Synthesis, polymorphic characterization and structural comparisons of the non-linear optically active and inactive forms of polymorphs of 3-(nitroanilino)cycloalk-2-en-1-ones

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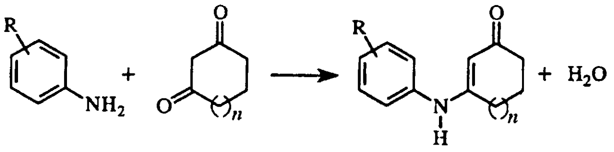
Three 3-(nitroanilino)cycloalk-2-en-1-ones have been synthesized and their non-linear optical (NLO) properties investigated. Two of these compounds have been found to exist in two polymorphic forms (α and β) that exhibit different second-order NLO properties. These polymorphic forms were prepared and characterized by second-harmonic generation measurements as well as the more conventional methods of X-ray powder diffraction and infrared spectroscopy. Of these polymorphs, the α- and β-forms of 3-(4-nitroanilino)cyclohex-2-en-1-one (4NACHD) have been further characterized by X-ray single-crystal diffraction and the crystal structures obtained have been compared with each other to rationalize why these two crystalline forms exhibit different second-order NLO properties. The α-form of 4NACHD crystallizes in a centrosymmetric space group ($P2_1/c$) with $a=6.863(7)$, $b=12.767(3)$, $c=13.410(4)$ Å, $\beta=104.59$ (5)°, $Z=4$, $D_c=1.356$ g cm^{-3} and $R=0.046$, whereas the β-form crystallizes in a non-centrosymmetric space group ($P2_12_12_1$) with $a=7.228(3)$, $b=12.064(3)$, $c=13.104(3)$ Å, $Z=4$, $D_c=1.350$ g cm^{-3} and $R=0.076$. Except for the slight difference in bond distances, both the α- and β-forms have the same orientation of the carbonyl group and hydrogen-bonding interactions. The carbonyl group is *anti* to the N–H group in both the two forms that result in the lambda (Λ) conformation. The whole molecule of 4NACHD is more twisted in the β-form than in the α-form. Based on structural comparisons of the polymorphs of 4NACHD and other compounds, the more twisted conformation in the β-form may bias molecules to pack into a non-centrosymmetric structure. Preliminary results suggest that 3-(nitroanilino)cycloalk-2-en-1-one compounds may have a higher chance of forming non-centrosymmetric crystal structures than normal achiral organic molecules.

Materials possessing non-linear optical (NLO) properties have received considerable attention in recent years because of their potential applications to laser devices and to optical communication, information processing and computing.[1] Second-harmonic generation (SHG), the second-order effect of NLO properties, of crystalline materials depends both on the magnitude of the molecular hyperpolarizability (β) (microscopic nonlinearity) and on the orientation of the molecules in the crystal lattice.[2] Organic NLO materials, in general, are thought to possess many potential advantages over existing inorganic materials such as large β-values, fast response time, high resistance to optical damage and the possibilities of designing molecules highly suitable for SHG.[3] Many organic compounds such as *p*-nitroaniline that have inherently large β-values, however, do not exhibit SHG in the solid state, since they pack into centrosymmetric crystal structures for which the macroscopic polarizability, $\chi(2)$, is necessarily zero.[4] Most of the presently known organic molecules with non-centrosymmetric crystal structures, including urea, *m*-nitroaniline and *p*-nitro-*o*-toluidine, were found by chance.

Hydrogen-bond directed cocrystallization has been demonstrated to be a useful way to form cocrystals (or molecular complexes) for studying the molecular recognition and hydrogen-bonding properties of a class of related host molecules.[5–7] In our continuing research on designing organic NLO materials using hydrogen-bonding interactions,[8] we unexpectedly obtained a class of compounds, 3-(nitroanilino)cyclohex-2-en-1-ones, from an attempt to cocrystallize the host nitroanilines with the guest cycloalkane-1,3-diones, as shown in Scheme 1.



R = *p*-NO$_2$ $n = 1$ 4NACHD
R = *m*-NO$_2$ $n = 1$ 3NACHD
R = *p*-NO$_2$ $n = 0$ 4NACPD

Scheme 1 General synthetic method for 3-(nitroanilino)cyclohex-2-en-1-ones. 4NACHD = 3-(4-nitroanilino)cyclohex-2-en-1-one; 3NACHD = 3-(3-nitroanilino)cyclohex-2-en-1-one; 4NACPD = 3-(4-nitroanilino)-cyclopent-2-en-1-one.

This class of compounds has been found to exist often in more than one polymorphic form. Interestingly, these polymorphic forms usually exhibit different second-order NLO properties. For instance, the α-form of 3-(4-nitroanilino)-cyclohex-2-en-1-one, referred to as 4NACHD hereafter in this study, is SHG inactive, whereas its corresponding β-form is SHG active. In this paper, besides the synthesis and polymorphic characterization of the different polymorphs of three 3-(nitroanilino)cyclohex-2-en-1-ones by X-ray powder diffraction, SHG measurement, infrared (IR) spectroscopy, hot-stage microscopy and differential scanning calorimetry (DSC) analysis, we have determined the crystal structures of the α- and β-forms of 4NACHD using X-ray single-crystal diffraction to rationalize why these two polymorphs exhibit different second-order NLO properties. In addition, the chance of forming non-centrosymmetric crystal structures for this class of compounds is preliminarily investigated and compared with that of the normal achiral organic molecules.

