Laser-induced enantioenrichment of tartaric acid *via* a multiphoton absorption process †

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It has been found that tartaric acid (TA) undergoes efficient enantioenrichment when it is irradiated with highly intense circularly polarized light (CPL) from an XeF (351 nm) excimer laser. The concentration of the L-form during the irradiation of racemic TA with a focused right CPL was shown to decrease dramatically with increasing absorbed energy; in contrast, the concentration of the D-form remains almost constant throughout the irradiation, demonstrating that the right CPL can induce the selective enrichment of the D-form. The maximum ee of the D-form was found to be *ca.* 7.5%. In sharp contrast, irradiation with the left CPL resulted in selective enrichment of the L-form through a decrease of the D-form. Thus, it was shown that high-intensity CPL irradiation can induce the enantiodifferentiation of racemic TA with reasonable enantiocontrol merely by switching the sense of the CPL. Furthermore, the fluence dependence studies revealed that this enantiodifferentiation using the CPL from an XeF laser proceeds by the selective excitation of the carboxyl chromophore in TA by two-photon absorption, followed by photodecomposition (*e.g.* decarboxylation).

Since the synthesis of a racemic compound is often much easier than absolute asymmetric synthesis of a specific enantiomer, enantiomeric enrichment from a racemate is of importance in the preparation of optically active compounds.[1,2] Of the many methods available to enrich racemates the success of such enrichment by photochemical methods using circularly polarized light (CPL),[2] is often related to the origin of the optically active biomolecules in Nature. In this connection, reported studies suggest that the enantiomeric enrichments by this method were less than satisfactory (mostly, ee < 3%) except for a limited number of compounds such as camphor.[2,3] It seems possible that the use of low-intensity light sources[4–6] and/or of mixed light or right (r)- and left (l)-CPL[4] are mainly responsible for such poor enrichments.

In enriching the enantiomer by photochemical methods, it has recently been demonstrated that the efficient laser-induced synthesis of D-tartaric acid **3** is possible by irradiation of racemic tartaric acid **1** with a highly intense r-CPL from an XeF
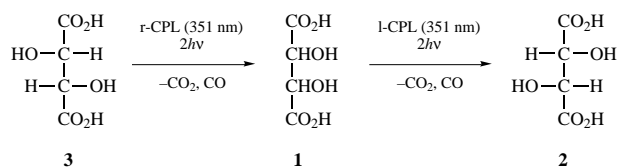
Scheme 1

(351 nm) laser;[7] subsequently it was found that high-intensity l-CPL induces enrichment of the L-tartaric acid **2**, revealing a clear correlation between enantioselection and the sense of the CPL.[8] These results indicate that high-intensity CPL irradiation can induce the enantiodifferentiating reaction of **1**, and prompted us to clarify the importance of the light intensity in

the enantiomeric enrichments by the photochemical methods using a laser. In the present work, the fluence effects of the r-CPL on the enantiomeric enrichment of **2** were investigated with varying light intensities and the results are discussed in terms of the photon parameter obtained in the fluence–dependence studies. In this paper, furthermore, further detail is reported with regard to the laser-induced asymmetric synthesis of tartaric acid in connection with the reaction mechanism.

Experimental

General
UV spectra were recorded on a Shimadzu UV-2100 spectro-photometer. Gaseous and liquid product analyses were performed using gas chromatographs (Shimadzu GC-3BT, column: molecular sieve 5A; GC-4C, column: Porapak N) and ion chromatograph (Yokogawa IC-100, column: SAX1 two), respectively. Optical rotations were measured in a thermo-statted micro-cell using a Nihon Bunko DIP-1000 digital polar-imeter; high-performance liquid chromatographic analysis was performed using a Shimadzu LC-6A instrument.

Materials
Racemic tartaric acid (DL-TA) **1**, L-TA **2** and D-TA **3** of guaranteed reagent grade were obtained from Tokyo Kasei and/or Nacalai Tesque.

