# Focusing hard X-rays with old LPs

A vinyl long-playing record can be used to form a cheap, aberration-free refractive lens.

We have found that two sections cut from a vinyl long-playing record can form a spherical aberration-free refractive lens for hard X-rays. Our manufactured saw-tooth refractive lens has a focal length of 22 cm for 23-keV X-rays. The low cost and short focal length of this lens make it feasible for use in small-scale experiments with conventional X-ray tubes.

Refractive X-ray focusing, although not a new idea[1], has generally been considered inefficient and impracticable[2,3]. A breakthrough was the compound refractive lens, in which the refractive effect was substantially increased by the combination of many individual cylindrical lenses[4,5]. From a manufacturing point of view, however, a design with only straight cuts would be preferable.

We have designed such a lens, comprising two identical halves that have a number ($N$) of regular saw-teeth of height $y_s$ arranged along the optical axis (Fig. 1). At one end the halves touch, and at the opposite end there is a gap ($2y_g$) between them that determines the focal length. Because an X-ray travelling farther away from the axis experiences more surfaces, the total deflection increases with increasing distance from the axis. The lens is tunable and the focal length for a given energy can be varied by a simple mechanical procedure.

In the small-angle approximation, a ray traverses the saw-tooth refractive lens in a straight line parallel to the optical axis. A ray separated by $y$ from the optical axis traverses a thickness of material given by

$$x(y) = y^2N/(y_g \tan\theta)$$

This is a parabola, with radius of curvature

$$R = y_g \tan\theta/2N$$

The total length of the lens is $L = 2Ny_s/\tan\theta$, and so $R = (y_g/2N)(2y_sN/L) = y_gy_s/L$.

Thus we can treat the saw-tooth refractive lens as a single parabolic lens with a focal length of $f = R/\delta$, where $\delta$ is the decrement of the real part of the index of refraction from unity (typically $10^{-6}$ for hard X-rays). The focusing properties are independent of the fixed free parameter $\theta$.

We can apply conventional geometrical optics to calculate the gain of flux. Suppose we wish to focus a beam to a slit with width $d_s$. The distance between source and lens is $s_o$, whereas that between lens and slit is $s_i$. The (de)magnification factor is then given by $M_y = s_i/s_o$. A ray that has lateral displacement $y$ is attenuated by a factor

$$\exp[-x(y)/l] = \exp(-y^2/2f\delta l)$$

where $l$ is the X-ray attenuation length. This is a gaussian beam with r.m.s. width

$$\sigma = \sqrt{f\delta l}$$

which is a key lens parameter. It can easily be shown that, to a good approximation, the gain of flux is $G = \sqrt{2\pi}(1 + M_y)\sigma/d_s$.

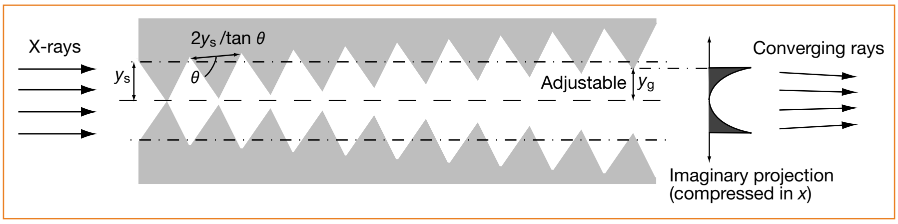

**Figure 1** The saw-tooth refractive lens for hard X-rays. Only ten of 300 teeth are shown. The lens bears a striking resemblance to phonograph records, the groove pitch of which is about 180 μm. Measurements of the profile indicate that the depth of the groove is insufficient (about 25μm) and that there is a large amount of material between the grooves, however, resulting in unnecessary X-ray attenuation. We therefore had a dedicated master cut with a groove depth of 90 μm, from which a vinyl record was pressed. Two 60-mm long sections were cut out to form the lens. With 180 μm separation at the end, the focal length is 218 mm for 23-keV X-rays.

Because absorption is a limiting factor of the performance of the saw-tooth refractive lens, a material with low atomic number should mitigate it — beryllium and polymethylmethacrylate would be good candidates. We used polyvinyl chloride for focusing as it contains a large fraction of chlorine and provides less gain.

A normal X-ray tube with tungsten anode and focal spot size of 50 μm was used for experimental verification, with a source-to-lens distance of 640 mm and a lens-to-slit distance of 330 mm. The measured gain at 23 keV was 1.7, 15% lower than expected. This was probably due to misalignment and bad surface quality of the cuts. For polymethylmethacrylate, the gain would be three times this (3 × 1.7).

