followed by multiple LGT events between eukaryotes. Indeed, eukaryotic homologues in the eukaryote–prokaryote clusters are often patchily distributed: some are present in only two of the six recognized high-level groups of eukaryotes, and many more are limited to three or four such groups. Although patchy gene distributions are often interpreted as evidence for LGT[1,5,10], Ku *et al.* conclude that the trees in which eukaryotic sequences are monophyletic are not the product of eukaryote-to-eukaryote LGT. Why? Statistical tests showed that the trees for eukaryote–prokaryote clusters are generally compatible with those inferred from the eukaryote-specific clusters, which are considered to be the product of vertical evolution.

The remaining 12.5% of trees for eukaryote–prokaryote clusters show the eukaryotic homologues branching apart from one another, consistent with prokaryote-to-eukaryote LGT. Ku *et al.* provide alternative explanations for such patterns, including sequencing contaminations and errors inherent in phylogenetic reconstructions. However, the authors identified several blocks of genes whose lineage-specific distributions are so striking that LGT is the only reasonable explanation. It will be interesting to see how these LGTs stack up against those identified by others[11].

Ku *et al.* conclude that gene evolution in eukaryotes is "resoundingly vertical" and that the punctate distribution of prokaryotic genes across eukaryotes is primarily the result of differential gene loss during evolution. Apart from the gene acquisitions associated with mitochondrial and chloroplast EGT, eukaryotes seem to sample prokaryotic gene diversity at a much lower level than do bacteria and archaea. Given evidence for at least some prokaryote-to-eukaryote LGT, the authors suggest that perhaps genes transferred by LGT are retained in the genome for only a short time, or that lineages that engage in LGT tend not to be successful in the long run. This latter idea is at odds with the prevailing view that LGTs are of benefit to the recipient organism[1,10].

At present, there are two types of eukaryotic gene whose histories are uncontroversial: ubiquitous genes that were probably present in the common ancestor of all eukaryotes; and lineage-specific genes with strong signatures of recent LGT. Between these two extremes lies a continuum of genes whose phylogenies and presence–absence patterns are exceedingly complex. The extent to which Ku and colleagues' analyses have fully captured the evolutionary forces that shaped the nuclear genome is unclear. Nonetheless, they have shown that EGT has been the dominant mode of gene acquisition in eukaryotes, that gene patchiness is the norm and that gene loss needs to be taken seriously. We now have the opportunity to compare notes on the strengths and weaknesses of the various approaches currently being used to distinguish lateral from vertical inheritance in eukaryotes. Consider the issue open for discussion. ■

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PHOTONICS

A stable narrow-band X-ray laser

An atomic laser operating at the shortest wavelength yet achieved has been created by bombarding a copper foil with two X-ray pulses tuned to slightly different energies. The results may lead to ultrastable X-ray lasers. SEE LETTER P.446

LINDA YOUNG

X-rays penetrate matter to image a system's internal 3D structure using contrast arising from spatial variations of elemental, chemical or magnetic properties. Lasers that function at X-ray wavelengths go beyond basic structure determination, because they can deliver bright pulses on ultrashort timescales to probe matter at the atomic level. This means that they can be used to characterize dynamic processes, such as chemical-bond formation, charge transfer and light-induced superconductivity, or to determine the macromolecular structure of a system without damaging it. Such lasers have been the subject of extreme fascination since physicist Theodore Maiman demonstrated[1] the first laser that operated at optical wavelengths in 1960. On page 446 of this issue, Yoneda *et al.*[2] demonstrate an atomic X-ray laser that yields a marked improvement in wavelength stability compared with X-ray free-electron lasers (XFELs), taking a major step towards an ångström-wavelength laser that remains in phase over its pulse duration — that is, which possesses longitudinal coherence.

XFELs[3–5], which use a high-energy electron beam as the laser-generating medium, have revolutionized X-ray science by introducing ultra-fast, ultra-intense X-ray pulses suitable for a vast range of applications. These facilities accelerate electron beams close to the speed of light (at energies in excess of 10^9 electronvolts), through 100-metre-long arrays of magnets that are arranged in a periodic pattern of alternating polarity along the beam path. These systems create, in a single passage of the electron beam, intense X-ray pulses lasting only a few femtoseconds (1 fs is 10^{-15} seconds) that contain a trillion X-ray photons and achieve peak brightness a billion times greater than radiation produced by conventional synchrotron light sources. XFELs typically operate on the principle of self-amplified spontaneous emission (SASE), whereby the accelerating electrons' incoherent emission of radiation is further amplified by continuous interaction with the electron beam over the length of the magnetic array.