Experimental

p-Nitroaniline, *m*-nitroaniline, cyclohexane-1,3-dione and cyclopentane-1,3-dione were purchased from Aldrich Chemical

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Table 1 Summary of the melting points of nitroanilines, cycloalkane-1,3-diones and the resulting products

nitroaniline	m.p./°C	cycloalkane-1,3-dione	m.p./°C	reaction temp.[a]/°C	product	m.p./°C
p-nitroaniline	149–151	cyclohexane-1,3-dione	103–105	80	4NACHD	187–189
m-nitroaniline	112–114	cyclohexane-1,3-dione	103–105	55	3NACHD	172–174
p-nitroaniline	149–151	cyclopentane-1,3-dione	151–153	110	4NACPD	239–242

[a] The lowest temperatures required to start the reactions in the solid state.

Table 2 NMR data of 4NACHD, 3NACHD and 4NACPD

compound	$\delta_H[(CD_3)_2CO]$[a]	$\delta_C[(CD_3)_2CO]$
4NACHD	8.45 (1 H, s), 8.24 (2 H, dd, *J* 2.0, 7.0), 7.43 (2 H, dd, *J* 2.0, 7.0), 5.76 (1 H, s), 2.63 (2 H, t, *J* 6.2), 2.27 (2 H, t, *J* 5.6) and 2.00 (2 H, quintet, *J* 5.6, 6.2)	197.6, 160.3, 147.1, 142.5, 126.9, 126.2, 121.2, 113.2, 103.2, 37.3, 29.5 and 22.2
3NACHD	9.16 (1 H, s), 7.86–7.94 (2 H, m), 7.60 (2 H, dd, *J* 1.1, 1.6), 5.48 (1 H, s), 2.53 (2 H, t, *J* 5.8), 2.20 (2 H, t, *J* 6.2) and 1.92 (2 H, dd, *J* 5.8, 6.2)	196.4, 160.8, 148.3, 140.7, 130.7, 128.2, 117.9, 116.0, 99.5, 36.5, 28.6 and 21.3
4NACPD[b]	10.12 (1 H, s) 8.17 (2 H, ddd, *J* 2.0, 3.1, 9.2), 7.36 (2 H, ddd, *J* 2.0, 3.1, 9.2), 5.73 (1 H, s), 3.39 (1 H, s), 2.77 (2 H, m) and 2.26 (2 H, m)	206.5, 205.1, 170.0, 146.8, 141.5, 125.4, 118.6, 104.7, 32.7, 30.7 and 29.1

[a] *J* Values are given in Hz. [b] In $[^2H_6]$DMSO, 4NACPD may exist in both the ketone and enol tautomeric forms (see illustration below in Results and Discussion section).

Company, Milwaukee, WI. Cyclopentane-1,3-dione was purified by recrystallization from acetone, whereas *p*-nitroaniline, *m*-nitroaniline and cyclohexane-1,3-dione were all purified by recrystallization from toluene. All solvents used in this study are spectroscopic grade that were purchased from Fischer Scientific Company, Pittsburgh, PA, and were used without further purification.

Melting points were determined using a Fisher-Johns apparatus and are uncorrected. Solution ^1H and ^{13}C nuclear magnetic resonance (NMR) spectra were recorded on a Varian VXR-200 and VXR-300 spectrometer, respectively. Chemical shifts are reported in parts per million (δ) with respect to tetramethylsilane (TMS). UV–VIS spectra were recorded using a Hewlett Packard 8452A diode array spectrophotometer. Elemental analyses were performed at the microanalysis laboratory of Purdue University.

4NACHD was synthesized by dissolving a 1:1 molar ratio of *p*-nitroaniline and cyclohexane-1,3-dione in acetonitrile at 50 °C for 5 min, and the resulting solution was allowed to evaporate slowly at room temperature. The α-form (orange plates) and the β-form (yellow rods) of 4NACHD were prepared by recrystallization from acetonitrile and a 3:1 methanol–water mixture, respectively.

3-(3-nitroanilino)cyclohex-2-en-1-one, referred to as 3NACHD, was synthesized from *m*-nitroaniline and cyclohexane-1,3-dione using the same method as described above for 4NACHD. This compound also exists in two polymorphic forms (α and β). The α-form was prepared by recrystallization from acetone as yellow prisms, whereas the β-form was prepared by recrystallization from methanol as yellow fine needles.

3-(4-nitroanilino)cyclopent-2-en-1-one, referred to as 4NACPD, was synthesized from *p*-nitroaniline and cyclopentane-1,3-dione using the same method as described above for 4NACHD. Preliminary tests showed that only one polymorphic form was observed for this compound.

All the three compounds synthesized were purified by recrystallization and characterized by melting point measurements, solution ^1H and ^{13}C NMR spectroscopy and elemental analyses. Melting points, NMR characterizations and elemental analyses of these compounds are given in Tables 1, 2 and 3, respectively.

All the polymorphic forms obtained were dried in a silica gel desiccator under a vacuum at room temperature overnight before polymorphic characterization. A Zeiss optical microscope equipped with a Mettler FP 52 temperature controller was used for the microscopic investigation. The crystals were heated at a rate of 10 °C min^{-1} and their melting points and physical changes were examined. X-Ray powder diffraction patterns were recorded by a Siemens D-500 Diffractometer-Kristalloflex with Ni-filtered Cu-Kα radiation ($\lambda = 1.5418$ Å) over the interval 4–40°/2θ. IR spectra of the samples were recorded from wavenumber 4000 to 450 cm^{-1} using a Perkin-Elmer 1600 FTIR spectrophotometer with both the Nujol mull and KBr pellet methods. Measurements of powder SHG efficiencies were performed on a modified apparatus of Kurtz powder technique[9] with the fundamental wavelength (1064 nm) of a Q-switched Nd:YAG laser. DSC analyses were carried out using a Perkin-Elmer DSC-4 instrument calibrated with an indium standard, and 3–5 mg samples were heated at a rate of 20 °C min^{-1} from 50–210 °C under a constant N_2 purge with the sample sealed in crimped aluminium pans.

