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Food chemistry

Acrylamide from Maillard reaction products

The discovery of the adventitious formation of the potential cancer-causing agent acrylamide in a variety of foods during cooking^{1,2} has raised much concern^{3,4}, but the chemical mechanism(s) governing its production are unclear. Here we show that acrylamide can be released by the thermal treatment of certain amino acids (asparagine, for example), particularly in combination with reducing sugars, and of early Maillard reaction products (*N*-glycosides)⁵. Our findings indicate that the Maillard-driven generation of flavour and colour in thermally processed foods can — under particular conditions — be linked to the formation of acrylamide.

We heated 20 amino acids individually at 180 °C for 30 min and found that acrylamide is formed under these conditions from methionine and from asparagine (3.65 ± 1.4 and 0.565 ± 0.05 μmol acrylamide per mol amino acid, respectively; all results are averages of *n*46 independent determinations unless stated otherwise).

When pyrolysed at 180 °C with an equimolar amount of glucose, asparagine in particular generates significant amounts of acrylamide, reaching an average of 368 μmol mol⁻¹ after an incubation time (*t*_i) of 30 min. If asparagine monohydrate was used in the incubation or water was added to the reaction (0.05 ml) before thermolysis, the release of acrylamide was enhanced nearly threefold (960 ± 210 μmol mol⁻¹), or over 1,700 times the amount formed from asparagine alone under the same conditions.

Reaction of methionine and glutamine with equimolar amounts of glucose at 180 °C also increased the formation of acrylamide, which occurred rapidly in each case (*t*_i45 min; Fig. 1a). Cysteine was found to liberate acrylamide after condensation with glucose (2.05 ± 0.8 μmol mol⁻¹ at *t*_i430 min and 180 °C).

Investigating the role of different carbohydrates in the formation of acrylamide, we

found that pyrolysing any of these amino acids (Asn, Gln, Met, Cys) with an equimolar amount of D-fructose, D-galactose, lactose or sucrose all led to a significant release of acrylamide, with comparable yields from each sugar. No acrylamide was detected when any of these carbohydrates was heated alone.

To test whether early Maillard products such as *N*-glycosides could be acrylamide precursors in thermal decomposition reactions, we measured the yields of acrylamide after pyrolysis (*t*_i420 min, 180 °C) of 0.2 mmol of four different *N*-glycosides (Fig. 1b). Yields were significant (in μmol per mol *N*-glycoside: compound 1, 1,305 ± 323; 2, 1,419 ± 278; 3, 145 ± 2.7; and 4, 8.15 ± 1.5) and comparable to those released from the amino-acid and reducing-sugar precursors under the same conditions. Furthermore, compound 1 was confirmed as an intermediate in the asparagine/glucose reaction by high-resolution mass-spectrometric analysis of a methanol extract of the pyrolysate.

On the basis of structural considerations, asparagine or the *N*-glycosides 1 and 2 could be direct precursors of acrylamide under pyrolytic conditions. Condensation of asparagine with ¹³C₆-labelled glucose confirmed that the amino acid is the carbon source of acrylamide. Upon pyrolysis, formation of the corresponding *N*-glycoside probably facilitates the decarboxylation step and heterolytic cleavage of the nitrogen-carbon bond to liberate acrylamide (CH₂5CHCONH₂). Although decarboxylation is favoured at higher temperatures, the *N*-glycosidic bond seems to facilitate the deamination step.

Further evidence to support this pathway to acrylamide production is provided by the 98.6% incorporation of nitrogen-15 label into acrylamide after the pyrolysis of ¹⁵N-amide-labelled asparagine with glucose; there was no incorporation into acrylamide when ¹⁵N-α-amino-labelled asparagine was used in the same reaction. Results from similar isotope-labelling experiments (not shown) to determine the route of acrylamide formation from different *N*-glycosides produced by glucose pyrolysis with glutamine or methionine are less clear-cut, which suggests that other pathways (such as that for homolytic cleavage) might also lead to acrylamide.

