harmonic spectrum, and this has been experimentally verified (*12*) using the long pulse duration (300 fs) of the Vulcan laser at the 3200th harmonic order.

In a related scheme based on a pulse of a few cycles (*13*), the relativistic mirror ceases to be planar and deforms because of the indentation created by the focused laser beam. As it moves, simulation shows that it simultaneously compresses the pulses but also scatters them in specific directions. This technique may lead to an elegant method for both compressing and isolating individual attosecond pulses. For intensities on the order of 10^{22} W cm^{-2}, the compressed pulse could be on the order of only a few attoseconds. Such short, intense pulses could provide a way to produce beams of x-rays or even γ-rays by scattering the pulses off of bunches of free electrons. A similar concept called the "relativistic flying mirror" has been advocated and demonstrated (*14*), using a thin sheet of accelerated electrons. Reflection from this relativistic mirror leads to a high efficiency and pulse compression.

When one wishes to go to the γ-ray regime, the mirror that compresses the laser into γ rays must be of extremely high density (~10^{27} cm^{-3}) so that the laser may be coherently reflected into γ photons. One possibility is to use a combination of the relativistic flying mirror with the implosion of this flying mirror so that its density may be enhanced by a factor of 10 in each dimension (thus by a factor of 1000 in its density). This may be achieved by a large energy pulse (~1 MJ) at the ultrarelativistic intensity of 10^{24} W cm^{-2} on a partial shell of a concave spherical target. This imploding ultrarelativistic flying mirror (*15*) would be capable of coherently backscattering an injected 10-keV coherent x-ray pulse into a coherent γ-ray pulse with a duration of 100 ys (10^{-22} s).

We know that matter exhibits nonlinearities when irradiated with a strong enough laser; the manifested nonlinearities vary depending on the strength of the "bending" field (and thus the intensity). The stronger we bend the constituent matter, the more rigid the bending force we need to exert; the more rigid the force is, the higher the restoring frequency (or the shorter the time scale) is. The nonlinearities of matter may vary, but this response is universal, ranging over molecular, atomic, plasma electronic, ionic, and even vacuum nonlinearities.

The observed correlation between laser pulse intensity and duration over 18 orders of magnitude provides an invaluable guide for the development of future laser systems for ultra-intense and short-pulse experiments. Most notably, the correlation shows that the shortest coherent pulse in the zeptosecond-yoctosecond regime should be produced by the largest lasers such as ELI, the National Ignition Facility, and the Laser Mégajoule facility under construction in France, if they are reconfigured (*16*) as femtosecond pulse systems.

References and Notes

1. Extreme Light Infrastructure European Project (www.extreme-light-infrastructure.eu).
2. G. A. Mourou, T. Tajima, S. V. Bulanov, *Rev. Mod. Phys.* **78**, 309 (2006).
3. T. H. Maiman, *Nature* **187**, 493 (1960).
4. A. Stingl, M. Lenzner, Ch. Spielmann, F. Krausz, R. Szipocs, *Opt. Lett.* **20**, 602 (1995).
5. D. H. Sutter *et al.*, *Appl. Phys. B* **70**, S5 (2000).
6. R. Ell *et al.*, *Opt. Lett.* **26**, 373 (2001).
7. M. Nisoli, S. De Silvestri, O. Svelto, *Appl. Phys. Lett.* **68**, 2793 (1996).
8. P. Antoine, A. L'Huillier, M. Lewenstein, *Phys. Rev. Lett.* **77**, 1234 (1996).
9. E. Goulielmakis *et al.*, *Science* **320**, 1614 (2008).
10. S. V. Bulanov, N. M. Naumova, F. Pegoraro, *Phys. Plasmas* **1**, 745 (1994).
11. G. D. Tsakiris, K. Eidmann, J. Meyer-ter-Vehn, F. Krausz, *N. J. Phys.* **8**, 19 (2006).
12. B. Dromey *et al.*, *Nat. Phys.* **2**, 456 (2006).
13. N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, G. Mourou, *Phys. Rev. Lett.* **92**, 063902 (2004).
14. S. V. Bulanov, T. Esirkepov, T. Tajima, *Phys. Rev. Lett.* **91**, 085001 (2003).
15. T. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, T. Tajima, *Phys. Rev. Lett.* **92**, 175003 (2004).
16. T. Tajima, G. A. Mourou, *Phys. Rev. Spec. Top. Accel. Beams* **5**, 031301 (2002).

17. We thank J. Nees, N. Naumova, E. Moses, and N. Artemiev, F. Krauz, as well as D. Verwaerde and C. L. Labaune, for fruitful discussions. T.T. was supported in part by the Blaise Pascal Foundation and by Deutsche Forschungsgemeinschaft Cluster of Excellence MAP (Munich Centre for Advanced Photonics). G.M. is supported by the École Polytechnique, the CNRS, ENSTA, and ELI 212105.