Table 3 Elemental analyses of 4NACHD, 3NACHD and 4NACPD

compound	analysis
4NACHD	Found: C, 61.7; H, 5.1; N, 11.8 Calc. for $C_{12}H_{12}N_2O_3$: C, 62.06; H, 5.21; N, 12.06
3NACHD	Found: C, 61.7; H, 5.0; N, 11.7 Calc. for $C_{12}H_{12}N_2O_3$: C, 62.06; H, 5.21; N, 12.06
4NACPD	Found: C, 60.2; H, 4.5; N, 12.5 Calc. for $C_{11}H_{10}N_2O_3$: C, 60.55; H, 4.62; N, 12.84

Single crystals of the α- and β-forms of 4NACHD were obtained as orange plates from acetonitrile and yellow rods from a 3:1 methanol–water mixture, respectively. The crystals used for the diffraction studies were $0.45 \times 0.35 \times 0.20$ mm (the α-form) and $0.60 \times 0.30 \times 0.20$ mm (the β-form). Crystallographic data for both the two polymorphic forms are given in Table 4.† Preliminary examination and data collection were performed with an Enraf Nonius CAD-4 single-crystal X-ray diffractometer with Mo-Kα radiation ($\lambda = 0.71069$ Å). The centrosymmetric space group of the α-form, $P2_1/c$, was determined based on the systematic absences of $h0l: l \neq 2n$ and $0k0: k \neq 2n$ and the successful solution and refinement of the structure. Similarly, the non-centrosymmetric space group of the β-form, $P2_12_12_1$, was determined based on the systematic absences of $h00: h \neq 2n$, $0k0: k \neq 2n$ and $00l: l \neq 2n$, and was confirmed by the positive powder SHG test. Data collection on the diffractometer was performed at 24 °C using the ω–2θ

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†Supplementary data available from the Cambridge Crystallographic Data Centre: see 'Information for Authors', *J. Mater. Chem.*, 1995, Issue 1.

Table 4 Crystallographic data for the α- and β-forms of 4NACHD

	α-form	β-form
chemical formula	$C_{12}H_{12}N_2O_3$	$C_{12}H_{12}N_2O_3$
formula mass	232.24	232.24
space group	$P2_1/c$	$P2_12_12_1$
a/Å	6.863(7)	7.228(3)
b/Å	12.767(3)	12.064(3)
c/Å	13.410(4)	13.104(3)
β/degrees	104.59(5)	90
V/Å^3	1137(2)	1143(1)
Z	4	4
D_c/g cm^{-3}	1.356	1.350
$F(000)$	488	488
μ(Mo-Kα)/cm^{-1}	0.93	0.92
scan type	ω–2θ	ω–2θ
scan rate/degrees min^{-1} (in ω)	5.0–20.0	1.5–10.0
$2\theta_{max}$/degrees	49.9	59.9
range of h, k, l	±8; 0–15; ±15	±8; 0–14; 0–16
no. observed reflections[a]	1157	953
R; R_w[b]	0.046; 0.059	0.076; 0.093
goodness-of-fit	1.55	2.15
max. shift/esd[c]	0.03	0.01
$\Delta\rho_{max}$/e Å^{-3}	0.14	0.26
$\Delta\rho_{min}$/e Å^{-3}	−0.17	−0.25

[a] $I > 3.0\sigma(I)$ for the α-form and $I > 3.0\sigma(I)$ for the β-form. [b] $R = \Sigma||F_0| - |F_c||/\Sigma|F_0|$; $R_w = [(\Sigma_w(|F_0| - |F_c|)^2/\Sigma w F_0^2)]^{1/2}$. [c] esd = estimated standard deviation.

scan technique to a maximum 2θ of 49.9° for the α-form and 59.9° for the β-form. All data were corrected for Lorentz and polarization effects. An empirical absorption correction using the program DIFABS[10] was applied to the α-form only which resulted in transmission factors ranging from 0.81 to 1.13. The crystal structures were solved by direct methods.[11,12] The final cycle of full-matrix least-square refinements was based on 1157 observed reflections [$I > 3.00\sigma(I)$] and 157 variable parameters for the α-form and 953 observed reflections [$I > 2.00\sigma(I)$] and 153 variable parameters for the β-form. Scattering factors for neutral atoms and $\Delta f'$ and $\Delta f''$ were taken from ref. 13. All calculations were performed using a TEXSAN crystallographic software package.[14]