The *N*-glycosidic bond is labile in the presence of water⁶ or under acidic and neutral pH conditions⁷, hydrolysing rapidly to the reducing sugar and amino acid. At higher pH, however, *N*-glycosides can be isolated as bimolecular complexes in the presence of polyvalent alkaline or transition-metal ions⁸. In food-processing systems that incorporate conditions of high temperature and water loss, *N*-glycoside formation could be favoured; when this condensation occurs between reducing sugars and certain amino acids, a direct pathway is opened up to

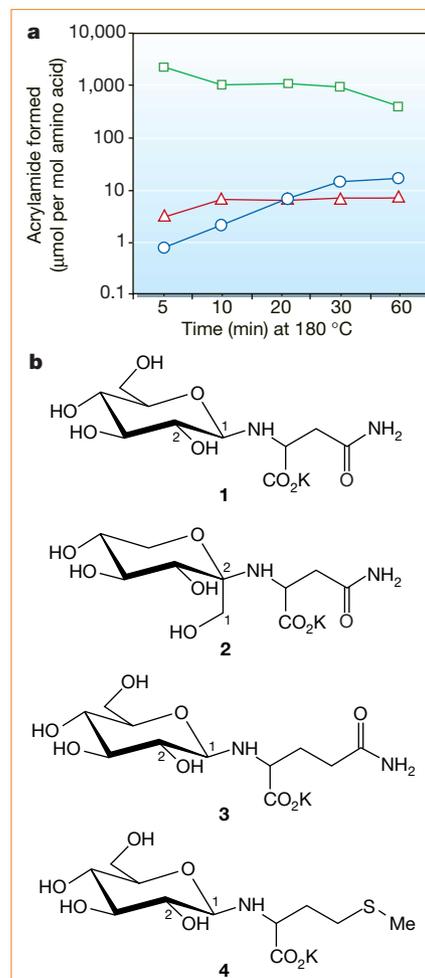


Figure 1 Production of acrylamide from *N*-glycosides. **a**, Logarithmic-scale plot of the formation of acrylamide over time in pyrolysates of glucose with glutamine (triangles), asparagine (squares) or methionine (circles). Each data point represents the average of *n*43 independent determinations; the coefficient of variation was less than 25%. For acrylamide analysis (by liquid chromatography coupled to electrospray ionization tandem mass spectrometry), pyrolysates were supplemented with ¹³C₃-acrylamide (50 ng), then suspended in hot water (more than 90 °C), sonicated and filtered before being applied to a solid-phase extraction cartridge (OASIS HLB, 0.2 g). Acrylamide eluted with 20% methanol was separated on a Shodex RSpak DE-613 polymer column with isocratic solvent flow. Detection by mass spectrometry was in the multiple-reaction monitoring mode with the characteristic fragmentation transitions for acrylamide (*m/z* 72 → 55, 72 → 27, 72 → 54) and confirmed by ion ratios (55/54 and 55/27). Further details are available from the authors. **b**, Chemical structures of the potassium salts of *N*-(D-glucos-1-yl)-L-asparagine (**1**), *N*-(D-fructos-2-yl)-L-asparagine (**2**), *N*-(D-glucos-1-yl)-L-glutamine (**3**) and *N*-(D-glucos-1-yl)-L-methionine (**4**).

potential progenitors of acrylamide.

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Quantum cryptography

A step towards global key distribution

Large random bit-strings known as ‘keys’ are used to encode and decode sensitive data, and the secure distribution of these keys is essential to secure communications across the globe¹. Absolutely secure key exchange² between two sites has now been demonstrated over fibre³ and free-space^{4–6} optical links. Here we describe the secure exchange of keys over a free-space path of 23.4 kilometres between two mountains. This marks a step towards accomplishing key exchange with a near-Earth orbiting satellite and hence a global key-distribution system.

The security of our key-exchange system is guaranteed by encoding single photons using two sets of orthogonal polarizations. Our transmitter module (Alice; Fig. 1) incorporates a miniature source of polarization-coded faint pulses (approximating single photons; C.K., P.Z., M.H. and H.W., unpublished results), where 0° or 45° polarization encode binary zero, and 90° or 135° code binary one. These light pulses are expanded and collimated in a simple telescope to a beam of about 50 mm and then accurately aligned on the receiver (Bob; Fig. 1), a 25-cm-diameter commercial telescope. Light is collected and focused onto a compact four-detector photon-counting module (Fig. 1). A detection in any one detector then has an associated bit value, measurement basis (0° or 45°) and detection time. The bit values then form a raw key string. Valid bits are measured in the same basis as that in which they were encoded.

