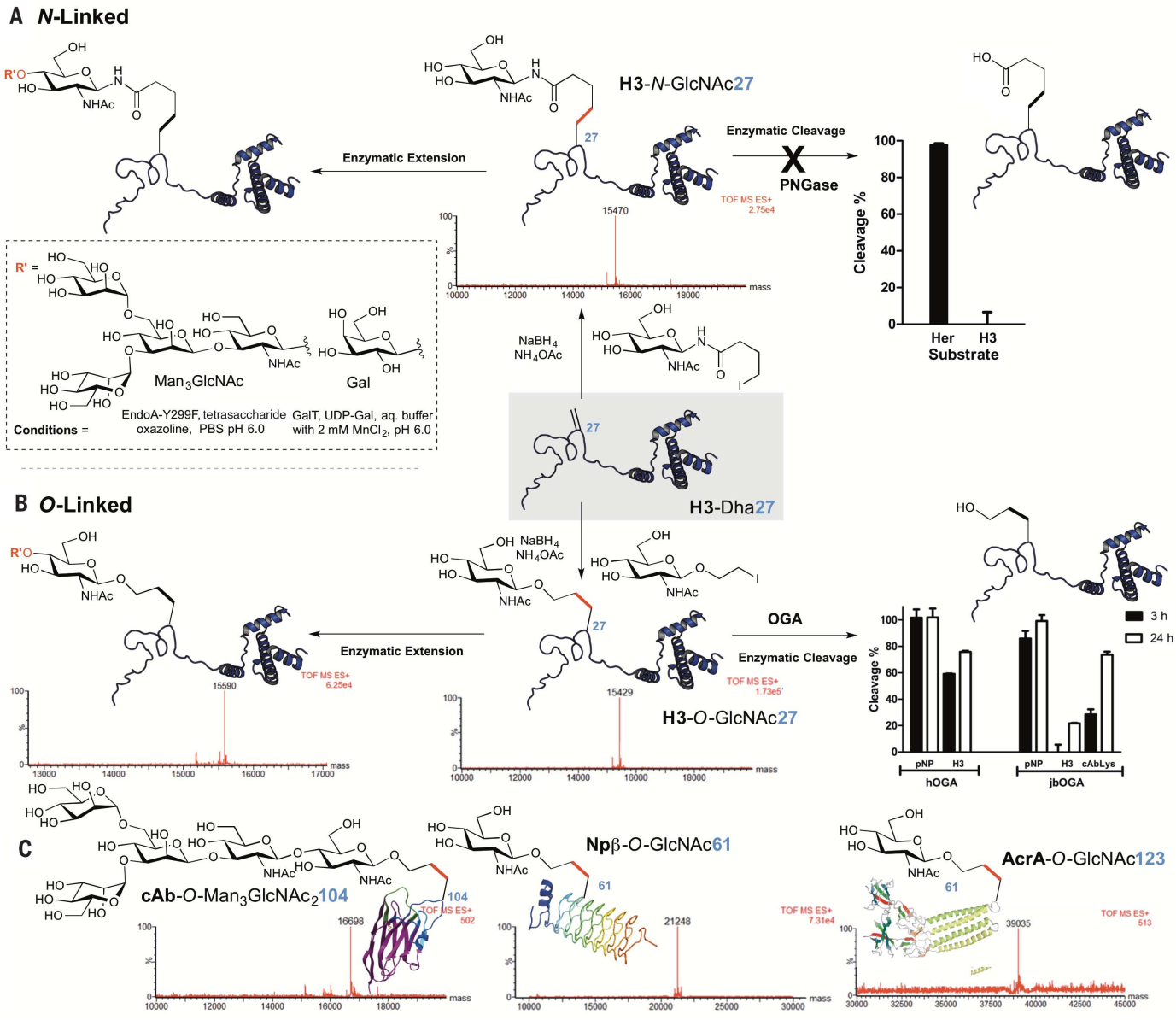

Fig. 4. Use of C–C bond-forming mutagenesis to create N- and O-glycosylated proteins. Using a common intermediate, H3-Dha[27], both forms of GlcNAc (O-linked and N-linked) could be readily introduced and their behavior in extension and cleavage by relevant glycan-processing enzymes tested. (**A**) Despite the position in histone H3, which is not normally glycosylated, N-linked GlcNAc was readily extended to either a disaccharide (Gal-GlcNAc, LacNAc) or the core pentasaccharide (found in all natural N-linked glycans) by appropriate enzymatic systems (GalT and EndoA, respectively). However, this site proved resistant to enzymatic cleavage under conditions that led to full cleavage in natural N-glycosylated sites (conditions, PNGase, 2 M urea, pH 8.0). (**B**) As for N-linked glycosylation, the disaccharide LacNAc (Gal-GlcNAc) and the core pentasaccharide were readily formed from O-linked GlcNAc, despite the unnatural site. Strikingly, O-GlcNAcase from a range of sources showed cleavage activity even at unnatural sites and notably with the human enzyme hOGA. (**C**) Glycosylation of varied protein platforms, antibody cAbLys, efflux protein AcrA, and pentapeptide repeat protein Nβ all proved possible. Experimental data reported in bar graphs represent the normalized percentage (mean ± SD) of cleaved substrate, taken in triplicate.

control experiments in which $NaBH_4$ was omitted from the reaction mixture showed that the halide reagents alone did not react with proteins under the standard conditions.