Results and Discussion

Three 3-(nitroanilino)cycloalk-2-en-1-ones, 4NACHD, 3NACHD and 4NACPD, were synthesized from cocrystallizations of nitroanilines with cycloalkane-1,3-diones (Scheme 1). This type of reaction is believed to proceed by a standard enamine formation in which nucleophilic addition to the carbonyl group of cycloalkane-1,3-diones by the amino group of nitroanilines is followed by dehydration. Since the amino groups of nitroanilines, particularly p-nitroaniline, are poor nucleophiles compared with other amines, the presence of acid catalysts and prolonged reflux are usually required to accelerate the reaction between nitroanilines and cycloalkane-1,3-diones in solution.[15] Interestingly, all three compounds can also be directly prepared in the solid state by heating equimolar amounts of nitroanilines and cycloalkane-1,3-diones at elevated temperatures. The reaction temperatures for the formation of 4NACHD, 3NACHD and 4NACPD are 80 °C, 55 °C and 110 °C, respectively, which are all below the melting points of their starting materials (Table 1). Nevertheless, these reactions may not be regarded as the 'true' solid-state reactions[16] since nitroaniline–cycloalkane-1,3-dione mixtures in all the three cases melted first and then the condensation took place. m-Nitroaniline seems to be more reactive than p-nitroaniline with cyclohexane-1,3-dione since the solid-state reaction occurred at a lower temperature for 3NACHD (55 °C) than for 4NACHD (80 °C). This is understandable because the amino group of m-nitroaniline is considered to be a stronger nucleophile than that of p-nitroaniline. In addition, the melting points of 4NACHD (187 °C), 3NACHD (172 °C) and 4NACPD (259 °C) are all much higher than those of the individual nitroanilines (149 °C for p-nitroaniline and 112 °C for m-nitroaniline), indicating that this class of compounds would have better thermal stability than nitroaniline compounds.

To understand the solvatochromic properties of 3-(nitroanilino)cycloalk-2-en-1-ones, the UV–VIS spectra of 4NACHD and 3NACHD as well as p-nitroaniline and m-nitroaniline in different solvents were investigated, and the results are listed in Table 5. The wavelength of maximum absorption (λ_{max}) of 4NACHD has a red shift relative to p-nitroaniline, particularly in nonpolar solvents like toluene. In contrast, the λ_{max} of 3NACHD has a blue shift with respect to m-nitroaniline. p-Nitroaniline has much larger maximum molar absorption coefficient (ε_{max}) than m-nitroaniline, whereas 4NACHD and 3NACHD have similar ε_{max} (Table 5). The solvatochromic properties of 3-(nitroanilino)cycloalk-2-en-1-ones and nitroanilines are significantly affected by the polarity of solvents. For instance, all the λ_{max} of these compounds have a red shift in weakly polar solvents such as chloroform compared with strongly polar solvents such as DMF and DMSO. Interestingly, the red-shift effect is smaller for 3-(nitroanilino)-cycloalk-2-en-1-ones than for nitroanilines. The $\Delta\lambda$ ($\lambda_{DMSO} - \lambda_{toluene}$) for 4NACHD and 3NACHD are 24 and 10 nm, respectively, and the corresponding $\Delta\lambda$ for p-nitroaniline and m-nitroaniline are 46 and 34 nm, respectively. Like nitroaniline compounds, 4NACHD and 3NACHD do not absorb radiation in the visible region, which is an important property in considering the applications for SHG in the visible spectrum.[17]

Both the α- and β-polymorphic forms of 4NACHD and 3NACHD were obtained by the preparation procedures described in the Experimental section and identified with data from X-ray powder diffraction, IR spectroscopy and powder SHG measurement.

The X-ray powder diffraction profiles of these polymorphic forms are shown in Figs. 1 and 2. For 4NACHD, the sharp X-ray diffraction peaks of the α-form occurred at 2θ = 9.85, 13.74, 15.50, 19.50, 21.73, 22.71, 25.25, 27.01 and 30.30°, and those of the β-form were observed at 2θ = 10.14, 13.66, 14.88, 15.33, 16.36, 20.54, 23.90, 24.81, 25.88, 26.85 and 37.61°. At a glance these two crystalline forms do not exhibit noticeably different X-ray powder diffraction patterns. However closer examination shows that the α- and β-forms of 4NACHD can be distinguished from each other by their different peak positions. In contrast, the X-ray powder patterns of the α- and β-forms of 3NACHD can be easily distinguished from each other. The sharp X-ray diffraction peaks of the α-form of 3NACHD occurred at 2θ = 8.95, 12.06, 13.74, 14.62, 16.41, 17.81, 21.99, 22.57, 26.64, 35.59 and 36.90°, and those of the β-form were observed at 2θ = 9.96, 10.58, 15.92, 19.26, 25.80, 26.49 and 26.93°.

Different polymorphic forms usually give different solid-state IR spectra because IR absorptions are very sensitive to

Table 5 Summary of UV–VIS data for 4NACHD, 3NACHD, p-nitroaniline and m-nitroaniline in different solvents

	λ_{max}/nm (ε_{max}/10^3 dm^3 mol^{-1} cm^{-1})			
compound	toluene	chloroform	DMF	DMSO
4NACHD	364 (18.2)	365 (17.8)	382 (19.5)	388 (20.5)
3NACHD	302 (18.8)	304 (22.9)	310 (23.7)	312 (24.9)
p-nitroaniline	344 (29.9)	348 (14.7)	382 (14.5)	390 (13.3)
m-nitroaniline	364 (1.7)	366 (1.4)	390 (0.9)	398 (0.8)