Alice and Bob use a standard communications channel, such as a mobile telephone, to ascertain which bits arrived (many are lost) and which measurement basis was used, then they both discard the invalid bits — which leaves them with nearly identical random bit-strings, the sifted key. Eavesdropping measurements on the single photons disturb the encoding and introduce errors of up to 25%, so Alice and Bob test for errors in a short section of sifted key to

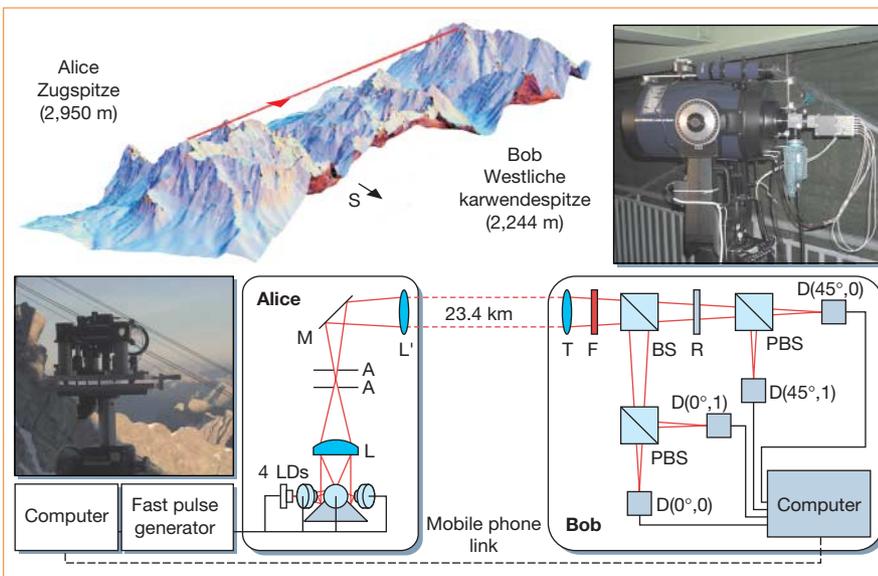


Figure 1 Overview of the experiment against a relief map of the trial site. In the Alice module, four separate lasers (LDs) encode the four polarizations based on a random bit-string fed from the Alice computer. They are combined in a spatial filter (A,A) using a conical mirror (M) and a lens (L). The beam expands to 50 mm and is collimated in an output lens (L_B). In the Bob module, a telescope (T) collects the light, which is filtered (F) and then split in a polarization-insensitive beam-splitter (BS), passing on to polarizing beam-splitters (PBS) and four photon-counting detectors (D). One polarizing beam-splitter is preceded by a 45° polarization rotator (R). A click in one of the photon-counting detectors D(*u*, *B*) sets the bit value *B* and the measurement basis *u*.

verify the security of the channel. Low error rates due to background light detection and polarization settings are securely eliminated by using classical error-correcting codes sent over the mobile-telephone link.

In the long-range experiment, Alice was located at a small experimental facility on the summit of Zugspitze in southern Germany, and Bob was on the neighbouring mountain of Karwendelspitze, 23.4 km away. At this distance, the transmitted beam was 1–2 m in diameter and was only weakly broadened by air-turbulence effects at this altitude. Lumped optical losses of about 18–20 decibels were measured and, using faint pulses containing 0.1 photons per bit, the detected bit rate at Bob was 1.5–2 kilobits per second (receiver efficiency of 15%).

Operating at night with filters of 10-nm bandwidth reduced the background counts, and errors appeared in less than 5% of key bits. After sifting and error correction, net key exchange rates were hundreds of bits per second. In a series of experiments, several hundreds of kilobits of identical key string were generated at Alice and Bob.

In associated experiments in poorer visibility, we showed that key exchange could be carried out when transmission losses were up to 27 decibels, but improvements in receiver efficiency and background counts should take us beyond 33 decibels. With this performance, key exchange to near-Earth orbit (500–1,000 km range) should become possible.

Until now, the principal method of high-security key exchange has been the

‘trusted courier’ carrying a long random bit-string, the key, from one location to the other. Our experiment paves the way for the development of a secure global key-distribution network based on optical links to low-Earth-orbit satellites. We note that a 10-kilometre key-exchange experiment has recently been announced⁷.

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erratum

Cognitive change and the APOE 4 allele

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In the second sentence of the seventh paragraph of this communication, the MMSE scores are incorrectly specified as less than or equal to 28; these should read as greater than or equal to 28.