Because of its simplicity, low cost and easy alignment, the saw-tooth refractive X-ray lens could be valuable as a tool in laboratory-scale arrangements for X-ray applications such as imaging, microscopy, fluorescence and diffraction. As the lens is chromatic, the desired energy can be selected from a broad X-ray spectrum by changing the gap between the lens halves. Two saw-tooth refractive lenses can be put in series to obtain focusing in two directions and squared gain.

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Evolution

# Symbiotic solution to arsenic contamination

Higher plants that are adapted to living on polluted soils are generally symbiotic with mycorrhizal fungi growing on contaminated sites[1,2]. It is not known whether these fungi benefit their host plants simply by fulfilling their normal ecological functions[3], or by enhancing the plant's resistance to pollutants. Arsenate contamination poses a particular challenge, as this toxin can enter plants through their phosphate transporters[4], causing mycorrhizal fungi to enhance both phosphate and arsenate uptake in plants[5]. We have found a plant host and its mycorrhizal symbiont that have evolved in parallel to obtain phosphate but exclude arsenate.

We took populations of the ericoid mycorrhizal fungus *Hymenoscyphus ericae* from the roots of *Calluna vulgaris* growing on an arsenic and copper mine spoil and on an uncontaminated heathland site. Arsenate (the arsenic species in soil solution) dose–response curves indicated that plants and fungal populations from the mine were much less sensitive to arsenate than the heathland populations (Fig. 1a). Both partners on the mine spoil have thus evolved resistance to arsenate: the comparatively low sensitivity of the fungus suggests that it may confer added arsenate resistance to the association.

Short-term arsenate- and phosphate-uptake kinetics of the fungus were identical for the mine and heathland populations. Efflux kinetics of arsenic species from mycelia preloaded for 1 h with 0.1 mol m$^{-3}$ arsenate showed that resistant *H. ericae*

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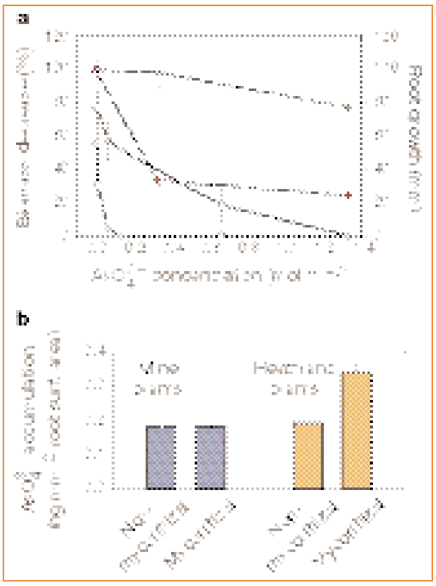

**Figure 1** Growth of plant and fungus in the the presence of arsenate and the influence of fungal colonization on arsenate accumulation by the host plant. **a,** Biomass of *H. ericae* mycelia after 17 d in medium containing arsenate ($n = 24$) and root-lengths of *C. vulgaris* seedlings grown on agar plates containing arsenate for 3 months ($n = 9$). Filled symbols, fungus; open symbols, plants. Triangles, mine populations; circles, heathland populations; dotted lines, fungus; solid lines, plants. **b,** Arsenate uptake (24 h) from a 0.1 mmol m$^{-3}$ arsenate solution by 4-month-old sterile *C. vulgaris* seedlings with or without *H. ericae* from site of origin ($n = 3$). Graphs show means ± s.e.

from the mine has enhanced efflux of arsenite (efflux from mine isolates, 14.4 ± 3.0% h$^{-1}$; heathland isolates, 6.6 ± 3.0% h$^{-1}$ ($P < 0.001$)). *H. ericae* has independently evolved the same strategy as one used by bacteria that reduce arsenate intracellularly to arsenite[6] for efflux.

Arsenate resistance in *C. vulgaris* is not achieved by exclusion, as we found no alteration to influx or efflux for either arsenate or phosphate. Higher plants normally resist arsenate through downregulation of arsenate/phosphate transporters[7], but *C. vulgaris* has adopted an alternative mechanism. We suggest that the fungus dominates arsenate/phosphate accumulation, acting as a filter to maintain low plant arsenic levels through arsenite efflux while enhancing plant phosphorus status. When exposed to arsenate for 24 h, heathland *C. vulgaris* inoculated with heathland *H. ericae* accumulated 100% more ($P = 0.01$) arsenate than uninoculated heathland plants or mine plants (with and without mine *H. ericae*), which all had comparable arsenate accumulation (Fig. 1b). Infection of mine *C. vulgaris* with mine *H. ericae* did not place the host under additional arsenate stress.