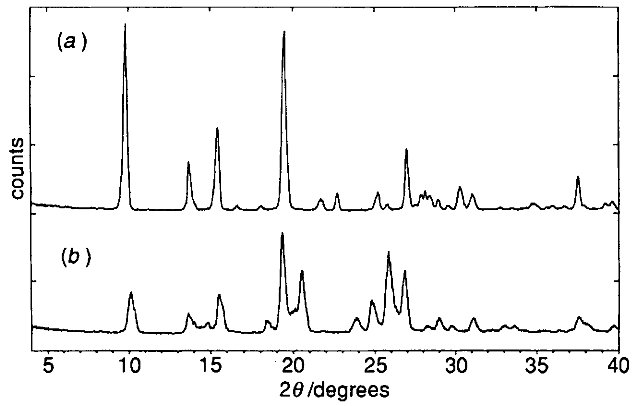


Fig. 1 X-Ray powder diffraction of the α-form (*a*) and the β-form (*b*) of 4NACHD

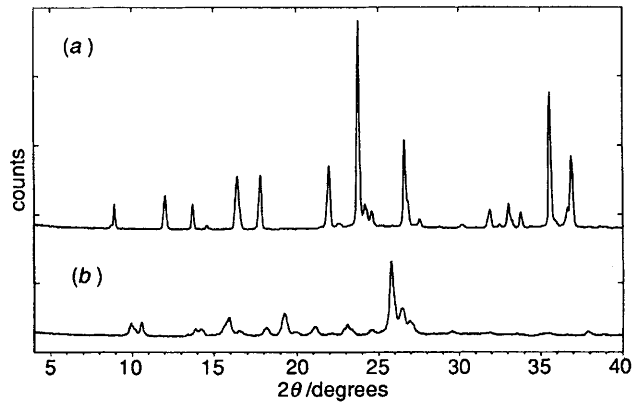


Fig. 2 X-Ray powder diffraction of the α-form (*a*) and the β-form (*b*) of 3NACHD

the solid-state environments, particularly hydrogen-bonding environments. The solid-state IR spectra of these polymorphic forms as well as 4NACPD are shown in Fig. 3. Interestingly, both the α- and β-forms of 4NACHD exhibit the same IR spectrum, suggesting that these two polymorphs may have similar molecular conformations or hydrogen-bonding interactions in the solid state. In contrast, the IR absorption spectra of the α- and β-forms of 3NACHD show recognizable differences in the positions and intensities of the absorption bands between the regions of 3600–3000 cm^{-1} and 1800–2000 cm^{-1} (Fig. 3). The major absorption bands observed in these two regions are 3277, 3203, 3131, 1602, 1579, 1533, 1357 and 1251 cm^{-1} for the α-form and 3305, 3217, 3139, 1614, 1579, 1549, 1531, 1480 and 1268 cm^{-1} for the β-form.

In addition to polymorphic characterization, solid-state IR spectroscopy could be useful for studying the solid-state structures of 3-(nitroanilino)cycloalk-2-en-1-ones. These compounds, in principle, can have three tautomeric forms, α,β-unsaturated ketone (**I**), β-anilino-enolic (**II**) and β-anilino ketone (**III**) structures, shown below. 4NACHD, 3NACHD and 4NACPD all exhibit N–H stretching bands in the region 3300–3000 cm^{-1} (Fig. 3).[18] In addition, all the three compounds exhibit a broad and strong C=O stretching band near 1540 cm^{-1} which is often observed in a number of open-chain compounds with the R–CO–C=C–N<structure.[19] The presence of both the N–H and C=O stretching bands suggest that 4NACHD, 3NACHD and 4NACPD all exist in the α,β-unsaturated ketone form (**I**). The preference of the form **I** for the α- and β-forms of 4NACHD is also confirmed by X-ray crystal structure determination.

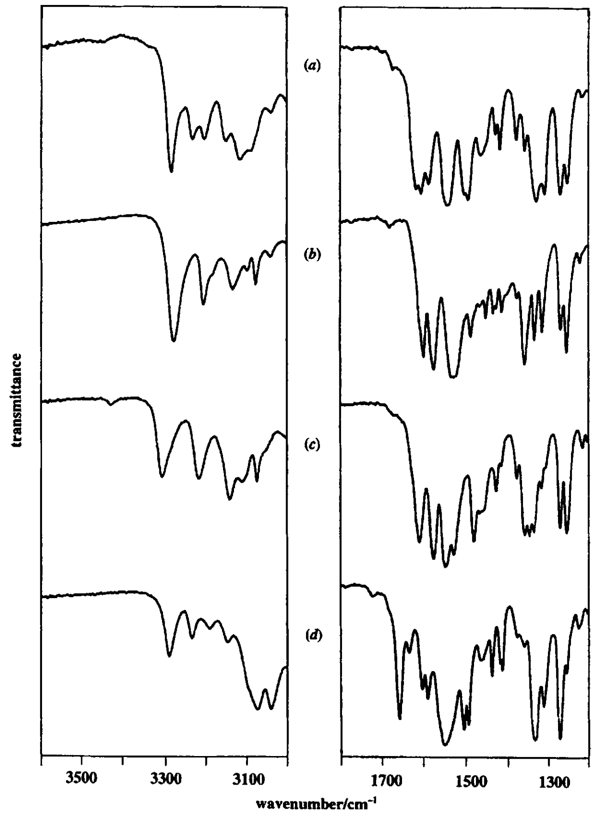
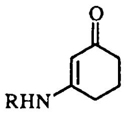


Fig. 3 Solid-state IR spectra of 4NACHD, 3NACHD and 4NACPD. (*a*) 4NACHD (its α- and β-forms exhibit the same IR spectrum); (*b*) the α-form of 3NACHD; (*c*) the β-form of 3NACHD; (*d*) 4NACPD.