Biocompatible C (sp^3)–C (sp^3) bond-formation enables a "toolbox" for building natural and unnatural proteins

With optimized conditions for C–C bond formation enabling chemical mutation in hand, we next explored the breadth of the side chains that could be introduced (and hence mutations that would be accessible) and the protein scaffolds that they could be introduced into (Fig. 3). Representative proteinogenic and nonproteinogenic; polar, nonpolar, aromatic, ionized, and modified amino acid residues, bearing both natural and unnatural motifs, were chosen and all readily incorporated. This demonstrated the tolerance of the reaction to many of the most common amino acid (and biological) functional groups: hydroxyl (OH), aminyl (NH), guanidine, amide, thereby highlighting its excellent biocompatibility (orthogonality). Choice of the corresponding organic iodide, typically readily available commercially or through chemical synthesis, allowed wide-ranging and systematic variations. Thus, not only could Leu be incorporated, so could a series of systematic variants of Leu: demethyl-Leu (smaller), *tert*-Leu (bulkier), *nor*-Leu

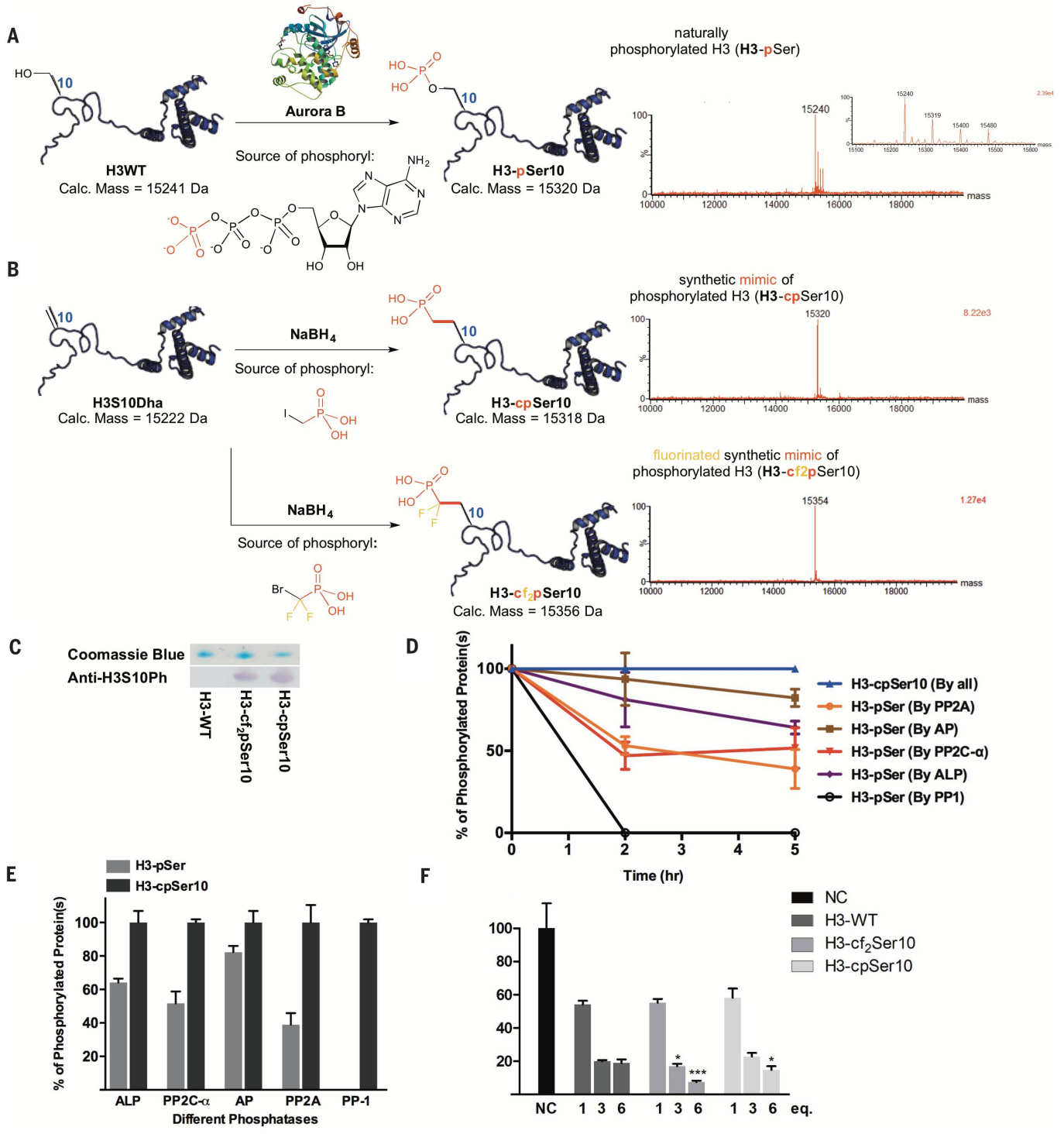

Fig. 5. Use of C–C bond-forming mutagenesis to build phosphorylated histone proteins. Formation of natural and synthetic phosphorylated histone H3 (H3-cpSer^{10} and H3-*cf2*pSer^{10}) via enzymatic phosphorylation and chemical mutagenesis, respectively. (**A**) Natural phosphorylation is catalyzed by Aurora B kinase and gives rise to a mixture (inset to mass spectrum) of phosphoforms. (**B**) Chemical phosphorylation via C–C bond formation gives essentially homogeneous products H3-cpSer^{10} and H3-*cf2*pSer^{10}. (**C**) Western blot analysis with antibody to H3-pSer^{10} and SDS-PAGE gel stained with Coomassie blue (for full gel, see fig. S29) shows that the phosphomimics carba-pSer (cpSer) and difluorocarba-pSer installed by building a C–C bond are faithfully recognized as phosphorylated by the corresponding antibody raised to bind the natural modification (pSer). (**D** and **E**) A comparison of stability of H3-pSer^{10} and H3-cpSer^{10} under the actions of five different protein phosphatases shows that the C–C bond in H3-cpSer^{10} provides full resistance even to enzymes that fully and readily degrade the naturally phosphorylated H3-pSer^{10}. The *y* axis shows normalized percentage (mean ± SD) of phosphorylated protein taken in triplicate. (**F**) Alpha-screen binding assay using phospho-reader protein MORC3 shows binding by H3-cpSer^{10} and enhanced binding by H3-*cf2*pSer^{10}. Measurements were performed at least three times and were analyzed by Student's *t* test at 95% confidence interval [H3-*cf2*pSer^{10} > H3-WT in binding, $P = 0.0285$ (3 eq.) and $P = 0.0004$ (6 eq.), respectively; H3-cpSer^{10} > H3-WT, $P = 0.0291$ (6 eq.)]. Error bars indicate SEM.