Generation of CPL
The XeF laser beam (Lumonics Hyper EX-460, initial power: 2.6 W, frequency: 16 Hz, pulse duration: 12–15 ns, beam shape: 9×34 mm²) was converted into r-CPL (initial power: 1.3 W at 16 Hz) by passing it through a polarizer (60×30 mm², 5 mm thick) arranged at an angle of 56.5° and a quarter-wave plate (40×40 mm², 0.6 mm thick) orientated with an angle of +45° to the plane of the incident beam by being mounted on a rotat-able stage. The l-CPL (initial power: 1.3 W at 16 Hz) was obtained by switching the sense of the r-CPL by rotation of the quarter-wave plate through 90°. Both r-CPL and l-CPL were

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Fig. 1 The concentration of **2** in the solution of **1** $(6.67 \times 10^{-1}$ M) irridiated with a focused r-CPL

Fig. 2 The concentration in the solution of **2** $(6.67 \times 10^{-1}$ M) irradiated with a focused r-CPL
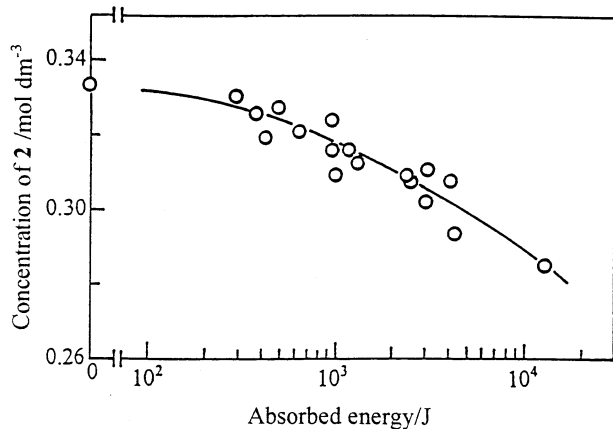

Fig. 3 The concentration of **3** in the solution of **1** $(6.67 \times 10^{-2}$ M) irradiated with a focused r-CPL

focused at the centre (initial fluence: 3.8 J cm^{-2} pulse^{-1}) of the reaction vessel (light path-length: 50 mm) with a condenser lens (φ 60 mm, focal length: 120 cm).

Laser-induced asymmetric synthesis
The photoreactions with the focused r- and l-CPL were carried out in a Pyrex glass cylindrical reaction vessel (58.5 cm^3) with a Suprasil window (3 mm thick) for the incidence of the light. The aqueous solutions $[6.67 \times 10^{-1}$ (c 10 g 100 ml^{-1}) and/or 10^{-2}, 10^{-3} mol dm^{-3}] of **1**, **2** and **3** were placed in the reaction vessel, respectively, and well-bubbled with N$_2$. The N$_2$-saturated solution was stirred magnetically, and irradiated with the light at room temperature. The quantity of light was determined using a calorimeter (Scientech 38-4UV5). The calorimeter was also placed behind the reaction vessel to determine precisely the quantity of light absorbed in the solution during the irradiation.

Determination of the enantiomer
Analyses of the irradiated solutions were carried out by high-performance liquid chromatography [column: SUMICHIRAL OA-5000, column size: 4.6×50 mm, mobile phase: 1 mmol dm^{-3} Cu(MeCO$_2$)$_2$ + 0.05 mol dm^{-3} NH$_4$MeCO$_2$ in H$_2$O/Pr^{i}OH (85/15), flow rate: 1.0 ml min^{-1}, column temp.: 55 °C, detector: UV 280 nm] by referring to the authentic samples in various concentrations. The peaks of **2**, **3** and the *meso*-form of TA were separated satisfactorily under these analytical conditions.