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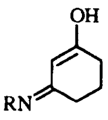

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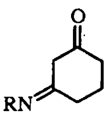


III

Since the second-order NLO property is sensitive to the orientation of molecules in the solid-state medium,[2] SHG measurements are particularly useful for characterizing polymorphic forms when one of them has a centrosymmetric crystal structure and the other has a non-centrosymmetric crystal structure. The results of SHG measurements are given in Table 6. The two polymorphic forms of 4NACHD are differentiated by their different SHG properties: the α-form is SHG inactive and the β-form is SHG active. Similarly, the α- and β-forms of 3NACHD can also be distinguished from each other because of their different SHG activities (Table 6).

Hot-stage microscopy and DSC were used for investigating the phase transformation of the polymorphic forms of 4NACHD and 3NACHD. For 4NACHD, the α-form endothermally transforms to the β-form at 132 °C and then melts at 187 °C, whereas the β-form directly melts at 187 °C. The transformation energy between the α-form and β-form was approximately 5 kJ mol^{-1} based on two determinations. For 3NACHD, both the α- and β-forms melt at 172 °C. However,

Table 6 Summary of powder SHG values of the polymorphic forms of 4NACHD, 3NACHD and 4NACPD (values relative to urea)

compound	polymorph	SHG (1064 nm)
4NACHD	α	0
4NACHD	β	2
3NACHD	α	0
3NACHD	β	1.5
4NACPD	—	0

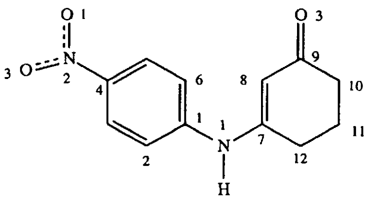


Fig. 4 Chemical structure of 4NACHD and atomic numbering used in this study

Table 7 Selected bond distances (Å), bond angles (degrees) and torsion angles (degrees) in the α- and β-forms of 4NACHD

	α-form	β-form
C(1)–N(1)	1.401(3)	1.445(8)
C(4)–N(2)	1.459(4)	1.456(8)
C(7)–N(1)	1.369(3)	1.314(7)
C(9)–O(3)	1.217(3)	1.231(7)
C(7)–C(8)	1.343(4)	1.357(8)
C(7)–C(12)	1.506(4)	1.554(9)
C(8)–C(9)	1.436(4)	1.455(8)
C(10)–C(11)	1.498(4)	1.48(1)
C(1)–N(1)–C(7)	130.4(2)	128.6(6)
C(7)–C(8)–C(9)	121.9(3)	122.5(6)
C(8)–C(9)–O(3)	121.4(3)	120.1(7)
C(10)–C(11)–C(12)	111.1(2)	114.0(7)
C(7)–C(8)–C(9)–O(3)	−176.9(3)	−174.4(6)
C(7)–C(8)–C(9)–C(10)	2.6(4)	−6.1(9)
C(9)–C(8)–C(7)–C(12)	−5.5(4)	−4.8(9)
C(8)–C(9)–C(10)–C(11)	−27.3(3)	20(1)

the β-form was obtained when the melt of the α-form solidified. DSC analysis showed that there is only one fusion peak at 172 °C for both forms, the transformation between the α-form and β-form may occur at 172 °C or the transformation energy is very small. All the thermal phase transformation results were tested and confirmed by SHG measurements and X-ray powder diffraction.

The atomic numbering of the α- and β-forms of 4NACHD is depicted in Fig. 4. Selected bond distances, bond angles and torsion angles of the α- and β-forms are given in Table 7. The crystal packing of the two polymorphic forms are illustrated by stereoviews in Fig. 5.

Except for the C(1)–N(1) and C(7)–N(1) bond lengths, the α- and β-forms of 4NACHD generally have a good agreement in their bond distances, bond angles and torsion angles (Table 7). The molecule of 4NACHD is composed of a nitroanilino moiety and a cyclic α,β-unsaturated ketone moiety. The carbonyl group is *anti* to the N–H group in both the two forms that result in the lambda (Λ) conformation. In both the two polymorphic forms, the nitro group and the phenyl ring of the nitroanilino moiety are quite planar and are coplanar with respect to each other. The cyclic ketone ring in the other moiety is in a puckered conformation where the C(11) is out of the plane of the remaining atoms, 0.642 Å for the α-form and 0.554 Å for the β-form. The puckered conformation is common for cyclohexyl rings that contain three adjacent sp^2 carbon atoms and three adjacent sp^3 carbon atoms.[20] To reduce the hydrogen–hydrogen repulsion between C(6) and C(8), the nitroanilino plane and the α,β-unsaturated ketone plane are twisted from each other, particularly in the β-form. The dihedral angle between the two least-squares planes is calculated as 25.1° for the α-form and 35.7° for the β-form.