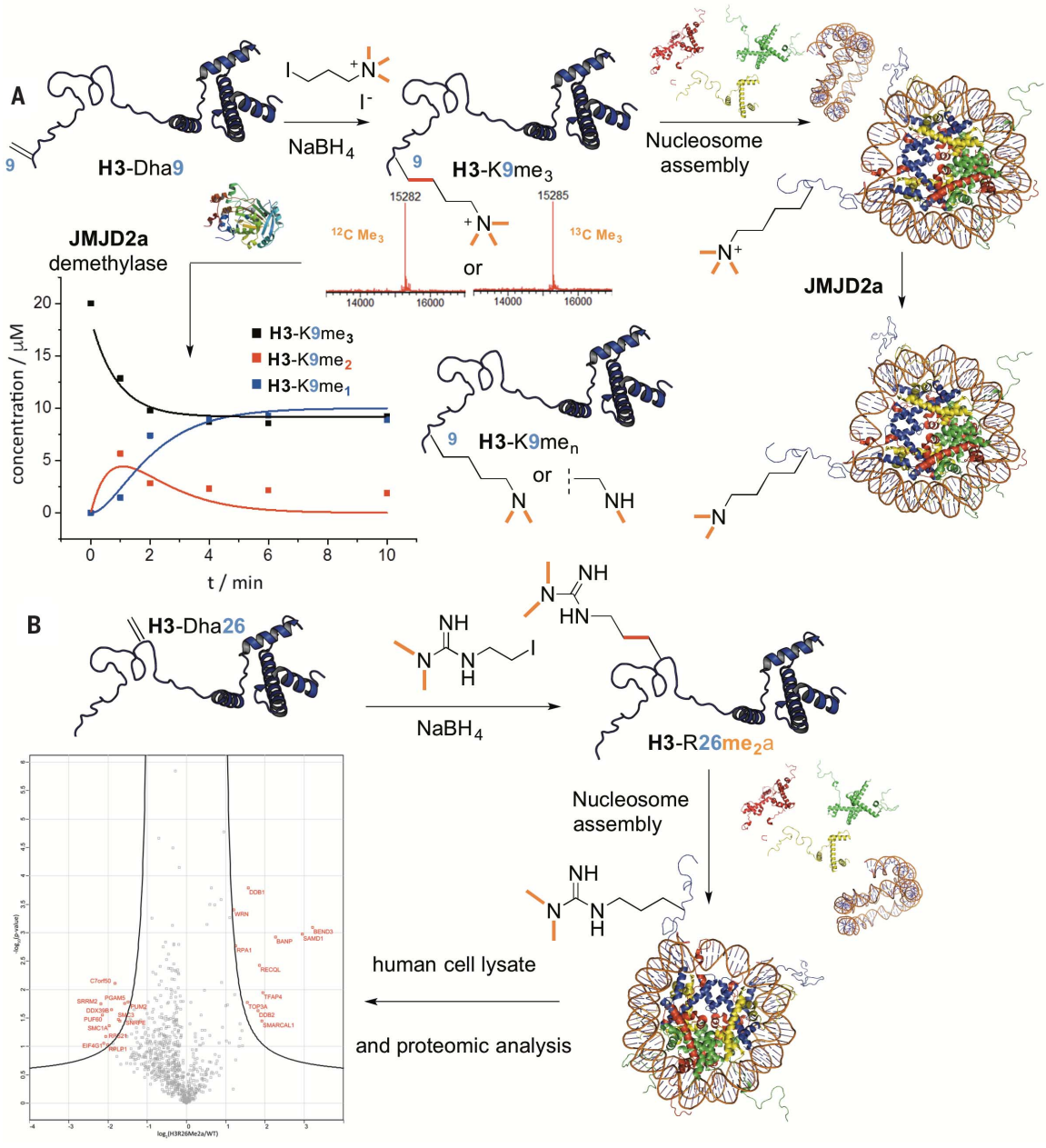

Fig. 6. Use of C–C bond-forming mutagenesis to build methylated nucleosomes. Formation of methylLys-modified (H3K9me$_3$) or methylArg-modified (H3R26me$_2$a) nucleosomes by chemical mutagenesis enables insight into the biological functions of key histone modifications. (**A**) Chemical methylation via C–C bond formation allows installation of not only K9me$_3$ with natural isotope distribution (primarily ^{12}C) but also a ^{13}C-enriched variant precisely placed at the methyl-group carbon atoms. These reveal the time course for demethylation by the demethylase enzyme KDM4a/JMJD2a, in both an isolated protein context (shown here by LC-MS), and, notably, in the context of intact nucleosomes. This suggests the use of such "isotope-PTMs" as probes of demethylase activity, for example, by ^{13}C NMR. Time points represent the mean of three independent experiments; error bars (SEM) shown in SI are omitted here for clarity; curves were fitted by global least-squares regression algorithm to solutions of a simplified first-order model. (**B**) C-C bond-forming mutagenesis also enabled the direct site-specific installation of asymmetric dimethylarginine residues into intact histones. H3R26me$_2$a was cleanly installed via C-C bond formation (see supplementary materials), assembled into nucleosomes. When used to probe human (HeLa) cell extracts for interaction partners (three independent biological and two technical replicates), previously unanticipated protein partners implicated in rDNA repression and recognition of DNA damage were identified among 797 quantified proteins in nuclear extract, which suggests that ablation of DNA-to-H3 hydrogen bonding may be critically affected by such R26 methylation. Significant interacting protein partners (denoted by their gene name) identified upon label-free quantification (LFQ) on Student's *t* test analysis are shown in red in the "volcano plot" inset (*x* axis, logarithmized ratio of LFQ intensity difference among two groups; *y* axis, logarithmized *P* value from the test statistics).