Although SASE results in intense, short-wavelength laser pulses that are coherent in a plane transverse to the direction of propagation, strong longitudinal fluctuations in the time and spectral domains are observed; these can greatly complicate experiments that use these lasers. Yoneda and colleagues' X-ray laser amplifies light that has a well-defined wavelength of 1.54 Å, generated by transitions of electrons from the 2*p* orbital to the 1*s* orbital of copper atoms. This is the shortest-wavelength atomic laser ever demonstrated, surpassing by a factor of 10 an atomic neon laser that has been shown[6] to operate at 14.6 Å.

The authors' laser uses the photoionization-pumping scheme presciently proposed[7] for copper in 1967. In this scheme, the ejection of an inner-shell electron of a copper atom by a suitable light source (the pump) leaves a deficit of electrons in a lower energy level of the resulting copper ion, achieving what is known as population inversion. Electrons drop into the vacated level, spontaneously emitting photons, which are amplified as they

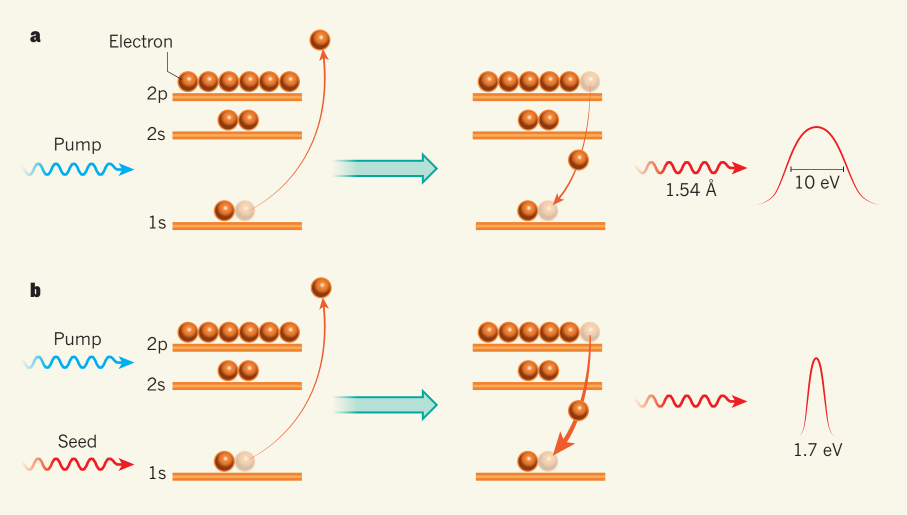

Figure 1 | An atomic laser that uses copper's inner-shell electrons. Yoneda *et al.*[2] report an X-ray laser that operates by focusing intense pulses from an X-ray free-electron laser on copper foil. **a**, They first use a 'pump' pulse that ejects an electron from the copper atoms' 1*s* ground level. This leaves a surplus of electrons in the upper 2*p* energy level of the resulting ions, achieving a state called population inversion. 2*p* electrons then spontaneously drop into the vacated 1*s* level, emitting 1.54-Å photons and starting a process called amplified spontaneous emission (ASE). The resulting laser output has a large spectral linewidth (about 10 eV), which increases with the intensity of the pump. **b**, The authors subsequently used an additional X-ray pulse called the seed, tuned to the lasing wavelength of 1.54 Å. This enhanced (thick orange arrow) the stimulated emission from the upper energy levels. The resulting laser has a much narrower spectral profile (1.7 eV) than the ASE laser and offers increased wavelength stability.

propagate along a path of other identical ions that have inverted electron populations, in a process known as amplified spontaneous emission (ASE). However, Yoneda *et al.* go beyond a simple observation of ASE to demonstrate the 'seeded' operation of the laser that offers improved performance.