Results and discussion

Irradiation with r-CPL
Fig. 1 shows the concentration of **2** in the solution of **1** irradiated with a focused r-CPL. The concentration of **2** decreases with increasing absorbed energy. The decrease at an irradiation dose of *ca.* 1×10^4 J was *ca.* 13.9% and the optical rotation also varied from zero before irradiation to a minus value, laevorotatory; this supported the conclusion that the solution is rich in **3**. Similarly, the concentration of **2** decreased with increasing absorbed energy by the irradiation of **2** with the light (see Fig. 2). It is noteworthy that the decrease in this case was determined to be *ca.* 8.9% which is in excellent agreement with that (8.8%) for the irradiation of **1** (Fig. 1) at *ca.* 3×10^3 J. On the other hand, as shown in Fig 3, the concentration of **3** remains almost constant throughout the irradiation of **1** with a focused r-CPL and, unlike **2**, did not decrease. The optical rotation of the solution was almost zero even after irradiation of *ca.* 1×10^4 J. Also, the *meso*-form of TA, malic and lactic acids were not produced in all cases, indicating that photoracemization did not occur in this system. Moreover, the formation of **3** in **2** irradiated with
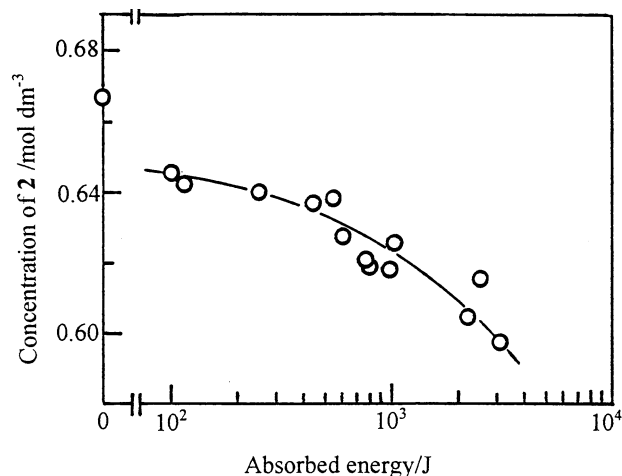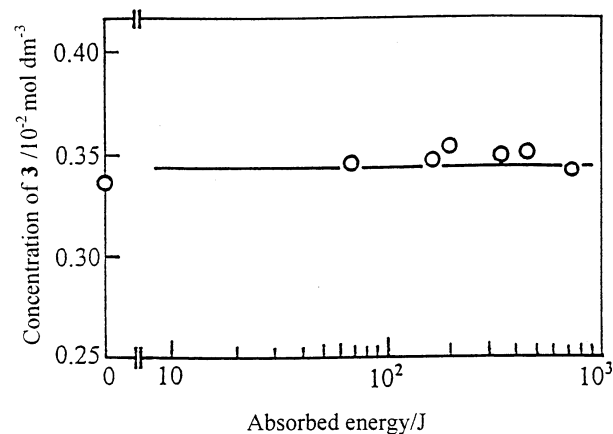
r-CPL was not detectable, indicating that no photoinversion in the chirality occurs during the irradiation. However, during irradiation, gaseous products such as CO, CO$_2$, H$_2$ and O$_2$ *etc.*, were detected, suggesting that decomposition had occurred. Furthermore, a decrease in the concentration of **2** was hardly observed on irradiation of **1** with a non-focused r-CPL (initial fluence: 26.7 mJ cm^{-2} pulse^{-1}).

These results indicate that **3** is enriched through the selective decomposition of **2** by irradiation with focused r-CPL from an XeF laser. The ee of **3** estimated from the decrease of **2** in Fig. 1 was *ca.* 7.5% at an irradiation dose of *ca.* 1×10^4 J. It is also considered that the composition of **3** and **2** in an aqueous solution after irradiation was converted into 54:46 from 50:50 before irradiation. This enantiomeric enrichment is much larger than that (optical purity $= 0.11$)[4] of irradiation with mixed CPL from an Xe lamp as continuous low-intensity light. This indicates that light intensity and the unmixed light are very important factors for the efficient enantiomeric enrichment of TA, and that efficient enrichment is favoured by higher intensity and pure CPL with r only. In this study, the intensity of the focused r-CPL was *ca.* 150 times larger than that of the non-focused. Thus, it was demonstrated that one enantiomer of TA can be efficiently enriched by the irradiation with a highly intense r-CPL from an XeF (351 nm) laser.