10.1126/science.1200292

CHEMISTRY

The Chlorine Dilemma

Chlorination of drinking water and municipal wastewater can create toxic chemical by-products, but alternatives pose their own set of hazards.

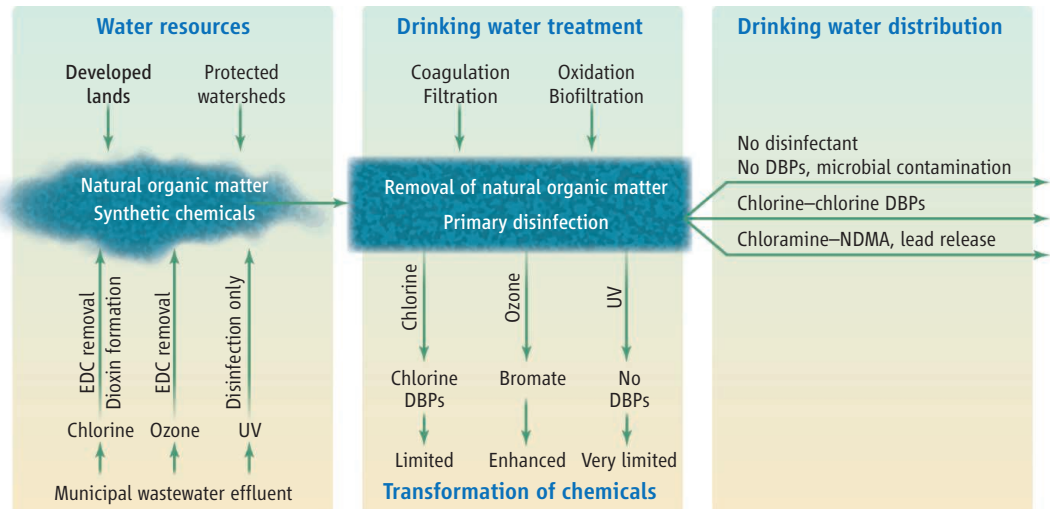
David L. Sedlak[1] and Urs von Gunten[2,3]

Chlorine disinfection has been instrumental in the provision of safe drinking water, but the use of chlorine has a dark side: In addition to inactivating waterborne pathogens, chlorine reacts with natural organic matter to produce a variety of toxic disinfection by-products (DBPs). Regulatory guidelines were established in the United States for DBPs, such as chloroform, shortly after they were discovered in chlorinated drinking water in the mid-1970s, and the discovery of a potential link between DBPs and increased rates of miscarriages and bladder cancer led to more stringent regulations and substantial changes in the operation of water treatment systems during the past decade (*1*). These concerns and the risks associated with storing chlorine gas have recently led many drinking-water and wastewater treatment plants to discontinue the use of chlorine disinfection (see the figure). A series of recent studies suggest that some of these changes have had unintended consequences that pose risks to public health and the environment.

Chlorine DBPs can be controlled in drinking-water systems by more effective removal of natural organic matter—the main precursors of DBPs—through physical-chemical treatment processes such as enhanced coagulation and activated carbon filtration. Although these approaches are effective and pose no known health risks, they are generally the most expensive way of minimizing DBP formation. As a result, many utilities worldwide have opted for the less expensive approach of using chloramine. This less reactive form of chlorine is produced by adding excess ammonia to water before addition of chlorine.

One unexpected consequence of this substitution has been the production of a different set of toxic DBPs. Most notably, carcinogenic nitrosamines such as *N*-nitrosodimethylamine (NDMA) are produced when chloramines react with nitrogen-containing organic compounds (*2*). Formation of NDMA was first recognized at advanced water reclamation plants where chloramine was being used to disinfect sewage effluent before its passage through mem-

[1]Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720, USA. [2]Eawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf 8600, Switzerland. [3]Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne-EPFL, Lausanne, Switzerland. E-mail: sedlak@berkeley.edu (D.L.S.); vongunten@eawag.ch (U.v.G.)



More than just water after water treatment. A schematic of water purification processes for drinking water and municipal wastewater. Water resources may contain not only microorganisms but also natural and synthetic compounds; the latter include endocrine-disrupting compounds (EDCs) that may or may not have been removed during wastewater treatment. After removal of natural organic matter, some disinfection processes can lead to unwanted reactions of dissolved compounds. Chlorination can create chlorine disinfection by-products (DBPs), and ozonation can introduce bromate or aldehydes. Further reaction in the drinking-water distribution system can increase concentrations of DBPs after chlorination, and chloramine use can cause increased release of lead from plumbing and can lead to formation of nitrosamines.

branes. Subsequently, NDMA and other nitrosamines have been detected in drinking-water treatment systems where chloramine reacts with the synthetic polymers used for water softening and flocculation (*3*).