(slimmer), and "cyclo"-Leu (conformationally restricted) (Fig. 3). Similarly, systematic variation of side chain length, methylene unit by methylene unit, was also possible (e.g., Ala, ethyl-Gly, demethyl-Leu, *nor*-Leu). We were also able to strategically replace, with atomic precision, methyl groups in residues with their labeled or precisely altered variants: thus, $CH_3 \rightarrow CF_3$ (e.g., in demethyl-Leu) or $CH_3 \rightarrow {}^{13}CH_3$ (e.g., in trimethyl-Lys). Current methods for isotopic labeling based on "feeding" experiments result in universal incorporation at every codon-determined site; here, isotopic labels can be installed at a single site. Such precisely fluorinated or isotopically labeled amino acids are not only powerful biophysical reporters (*45*–*47*), with use particularly in protein (e.g., ^{19}F and ^{13}C) nuclear magnetic resonance (NMR) methods, but can also act as modulators of protein structure and binding (*48*). Indeed, use of ^{19}F NMR allowed us to further confirm both the regioselectivity and stereoselectivity for chemical mutations (fig. S19), which proved to be essentially identical to that found on peptide models (>98% and diastereomeric ratio ~1:1).

Key posttranslational modifications also proved accessible, including glycosylation (*2*) (in O- and N-linked form), Lys methylation (*49*) (in all three states: mono-, di-, and tri-, as well as labeled tri-^{13}C), Arg methylation (*50*) (mono- and di-), and Gln methylation (*51*). Notably, no other chemical methods exist (barring total protein synthesis) for the installation of the majority of these

residues. Moreover, several residues that have been previously biologically inaccessible in proteins were also readily introduced. These included ornithine (Orn), which by virtue of intramolecular cyclization chemistry cannot be loaded onto tRNAs and hence is incompatible with ribosomal incorporation (*52*), and di- and trimethylated Lys that cannot yet be incorporated into proteins [even indirectly, as mono-methyl-Lys currently is (*53*)] by cellular stop-codon suppression (*13*).