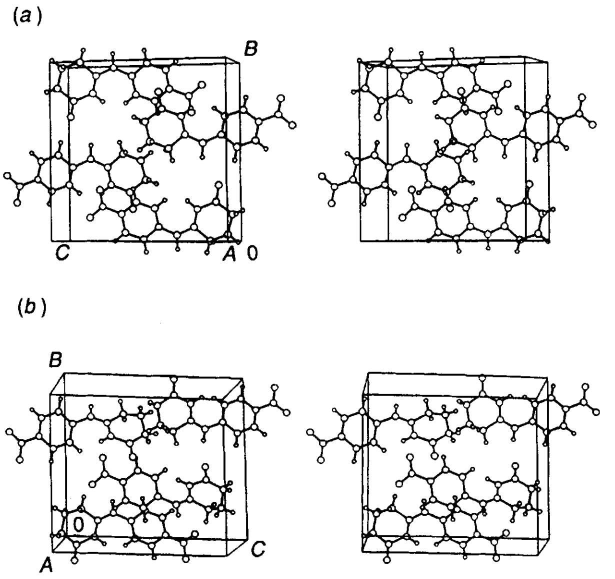
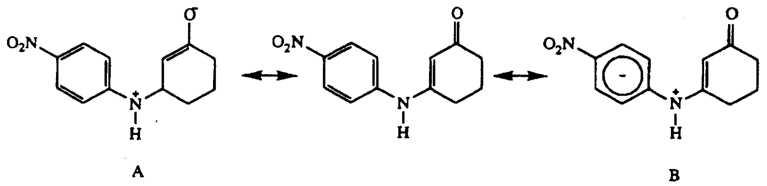


Fig. 5 Stereoviews of the crystal packing for the α-form (*a*) and the β-form (*b*) of 4NACHD

Since the nitro and N–H groups are *para*-related to each other in the nitroanilino moiety and since the bond distance of C(7)–N(1) in the α-form (1.369 Å) and β-form (1.314 Å) is noticeably shorter than 1.47 Å of the normal C–N (sp^3–N),[21] three resonance forms are proposed for 4NACHD (shown below). Since the bond distance of C(7)–N(1) in the two polymorphic forms (1.369 Å for the α-form and 1.314 Å for the β-form) is considerably shorter than that of C(1)–N(1) (1.401 Å for the α-form and 1.445 Å for the β-form), the lone pair electrons in the N–H group would be more easily delocalized into the cyclic α,β-unsaturated ketone group than into the nitroanilino group. As a result, the resonance form **A** should be more favourable than the resonance form **B**. The preference for form **A** is also supported by the shorter C(8)–C(9) bond length (1.436 Å for the α-form and 1.455 Å for the β-form) compared with 1.48 Å for the normal sp^2–sp^2 C–C bonds[21] and by the longer C(1)–N(1) bond length (1.401 Å for the α-form and 1.445 Å for the β-form) compared with 1.371 Å for the corresponding C–N bond observed in *p*-nitroaniline.[22]

As illustrated in Fig. 6, the amino proton in the α- and β-forms participates in hydrogen bonding as a proton donor. The carbonyl oxygen, rather than the nitro group, is the sole proton acceptor in the two structures that accepts the amino proton to form an intermolecular N–H···O hydrogen bond. As a consequence, the 4NACHD molecules aggregate to form an infinite hydrogen-bonded chain along the two-fold screw axis in which the nitroanilino group is positioned alternatively in the chain. The N–H···O hydrogen bond observed in these two structures is very strong since the N···O distance, 2.801 Å for the α-form and 2.813 Å for the β-form (Table 8), is much shorter than van der Waals distances (3.14 Å for N···O interactions)[23] and shorter than most intra- and inter-molecular N···O hydrogen bond distances (2.85 Å).[24] Because the α- and β-forms are all involved in the same hydrogen-bonding interactions, they exhibit the same IR absorption spectrum (Fig. 3). Although the α- and β-forms exhibit the same orientation of the carbonyl group and hydrogen-bonding interactions, they



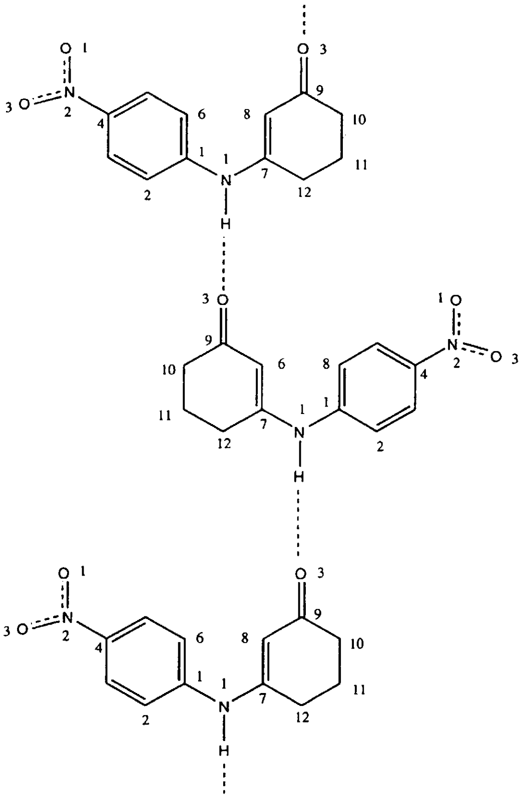
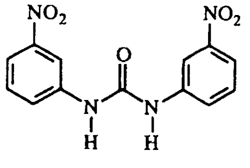


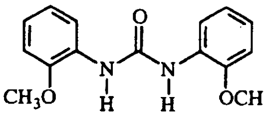
Fig. 6 The hydrogen-bonding interactions in the α-form and the β-form of 4NACHD. Hydrogen bonds are indicated by dashed lines.

pack into quite different crystal structures, $P2_1/c$ (monoclinic) for the α-form and $P2_12_12_1$ (orthorhombic) for the β-form.