In addition to forming carcinogenic nitrosamines, the switch from chlorine to chloramine has also been implicated in elevated levels of lead recently observed in drinking water and human blood in Washington, DC, and other cities (*4*). In these drinking-water distribution systems, the leaching of lead from pipes had been inhibited for many decades by the presence of chlorine, which had created a coating of sparingly soluble lead oxide (PbO_2), a Pb(IV) compound, on the surface of the pipes. After chlorine was replaced by chloramine, which is not as strong an oxidant, the coatings were reduced to Pb(II)-containing minerals, which are more soluble, thereby releasing higher concentrations of lead into the drinking water (*5*).

Several recently published studies have also uncovered unexpected findings related to the reactions of chlorine with synthetic chemicals now commonly found in surface water and groundwater, such as pharmaceuticals, personal care products, and polar pesticides. Many of these compounds contain electron-rich phenolic and amine moieties that are transformed during chlorine disinfection through electrophilic substitution (*6*). For example, chlorination of the phenolic compound triclosan, an antimicrobial widely used in soaps, leads to chlorination of the aromatic ring. The ring then undergoes cleavage reactions and releases chloroform and related trihalomethanes (*7*). In surface waters downstream of sewage treatment plants, where wastewater is disinfected with chlorine, the ring-chlorinated triclosan derivatives undergo photochemical transformation to form di-, tri-, and tetrachlorinated dioxins that accumulate in downstream sediments (*8*).

The production of potentially toxic compounds by chlorine disinfection can be problematic, but transformation reactions occurring during chlorination also can be beneficial. For example, endocrine-disrupting compounds (EDCs) in wastewater effluent that enters natural waterways have been implicated in the feminization of fish. The EDCs most often responsible for fish feminization—17β-estradiol, 17α-ethinylestradiol, estrone, and nonylphenol (*9*)—are transformed during chlorine disinfection through reactions with phenolic moieties (*10*). The estrogen receptor has high specificity, so the products of these reactions are much less estrogenic than the parent compounds (*11*, *12*). Other compounds in wastewater effluent that pose potential risks to aquatic ecosystems, including antibiotics and β-blockers, also are transformed to less reactive products during chlorine disinfection (*6*). Because of concerns associated with chlorine DBPs and potential hazards associated with handling of chlorine gas, many wastewater utilities are now switching to ultraviolet (UV) disinfection systems that leave these biologically active compounds unchanged. This switch has resulted in the loss of the beneficial side effect of chlorine's reactivity with electron-rich organic compounds.

Recognition of these unexpected consequences of the shift away from chlorine disinfection raises new challenges with respect to the operation of drinking-water and wastewater treatment plants. For drinking-water treatment plants with aging distribution systems, chlorine plays an important role in controlling microbial growth and preventing the release of lead. Research is needed into more effective methods of removing DBP precursors and applying disinfectants other than chlorine (such as UV light and ozone) at the drinking-water treatment plant. Such advances could lower the concentrations of DBPs enough to make it possible to continue to add some chlorine as a residual disinfectant. For treatment plants with newer or better-maintained drinking-water distribution systems, research may help to identify ways of more effectively operating water distribution systems without residual disinfectants. To avoid the formation of chlorine DBPs when wastewater is disinfected (while still disinfecting water and removing EDCs), a disinfectant with oxidizing capacity may be useful. Ozone appears to meet these needs, provided that the challenges associated with ozone DBPs, such as bromate and low-molecular-weight aldehydes, are effectively addressed.

References

1. Federal Register (U.S. Government Printing Office, Washington, DC, 1998), vol. 40, pp. 69390–69476.
2. W. A. Mitch, D. L. Sedlak, *Environ. Sci. Technol.* **36**, 588 (2002).
3. S. H. Park *et al.*, *Environ. Sci. Technol.* **43**, 1360 (2009).
4. M. Edwards, A. Dudi, *J. Am. Water Works Assoc.* **96**, 69 (2004).
5. H. Z. Liu, G. V. Korshin, J. F. Ferguson, *Environ. Sci. Technol.* **43**, 3278 (2009).
6. M. Deborde, U. von Gunten, *Water Res.* **42**, 13 (2008).
7. K. L. Rule, V. R. Ebbett, P. J. Vikesland, *Environ. Sci. Technol.* **39**, 3176 (2005).
8. J. M. Buth *et al.*, *Environ. Sci. Technol.* **44**, 4545 (2010).
9. J. P. Sumpter, A. C. Johnson, R. J. Williams, A. Kortenkamp, M. Scholze, *Environ. Sci. Technol.* **40**, 5478 (2006).
10. M. Deborde, S. Rabouan, H. Gallard, B. Legube, *Environ. Sci. Technol.* **38**, 5577 (2004).
11. B. C. Lee *et al.*, *Water Res.* **38**, 733 (2004).
12. Y. Lee, B. I. Escher, U. von Gunten, *Environ. Sci. Technol.* **42**, 6333 (2008).

10.1126/science.1196397

The Chlorine Dilemma

David L. Sedlak and Urs von Gunten

Science **331** (6013), 42-43.
DOI: 10.1126/science.1196397