Finally, we surveyed the introduction of side chains to representative examples of protein functions (structural, channel, enzyme, glycoprotein) from differing protein folds (with varying levels of α, β, and unstructured secondary motifs) and species types. Thus, as well as SBL and histone H3, we also surveyed the variously structured histone H4; the transmembrane bacterial efflux component protein AcrA (*54*); p38α mammalian mitogen-activated MAP kinase (*55*); the mammalian antibody cAbLys3 (*56*); the apoptosis marker binding protein annexinV (*57*); and the pentapeptide-repeat protein Npβ (*58*). These also represent proteins that are variously associated with localization in different cellular environments: nuclear (histones H3 and H4), cytosolic (p38α, annexinV), transmembrane (AcrA, Npβ), and extracellular (cAbLys3, annexinV). They also allowed us to survey highly diverse architectures: α helix–coiled coil (AcrA); histone fold (mixed unfolded and α helix, histones H3 and H4); mixed α/β fold (SBL, p38α); variable-domain immunoglobulin fold (four-strand β sheet plus five-strand β sheet, cAbLys); α helix–rich globular annexin fold (four × 5–α-helix domains in a "super-helix," annexinV); and even a right-handed quadrilateral β helix (Npβ). Sites of modifications sat within various feature types including helix, sheets and loose loops (table S2). Notably, all proteins proved compatible with side-chain attachment at all targeted sites (see supplementary materials for full characterization details). Multiple sites in the same proteins were also surveyed: five different sites in histone H3 (sites 9, 10, 26, 27, and 64) and two in histone H4 (sites 16 and 17). Together, these cumulative variations of side chains in different protein substrates at different sites allowed access to >50 "chemical mutants."

Analysis of sequence (e.g., by tryptic MSMS peptide mapping; fig. S20), structure (e.g., secondary structural content by circular dichroism, amide- and aliphatic-resonance analysis and diffusional analysis by protein ^{1}H-NMR; figs. S21 to S23) and retention of function (e.g., enzymatic activity, antibody-binding function and biomarker recognition, protein complex assembly), not only confirmed the site selectivity of the C–C bond-forming chemical mutation but also suggested no gross alteration of global structure (see supplementary materials), although it should be noted that localized structural changes cannot be discounted. Notably, too, test experiments in both model systems and proteins containing disulfides suggested good compatibility of reagents [including 2,5-dibromohexane diacetamide (DBHDA), consistent with prior results (*27*), and $NaBH_4$; see supplementary materials and figs. S24 and S25] with disulfides.

C (sp^3)–C (sp^3) bond-formation chemical mutation enables diverse techniques for the study of protein methylation, glycosylation, and phosphorylation

With this ability to directly insert side-chain alterations and hence perform chemical mutagenesis on proteins with wide variation in protein and site, we chose to test differing proof-of-principle strategies that would allow insight into the biological function of posttranslationally modified residues (and their mimics) that are ordinarily difficult to install with fidelity into proteins by other means. To this end, we chose three of the most important PTMs: glycosylation, phosphorylation, and methylation.

Glycosylation is the most diverse of the posttranslational modifications (*1*, *59*), yet has been prominently absent as a readily accessible motif in proteins via chemical or genetic mutagenesis methods (*60*). Until now no general chemical method for convergently installing N- and O-linked glycans has been possible (*59*, *60*). We used C–C bond-forming mutagenesis along with corresponding (entirely unprotected) N- and O-linked glycosidic iodides to install *N*-acetylglucosamine (GlcNAc), a glycan that is found naturally in both N- and O-linked form, to create an unnatural glycosylation site at position 27 of histone H3 (using the same, common divergent histone H3–Dha^{27} protein intermediate, Fig. 4). Despite the unnatural constitution of this site, enzymatic extension with either glycosyltransferase or endoglycosidase allowed the overall installation of more complex glycans onto both N- and O-linked GlcNAc, even up to the N-linked core pentasaccharide that is found in all N-linked glycoproteins (*1*, *59*). We discovered that despite an apparent plasticity with respect to protein scaffold (*61*), PNGase (peptide-*N*-glycosidase), a widely used *N*-glycosidase (*62*), did not cleave synthetic variants with extended side-chain length (Fig. 4A and fig. S26). In striking contrast, we discovered that a variety of synthetic O-GlcNAcylated glycoproteins were cleaved quite readily by O-GlcNAcases from different sources (Fig. 2B and fig. S27), including the human O-GlcNAcase (hOGA) enzyme. The latter, which is implicated in diabetes (*63*), dementia (*64*), and cancer (*65*), has until now been presumed selective, given that it is the sole encoded protein O-GlcNAcase in the human genome (*66*); our results suggest a previously unappreciated and surprising plasticity. In addition to the N- and O-glycosylation of histone H3, we were able to chemically N-glycosylate and O-glycosylate other sites and proteins, including the naturally glycosylated protein AcrA, the pentapeptide repeat protein Nβ, and notably the heavy-chain antibody cAbLys with the putative Fcγ receptor ligand glycan $Man_3GlcNAc_2$ (Fig. 4C and fig. S28).