Irradiation with l-CPL
In sharp contrast to the r-CPL irradiation, a decrease in the concentration of **3** was observed when **1** was irradiated with a CPL of the opposite sense, *i.e.*, focused l-CPL, and it decreased with increasing absorbed energy (see Fig. 4). The decrease was determined to be *ca.* 19.6% (ee = 10.9%) at an irradiation dose
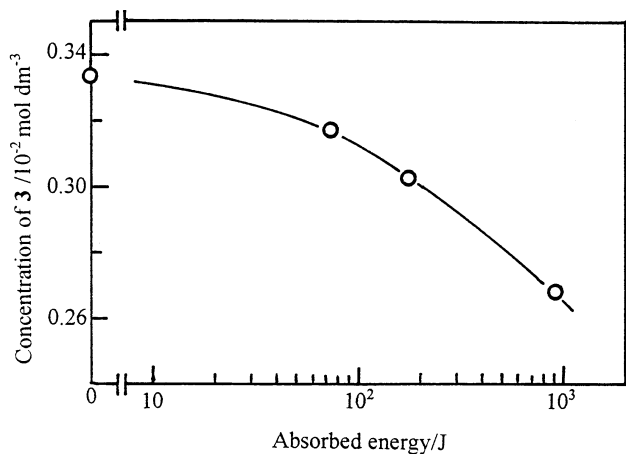
Fig. 4 The concentration of **3** in the solution of **1** $(6.67 \times 10^{-2}$ M) irradiated with a focused l-CPL
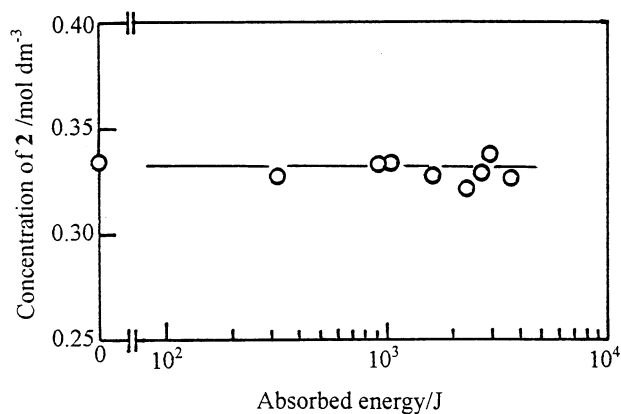

Fig. 5 The concentration of **2** in the solution of **1** $(6.67 \times 10^{-1}$ M) irradiated with a focused l-CPL
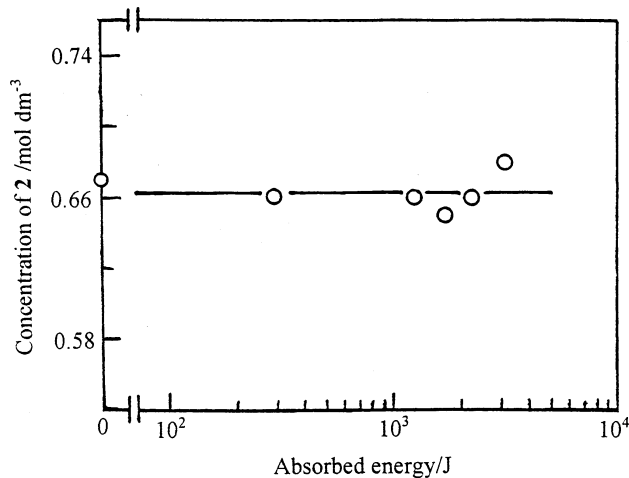