Like nitroaniline compounds,[25] 3-(nitroanilino)cycloalk-2-en-1-ones such as 4NACHD might have large intrinsic molecular hyperpolarizability; thus this class of compounds could be good candidates for NLO materials. Since the α- and β-forms of 4NACHD crystallize in the centrosymmetric ($P2_1/c$) and non-centrosymmetric ($P2_12_12_1$) space groups, respectively, the α-form is SHG inactive and the β-form is SHG active. It is well known that intermolecular interactions are important in the crystal packing of molecules; however, how these interactions affect and control the crystal packing is still not clearly known. As discussed earlier, except for the differences in the bond lengths of C(1)–N(1) and C(7)–N(1) and in the dihedral angle between the nitroanilino and α,β-unsaturated ketone planes (25.1° for the α-form and 35.7° for the β-form), both the α- and β-forms of 4NACHD have the same orientation of the carbonyl group and hydrogen-bonding interactions. In the previous study of the relationship between the NLO properties and polymorphism of 1,3-bis(*m*-nitrophenyl)urea and 1,3-bis(*o*-anisoyl)urea (shown below), we found that polymorphs with the more twisted conformations (the larger dihedral angles between the two phenyl rings) crystallized in a non-centrosymmetric space group whereas those with the less twisted conformation crystallized in the centrosymmetric space group.[26] A reasonable rationale for this phenomenon is that the more twisted conformation would result in a smaller net dipole moment for the molecule, a similar effect to the vanishing dipole moment proposed by Zyss *et al.*[27] Interestingly, the same trend is also observed in the polymorphs of 4NACHD in which the more twisted conformer crystallized in a non-centrosymmetric space group (β-form), whereas the less twisted conformer crystallized in a centrosymmetric space group (α-form).

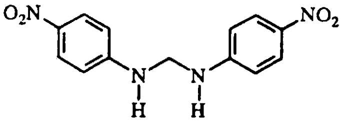


1,3-bis(*m*-nitrophenyl)urea



1,3-bis(*o*-anisoyl)urea

As with other organic and pharmaceutical compounds,[28,29] two of the three compounds synthesized, 4NACHD and 3NACHD, have been found to exist in two polymorphic forms (α and β). Of the four polymorphs, two of them do not exhibit SHG and the other two do exhibit SHG (Table 6). Since SHG is exhibited in the non-centrosymmetric media only, these two polymorphs with positive SHG should have non-centrosymmetric crystal structures. Thus, the chance of having a non-centrosymmetric crystal structure is 40% for the five samples which is significantly higher than 11% for the normal achiral organic compounds.[30] Although the number of samples studied here may not be large enough, these preliminary results suggest that 3-(nitroanilino)cycloalk-2-en-1-one compounds may have a higher chance of forming non-centrosymmetric crystal structures than normal achiral organic compounds. If this is true, the chemical structure and molecular conformation of this class of compounds could be important to their high incidence of forming non-centrosymmetric crystal structures. Curtin and Paul have demonstrated that the crystal structures of *meta*-substituted compounds such as *m*-nitroaniline are more likely to be non-centrosymmetric than the other organic compounds,[31] probably because the non-centrosymmetric molecules could induce non-centrosymmetricity in developing crystal nucleation sites. In addition, the lambda (Λ) conformation observed in the α- and β-forms of 4NACHD may be important to encourage the molecules to pack into a non-centrosymmetric crystal structure since Watanabe and coworkers have reported that a number of the lambda (Λ) molecules such as *N*,*N*′-bis(4-nitrophenyl)methanediamine, shown below, often tend to crystallize in a non-centrosymmetric space group.[32]



N,*N*′-bis(4-nitrophenyl)methanediamine

Conclusions

Three 3-(nitroanilino)cycloalk-2-en-1-ones, including 4NACHD, 3NACHD and 4NACPD, were synthesized from the reactions of nitroanilines and cycloalkane-1,3-diones. 4NACHD and 3NACHD have been found to exist in two polymorphic forms (α and β) that exhibit different second-order NLO properties. The α-polymorph of 4NACHD transforms to the β-polymorph at 132 °C, whereas the α-polymorph of 3NACHD melts at 171 °C and then transforms into the β-

Table 8 Hydrogen-bond parameters in the α- and β-forms of 4NACHD

D-H	acceptor	H···A/Å	D···A/Å	D-H···A/°	symm. oper.
A. α-Form					
N(1)-H[N(1)]	O(3)	1.81(3)	2.801(3)	170.3	$-x, 1/2+y, 1/2-z$
B. β-Form					
N(1)-H[N(1)]	O(3)	1.96(5)	2.813(7)	168.5	$2-x, -1/2+y, 1/2-z$

polymorph. To understand why these polymorphic forms exhibit different SHG properties, the crystal structures of the α- and β-forms of 4NACHD were determined by X-ray single-crystal diffraction. Except for the slight difference in bond distances, both the α- and β-forms have the same orientation of the carbonyl group and hydrogen-bonding interactions. The carbonyl group is *anti* to the N–H group in both the two forms that result in the lambda (Λ) conformation. The whole molecule of 4NACHD is more twisted in the β-form than in the α-form. Based on the crystal structural comparisons of the polymorphs of 4NACHD and other compounds, the different NLO properties of these two polymorphs may be related to the twisted conformation between the nitroanilino and α,β-unsaturated ketone planes. The preliminary results show that 3-(nitroanilino)cycloalk-2-en-1-one compounds may have a higher chance of forming non-centrosymmetric crystal structures than the normal achiral organic molecules.

We gratefully acknowledge financial support for this research from the Office of Naval Research and the Byrn/Zografi joint project for study of the effect of water on the molecular mobility of pharmaceutical solids.

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Paper 5/02040I; *Received* 31*st March,* 1995