Aurora B kinase, which is overexpressed in cancers (*67*), phosphorylates Ser^{10} of histone H3 during mitosis (*68*) and is hence implicated as a controlling factor in cell division and proper distribution of genetic information. The lability of phosphorylation and the mixtures of phosphorylated proteins often formed from natural enzymatic phosphorylation greatly complicates the study of phosphoryl groups on given sites, such as H3-pSer^{10} (*69*). We used C–C bond-forming mutagenesis along with corresponding (notably unprotected) iodophosphonates to create stable analogs of H3-pSer^{10} in which a single oxygen atom was replaced by methylene or difluoromethylene units to create the carba-phosphoSer variants *c*pSer (*70*) and *cf2*pSer (*71*) (Fig. 5A); MS analysis revealed that this could be achieved with a purity that is not possible with current biological methods for phosphorylating histone H3 (Fig. 5B). Antibodies and appropriate binding proteins [such as the "reader" protein MORC3 (*72*)] not only recognized the resulting phosphomimic proteins (Fig. 5, C and F, and fig. S29) but also proved stable to either chemical or enzyme-catalyzed dephosphorylation (Fig. 5, D and E, and fig. S30), even with phosphatases that readily processed naturally phosphorylated histone H3 (e.g., protein phosphatases 1 or 2A). It also proved possible to readily install carba-pSer into other proteins (fig. S31). Although *c*pSer^{10} proved to be a functioning mimic of pSer^{10}, it has been argued (*73*, *74*) that fluorophosphonates may act as more effective phosphate mimics by virtue of pK_a (*71*), polarity, and shape (*75*). The C–C bond-forming mutagenesis allowed us to also install a difluorophosphonate-Ser variant (difluoro-carba-pSer, *cf2*pSer) at the same site of histone H3 to create H3-*cf2*pSer^{10}. Consistent with improved mimicry, this variant showed enhanced binding to MORC3, validating proposed (*71*, *73*–*75*) difluorophosphonate mimicry of phosphates in proteins (Fig. 5F).

Protein methylation (*76*) is a central biological process (e.g., in epigenetic regulation and cell signal transduction). Yet the precise elucidation of the functional mechanistic role of methylation at the molecular level and the ready delineation of proteins associated with the "methylproteome" (e.g., "writers," "readers," and "erasers") remains a grand challenge in biological science. We chose two methylated protein targets that have not been possible to create through other protein generation methods and created these through the site-selective C–C bond-forming mutagenesis reaction: a site-selectively ^{13}C-labeled variant of trimethylated Lys in histone H3 (Fig. 6A) and a dimethylated Arg residue site-selectively installed into in an intact nucleosomal particle (Fig. 6B). We created H3-[^{13}C-Me]$_3$-Lys^9 (Fig. 6A) with precise trimethylation on Lys^9, which has been previously been observed and implicated in direct transcriptional regulation (*77*, *78*). The structure and function of this chemical mutant of histone H3 was explored by protein MS and NMR. These revealed ready observation of the ^{13}C-labeled protein, by virtue of its isotopic label, and the readily observable processing and release of the ^{13}C-labeled methyl groups ([^{13}C]Me) from ([^{13}C]Me)$_3$-Lys^9 in histone H3 by the known demethylation enzyme JMJD2A/KDM4a (Fig. 6A and fig. S32A) (*79*, *80*).

Having installed and explored precise Lys methylation in an isolated histone protein, we explored precise Lys and Arg methylation in the context of an entire, intact, nucleosomal particle (Fig. 6, A and B); both LysMe3 and ArgMe2a were readily introduced. Both anti-LysMe3 antibody recognition and JMJD2a/KDM4a-catalyzed demethylation were readily demonstrated using synthetically methylated nucleosome (fig. S32B). Arg methylation, and especially asymmetric dimethylation (ArgMe2a), remains only a partially understood alteration. Moreover, given the variant isomeric forms of Arg methylation and dimethylation, precise control of the installation of methylation to create representatively methylated proteins has also not proved possible. Using the C–C chemical mutagenesis method (Fig. 6B), we precisely installed ArgMe2a into site 26 of histone H3 (H3R26me$_2$a) [a site implicated (*81*) in so-called "cross-talk" epigenetic modifications with an order that is not clearly understood] in intact nucleosomal particles.