Fig. 6 The concentration in the solution of **2** $(6.67 \times 10^{-1}$ M) irradiated with a focused l-CPL

of *ca.* 1×10^{3} J. On the other hand, as shown in Fig. 5, the concentration of **2** did not decrease and was almost constant throughout the irradiation of **1**. Such behaviour was also confirmed from the fact that the concentration is hardly changed by the irradiation even when **2** was used instead of **1** (Fig. 6). Moreover, the decrease in concentration of **3** was negligible on irradiation of **1** with a non-focused l-CPL (initial fluence: 26.7 mJ cm^{-2} pulse^{-1}). Also, the respective behaviour of *meso*-TA, malic acid *etc.*, and gaseous product formation was the same as that with r-CPL. Thus, it was demonstrated that the l-CPL irradiation can induce the selective enrichment of **2** in **1** in
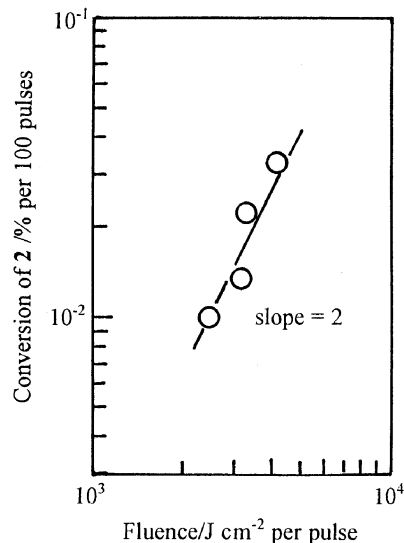

Fig. 7 Laser fluence dependence of the conversion of **2** $(6.67 \times 10^{-1}$ M) irradiated with a focused r-CPL (9600 pulses)

which **3** is selectively decomposed and disappears, leading to the formation of gases, and responsible for the enantioselectivity which is completely opposite to that with r-CPL.

As can be seen, the switching of the sense of rotation of the plane of polarization in CPL has caused an inversion in the enantioselection. From these results, it can be concluded that high-intensity CPL irradiation can induce the enantiodifferentiating reaction of racemic tartaric acid through the selective photodecomposition of the other enantiomer with high enantioselectivity and excellent enantiocontrol only by switching the sense of the CPL.

Effects of the fluence

Since TA scarcely has absorption at a wavelength of >300 nm, the enantiomeric enrichment is hardly observed using nonfocused CPL. Therefore, it is expected that this enantiodifferentiation using focused CPL from an XeF laser proceeds *via* a multiphoton absorption process. We, therefore, examined the fluence effects on the decrease in the concentration by the irradiation of **2** with a focused r-CPL from the laser. As shown in Fig. 7, the conversion of **2** per 100 pulses was proportional to the square of the fluence. This strongly suggests that the present reaction mainly proceeds *via* two-photon absorption excitation, in analogy with the case of the photochemical rearrangement of a diazo ketone to a ketene.[9] Furthermore, the decrease in the concentration of **2** increases with the fluence, indicating the advantage of highly intense light for the present reaction, again.

As mentioned above, it can be considered that this enantiodifferentiation proceeds through selective photodecomposition, *e.g.* decarboxylation, of the other enantiomer *via* two-photon absorption excitation (Scheme 1), as judged from the gaseous products. For this process to occur, we assume that excitation of the carboxyl chromophore in TA occurs and that the C–CO$_2$H and O–H bonds are cleaved by the absorption of two photons. In fact, it is probable that this assumption applies to the present reaction: $2h\nu$ (XeF) = 7.1 eV; E_d (C–C) = 4.2 eV; E_d (O–H) = 4.4 eV.[10] Furthermore, the photon efficiency upon this enantiodifferentiation calculated from the number of the molecules decomposed and quantity of photons absorbed in the solution during the laser irradiation was *ca.* 4% for a two-photon absorption process.

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