The authors first demonstrate amplification of the 1.54-Å transition by focusing brief (7 fs), 9-keV-energy XFEL pulses to a 100-nm-wide spot on a 20-µm-thick copper foil. These are known as pump pulses, and they preferentially eject a 1*s*-orbital electron to ionize the copper atoms in the foil and produce a wave of ions with inverted electron populations that travels collinearly with the generated ASE (Fig. 1a). For a 2-fold increase in the XFEL's power, the authors observe a roughly 15-fold increase in the intensity of the output lasing emission, although no saturation of the laser was observed over the accessible range of pump power — the energy output of the laser never levelled off with increasing pump power.

The authors then demonstrate the seeded operation of the atomic laser (Fig. 1b). For this, they use two XFEL pulses: the pump and another known as the seed, which have energies of 9 and 8 keV, respectively. These are generated by a single electron bunch, ensuring temporal and spatial overlap between the respective pulses. The authors observe that the output of the seeded laser has a narrower linewidth (1.7 eV) than the ASE laser generated using only the pump source, whose linewidth unexpectedly broadens at high pump powers. Thus, the seeded laser output is spectrally more coherent and offers increased wavelength stability. The seeded laser also represents a substantial improvement compared with the 40-eV-wide input pump pulse.

Why did we have to wait more than 50 years after Maiman's achievement for an atomic X-ray laser operating at such a short wavelength? The main obstacle has been that the power of the pumping source required to create population inversion scales inversely with the fourth power of the output lasing wavelength. This simple consideration necessitates an approximately 10^{15}-fold increase in pump power density to go from a laser operating at 7,000 Å to one at 1.54 Å.

Before XFELs, there were many approaches to achieving such power densities, including the nuclear-bomb-pumped lasers[8] in the US Strategic Defense Initiative programme of the 1980s and optical (or infrared) pumping[9,10]. In the optical-pumping scheme, a 532-nm-wavelength laser was focused on a thin foil of selenium to create a plasma of highly charged ions and electrons[9]. Collisions between electrons and selenium that had lost its outer electrons populated the upper level of the 3*p*-to-3*s* transition of the ions and resulted in a 209-Å laser. By contrast, the photo-ionization-pumping scheme[7] used in the current work directly creates population inversion in a single step by ejecting an inner 1*s* electron, but the method had to wait for the development of XFELs to generate the requisite X-ray power density.

Despite this giant step in X-ray-laser development by Yoneda *et al.*, their atomic copper laser is not quite ready for general use. Their seeded laser did not achieve saturation, and the absolute energy, angular divergence and duration of the output pulse were not measured. The authors' simulations predict that the conversion efficiency of the laser, which is the ratio of the output power to the input power, is only 2%, corresponding to laser energies of about 1 microjoule. For comparison, the atomic neon laser[6] eventually achieved saturation with about 10% conversion efficiency[11] and yielded energies of about 15 µJ.

Considering slightly longer wavelengths, there are viable alternatives for users seeking the absolute wavelength stability and coherence of atomic lasers. Pulses from tabletop optical lasers can be used as pumps to generate soft X-ray atomic lasers, which operate on the 4*d*-to-4*p* transition of elements with a nickel-like electronic configuration. These lase at 7.3 nm with a power of several microjoules per pulse[12], albeit at a low pulse-repetition rate of 1 hertz. Recently, a tabletop atomic laser with a high average power (1 µJ per pulse; 100 Hz) was demonstrated at 13.9 nm (ref. 13). Tabletop infrared lasers generating 'high-harmonic' emission can provide ultrafast coherent X-ray pulses in a slightly different parameter space (sub-femtosecond duration, broad bandwidth with lower X-ray pulse energies[14]) compared with the optically pumped, atomic X-ray lasers[12,13].

For those seeking improved longitudinal coherence together with narrow-bandwidth and wavelength-tunable X-ray radiation, various seeding schemes have been demonstrated using XFELs, including self-seeding in the high-energy X-ray range[15] and high-gain harmonic generation at the FERMI[16] facility in Trieste, Italy. Yoneda and colleagues' work, together with other improvements to X-ray lasers beyond SASE radiation, ensure that researchers can look forward to a rich playground of very-short-wavelength sources. ■

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