These synthetic nucleosomal probes bearing asymmetric-dimethylation at H3R26me$_2$a allowed the identification of key partner proteins through affinity enrichment proteomics in human cells (Fig. 6B and table S1). Notably, two of the strongest interacting partners, BEND3 and BANP, contain BEN domains, a recently characterized α-helical module found in chromatin-associated proteins (*82*); BEND3 (*83*), a novel rDNA transcription repressor, is the most enriched interacting protein partner. Interestingly, BEND3 can recruit PRC2 complex that promotes H3K27me$_3$ modification, a known transcription repression marker (*84*); this suggests potential cross-talk between these two modifications leading to generation of a repressive chromatin state. Intriguingly, a majority of the remaining significant interactors (SMARCAL1, RECQL, DDB1, DDB2, TOP3A) are annotated as being involved in DNA replication/repair. Although a link between histone arginine methylation and DNA repair has not been previously reported, the results of this experiment suggest increased accessibility of nucleosome-bound DNA to a range of relevant DNA-binding effectors; such a loss of DNA-to-arginine hydrogen bonding would be anticipated upon methylation. Such is the flexibility of the C–C chemical mutagenesis method that it also proved possible to readily install methylated Lys (LysMe, LysMe2, LysMe3), methylated Arg (ArgMe2a, ArgMe1), and methylated Gln into a wide range of other sites and proteins (fig. S33). On the basis of the ready discovery of previously unanticipated interacting partners for Arg26Me2a (see above), we anticipate that these too will prove to be powerfully precise probes of methylation function and direct "methyl-proteome" interactions.

Finally, we tested the scalability of the C–C chemical mutagenesis method; applications such as translational trials of biologics and structural biological studies can necessitate larger (multimilligram) amounts of proteins. Reaction of 10 mg of the Dha protein H3S10Dha with the relevant bromide and sodium borohydride allowed the installation of difluoromethylenephosphohomoalanine (*cf*2pSer) in useful "synthetic" (isolated, 65 to 70%) yield after desalting thereby suggesting utility even for larger-scale synthetic applications in protein chemistry (fig. S34).

Discussion

The compatibility in the use of radicals as effective and yet benign reactive intermediates for protein modification suggests that other radical-based methods (*35*) may prove powerful in the field of protein chemistry. Indeed, the key implicated propagating intermediate in our C–C bond-forming mutagenesis, the capto-datively stabilized Cα backbone radical, is similar to other stabilized radicals suggested in natural processes (*35*); not only may nature have long been taking advantage of such methods, but other routes of access to such intermediates could allow similarly powerful bond-forming strategies. This protein radical chemistry is likely to require new reagents such as boron-based compounds, which have played an important role in radical chemistry (*85*, *86*). The associated mechanisms of these reagents remain a topic of active debate (*43*, *44*), and mechanisms other than the one we propose here cannot be discounted.

Given their benign application and compatibility, we can also envisage the ready combination of the C–C mutagenesis reaction with other protein chemistries or assembly methods. For example, thioester-mediated backbone assembly methods ("native chemical ligation") (*15*) typically use peptide fragments with N-terminal Cys residues that remain at the junction point after "ligation." Using the C–C mutagenesis reaction, these Cys residues could be readily converted to Dha and thence to almost any residue of choice. Indeed, in a proof-of-principle of such a combined strategy, we have been able to generate Thr- and Leu-containing peptides in which the Thr-Leu moiety is derived from thioester-mediated amide ligation with Cys followed by C–C chemical mutagenesis to Leu (see fig. S35 and supplementary materials).

Because the simple choice of reagent allows for the variation of single-atom substituents (e.g., O → CH_2 → CF_2 in pSer, *c*pSer, and *cf*2pSer, as we have shown here), our approach may enable a more molecular understanding of mechanism of proteins and a fine-tuning of function. The use of stable phosphoryl mimics (such as *c*pSer or *cf*2pSer) suggests itself as a promising way to "fish" not only for phospho-binders ("phospho-readers," as we have shown here) but for enzyme partners that would process their natural modification counterparts (e.g., phosphatases that would cleave pSer but, as we have shown here, cannot cleave *c*pSer). It should be noted in this context that although amber-codon suppression ("genetic code expansion") methods have proven highly powerful in certain cases, many useful and biologically relevant structures elude current approaches. For example, the residue types (^{13}C-trimethyl-Lys, dimethyl-Arg, O- and N-linked glycosylated residues, difluorocarba- or carba-pSer) installed in the proof-of-principle studies (see above) have proven intractable to direct installation into biologically relevant sites by amber-codon suppression (*87*). Indeed, residues bearing only small differences from their natural counterparts (methylated Lys, Arg, Gln), which we were able to incorporate chemically, sometimes prove difficult to incorporate by such genetic methods because of their strong structural resemblance in the translational machinery to their unmodified counterparts.

Note that although the C–C bond-forming mutagenesis method described here allows the creation of the relevant constitution (connectivity) found in proteins, our analysis of the stereoselectivity in both peptides and proteins (see above) suggests approximately equal formation of both D- and L-configurations at the mutation site. This would result in yet more complex mixtures of protein diastereomers for multiple mutation sites.