We found that mine and heathland *H. ericae* were constitutively copper resistant, which confers resistance upon non-resistant *C. vulgaris*[8]. In contrast, *H. ericae* and its host must have adapted to arsenate contamination in parallel, by the fungus selectively accumulating phosphate over arsenate. Our data show that evolution of host and symbiont is fundamental to the colonization of polluted soils by key plant taxa.

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**Pattern recognition**

# Tunes and templates

A tune is a succession of musical tones that is easily recognizable when repeated. Here we describe an experimental technique and preliminary results that test a simple theoretical idea about tune recognition.

The theory is that the initial experiences of the melody form a template in the plane defined by pitch and time[1]. When the tune is repeated, it is compared with this template, and for the appropriate starting time there will be matches between what is received and what is predicted from the template: the number of these matches is a decision variable determining the detectability of the tune. Detectability can be impaired either by randomly removing some of the notes from the tune, or by adding interfering 'noise' notes to it. The theory predicts how these two types of interference should combine with each other, and we have experimentally tested whether this prediction is correct.

We took a well known melody (the first four bars of *Eine Kleine Nachtmusik* by W. A. Mozart) and mixed random notes with it to find out how many such 'noise' notes could be tolerated while still recognizing the tune. We did the experiment with the whole melody, and also with 1, 2, 4 or 9 notes selected randomly and independently on each trial from the full set of 18, preserving their order and timing. In any one experiment, the number of melody notes was fixed and the task was to identify whether they were present.

It is easiest to understand the experimental design by considering a matrix of 37 rows for the note pitches by 128 columns for their timing. For a given starting time, the melody notes marked 18 elements of the matrix. The masking or noise notes were then scattered randomly within the matrix. The subject's task was to decide whether the stimulus contained part or all of the melody, or alternatively whether it belonged to the set of noise-only notes. For each number of melody notes, Fig. 1 shows the number of masking noise notes that could be tolerated while still allowing 75 per cent correct responses in the single-interval forced-choice trials.

The simplest theory assumes that the starting time of the melody is known. The template acts as a sieve and performance depends on the total number of notes that passed through the holes corresponding to the expected positions of the melody notes. For the 'melody' trials, these numbers exceed those on the 'noise-only' trials by $\Delta\mu$, which is the average number of melody notes in those trials, namely 1, 2, 4, 9 or 18. If $\sigma$ is the standard deviation of the number that occur in the noise-only trials, then $d' = \Delta\mu/\sigma$ (ref. 2). The statistics of the number of melody-matching notes from the masking noise is binomial; hence $\sigma$ is equal to $\sqrt{(npq)}$. In our case, $p$ and $q$ are constant, so $\sigma$ is proportional to $\sqrt{n}$, the

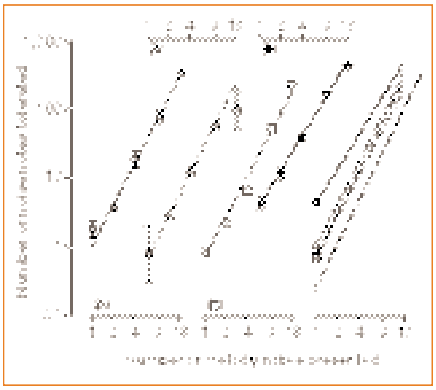

**Figure 1** The subjects' task was to distinguish between a 'noise' sequence of notes and a 'melody' sequence. The melody sequence differed from the noise sequence by containing 1, 2, 4, 9 or 18 notes drawn from a melody in addition to noise. The number of noise notes that could be tolerated for 75% correct answers was estimated from 200 trials. The four sets of data points on the left show these results plotted on logarithmic scales; the results for each subject are separated by horizontal shifts. Straight lines were fitted, and these lines with their appropriate symbols are replotted at the right with a single horizontal scale, together with the theoretically predicted line of slope 2 (broken line). Three of the subjects (open symbols) were musically untrained or amateur musicians, and for them the fitted values of the slopes lie reasonably close to the predicted value of 2 (circle, 2.02 ± 0.054; triangle, 2.04 ± 0.067; square, 1.94 ± 0.12). The fourth subject (filled circles) is a professional musician and was the only subject with absolute pitch. She tolerated more noise notes, her results have less variability and lie on a shallower slope (1.63 ± 0.067) than the others.

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