The improved access to relevant protein architectures will potentially reveal surprising biological functions. For instance, our data have revealed that the human enzyme hOGA is more plastic in its cleavage activity of O-GlcNAcylated proteins than had been previously anticipated. Coupled with inferred plasticity of the corresponding glycosyltransferase (OGT) that was recently suggested by studies on peptides (*88*), this suggests that any O-GlcNAcylation–associated regulatory mechanism may be much looser than previously realized. The elucidation of new binding partners for nucleosomes in previously inaccessible methylation states (e.g., asymmetrically dimethylated ArgMe2a) suggests that many other new interactions may be discoverable via C–C chemical mutagenesis. These in turn will allow us to identify and synthetically "program" into proteins exactly those residues that engender wanted functional (e.g., pharmaceutical) benefit in a truly broad manner. For instance, the chemical glycosylation (via C–C bond mutagenesis) of an antibody fragment with possible sugar ligands for the Fcγ receptor raises the possibility of new cell-killing strategies (*89*) mediated by synthetic antibody fragments. In this way, we envisage access to synthetic proteins that will allow application of newly elucidated functions in, for example, new protein drugs or "synthetic biologics" (*90*).

Materials and methods

General Dha formation on histone protein substrate

The relevant protein cysteine mutant (10 mg of lyophilized powder) was dissolved in 500 μL of reaction buffer (3M guanidinium hydrochloride, 100 mM sodium phosphate, pH 8.0) and 30 mg DTT was added. The resultant protein solution was shaken at room temperature for 30 min. Excess DTT was removed by passing the solution through a PD MiniTrap G25 (equilibrated with the same buffer). Eluting with 1 mL of the reaction buffer gave the protein at a final concentration of 10 mg/mL. To the reduced protein

mutant was added 50 μL of a 2,5-dibromohexane diacetamide (DBHDA) stock solution (0.5 mM, 100 mg in 610 μL of DMF). The reaction was gently shaken for 45 min at room temperature and then 90 min at 37°C. The reaction mixture was concentrated to 500 μL using a Vivaspin 500 concentrator (MWCO 10 kDa) and excess reagent was removed by passing the solution through a PD MiniTrap G25 (equilibrated with chemical mutagenesis reaction buffer). Eluting with 1 mL of the same buffer provided the dehydroalanine-containing protein.

General chemical mutagenesis method

A 2 mL eppendorf tube containing a solution of protein (typically 0.2- 5 mg/mL, 200 μL, ~ 10-200 μM) in reaction buffer (pH 4-8, most common buffers tolerated) was ported into a N_2 atmosphere glovebox (Belle Technologies) and equilibrated to anaerobic conditions (cap open) overnight at 4°C in a standard benchtop eppendorf cooler. In parallel, a stock solution of the bromide or iodide of interest (prepared by dissolving solids in water and adjusting the pH to that of the reaction buffer), or the solid reagent itself, was also ported into the glovebox. In the case of liquid reagents, either a stock solution was prepared as above, or the neat reagent was ported into the glovebox and stored at the appropriate temperature. Solid sodium borohydride (0.3 – 1 mg, smaller amounts of sodium borohydride can be difficult to weigh accurately) was ported into the glovebox in a 2 mL eppendorf tube and placed in the cooler kept at 4°C. Following a minimum of 8 hours degassing, inside the glovebox, the volume of the protein solution was ascertained by pipette and "topped up" with reaction buffer to the desired volume (e.g., 200 μL). 1-20 μL of the previously prepared iodide or bromide stock solution (typically 100 – 2000 molar equivalents relative to protein) was then pipetted into the protein solution, and the resultant solution gently mixed by pipette. The entire volume (~200 μL) of the protein solution was then added to the 2 mL eppendorf tube kept at 4°C and containing solid $NaBH_4$. The tube was gently shaken by hand, causing effervescence/foaming to spread through the solution. Any discoloration from the iodide reagent should rapidly disappear (In some cases, particularly at high pH where the hydrolysis of borohydride is retarded, sustained effervescence is observed, whereas for most iodides a colorless and still solution is obtained after ~20 min incubation at 4°C). The reaction was incubated at 4°C for 30 min (cap open) before being removed from the glovebox. Shaking is not necessary but may assist in removing evolved gases. The eppendorf tube was then capped and removed from the glovebox. Outside the glovebox, the reaction solution was loaded onto SpinTrap G-25 desalting column, pre-equilibrated with the desired storage buffer. Elution according to manufacturers instructions afforded the desired chemical mutagenesis product, which was analyzed by LC-MS. For downstream applications, additional SEC may be necessary for sample desalting.

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SUPPLEMENTARY MATERIALS

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Posttranslational mutagenesis: A chemical strategy for exploring protein side-chain diversity

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Editor's Summary

Radicals push proteins beyond genes

Chemically modifying proteins after their translation can expand their structural and functional roles (see the Perspective by Hofmann and Bode). Two related methods describe how to exploit free radical chemistry to form carbon-carbon bonds between amino acid residues and a selected functional group. Wright *et al.* added a wide range of functional groups to proteins containing dehydroalanine precursors, with zinc ions mediating the radical chemistry. Yang *et al.* employed a similar approach, using zinc in combination with copper ions. Together, these results will be useful for introducing functionalities and labels to a wide range of proteins.

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