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Stereoselective Synthesis of 2-Aminocyclobutanols via Photocyclization of α-Amido Alkylaryl Ketones: Mechanistic Implications for the Norrish/Yang Reaction

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Abstract: A series of chiral *N*-acylated α-amino *p*-methylbutyrophenone derivatives **1a**−**1h** was synthesized from α-amino acids via a three-step procedure. These substrates were photolyzed in benzene and gave Norrish II and Norrish I cleavage products as well as the *N*-acylated 2-aminocyclobutanols that derive from γ-hydrogen abstraction and 1,4-triplet biradical combination (Yang cyclization). The products were formed with characteristic Yang/cleavage ratios. The quantum yields for the photodecomposition of the *N*-acetyl-protected substrates **1b**,**e**,**f** were moderate (12−26%); the diastereoselectivities of the cyclobutanol formation were remarkably high for all substrates. High diastereospecificity was observed for the isoleucine derivatives (2*S*,3*S*)-**1g** and *allo*-(2*S*,3*R*)-**1g**; the Yang reaction dominated the photochemistry of *allo*-**1g**, whereas **1g** gave preferentially Norrish II cleavage. The role of hydrogen bonding as one of the stereo-directing effects was demonstrated by comparison of the cyclization efficiency of the valine derivative **1e** with **1h**,**i**,**j**. Also, aromatic β-keto esters gave the Yang cyclization products in low yields. The diastereoselectivity of the cyclobutanol formation was rationalized by a three-step mechanism where every step is connected with one distinct stereochemical induction mechanism: (a) diastereoselective hydrogen abstraction, (b) conformational equilibration of the 1,4-tetramethylene biradicals (as calculated by semiempiric methods) controlled by hydrogen bonding, and (c) diastereoselective biradical combination (versus cleavage) influenced by spin−orbit coupling controlled intersystem crossing geometries.

Introduction

Photochemical C−H-abstraction reactions initiated by electronically excited triplet carbonyl species are one of the archetype reactions in organic photochemistry. The spin-isomeric singlet excited states also undergo Norrish II reactions with hydrogen-transfer reactions in less than 100 fs and secondary processes on the subpicosecond time scale.[1] The time domain for triplet reactions is shifted into the nanosecond region,[2] and therefore spectral and kinetic information concerning the excited state reactivity and the structures of the intermediate 1,4-triplet biradical (tetramethylenes) have been available for more than two decades.[3,4]

The following rules of thumb are appropriate for a multitude of intramolecular C−H-abstraction (Norrish type II) reactions initiated by electronically excited triplet carbonyls:[5] (a) Optimal hydrogen abstraction geometry in flexible substrates is achieved in a six-membered H-transfer geometry, thus implying a strong preference for γ-hydrogen-activation. Less accessible δ- or β-CH positions can be triggered either by exchange of the γ-CH carbon by a heteroatom or another functional group[6] or simply by peralkylation of the γ-carbon.[7] The Scheffer group has intensively investigated the geometrical parameters which guide efficient versus nonefficient hydrogen transfer and reported the bandwidth of the critical O·····HC_γ distance and the bond angles involved.[8,9] These data originated from profound solid-state investigations which were recently also modified to give highly enantioselective photochemistry using Norrish II reactions followed by Yang[10] cyclization.[11−13] A similar study was conducted by us for the liquid-phase hydrogen-transfer reactions of *N*-alkylated phthalimides.[14] (b) There are three competing pathways following the primary hydrogen transfer from the γ-CH position: cyclization of the biradical to give the cyclobutanol (Yang reaction), cleavage of the central C2−C3 single

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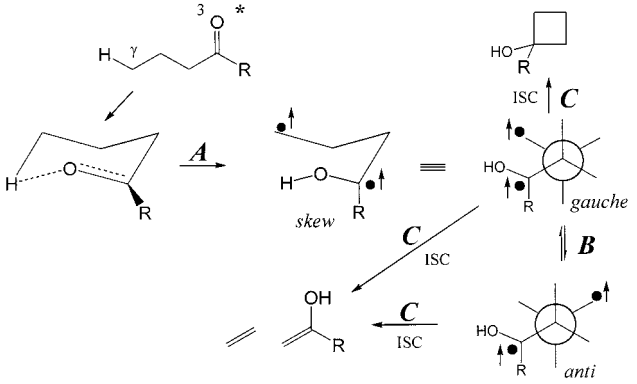
Scheme 1. Three-Step Process of the Norrish II/Yang Reaction



bond to give an enol and the corresponding alkene (Norrish II cleavage), and hydrogen back-transfer to reconstitute the starting material in its electronic ground state.[15] In all of these cases, the spin conservation rules require triplet/singlet intersystem crossing (ISC) because the formation of triplet excited products is energetically improbable. (c) In singlet photochemical reactions, stereoselectivity of C−C bond-forming steps is often controlled by the optimal geometries for radical−radical combinations, whereas in triplet photoreactions, the geometries most favorable for ISC are considered to be of similar relevance.[16] These geometries can be quite different from the former ones due to differences in spin−orbit coupling (SOC) values. We have described this phenomenon for [2 + 2]-photocycloadditions of carbonyl compounds with cycloalkenes[17,18] and allylic alcohols.[19] The "90° rule" can be used as a useful approximation to estimate the reactive conformers.[20] After transition from the triplet to the singlet potential energy surface, immediate product formation is expected. Thus, the ISC is expected to proceed concerted with the formation of a new bond or the cleavage of the primarily formed single bond (Scheme 1). Concerning the chemoselectivity (cyclization versus fragmentation) as well as the stereochemistry of the cyclobutanol formation, the processes a−c were expected to disclose different influences.

To "separate" these effects and to investigate similar compounds with small but defined changes in substrate and intermediate structures, we conceptualized a series of α-branched butyrophenone derivatives. In line with our recent investigations on the photochemistry of *N*-activated α-amino acids,[21−23] we transformed *N*-acylated α-amino acids into C-activated α-amino *p*-methylbutyrophenone derivatives **1** and studied their photochemistry.[24] Herein we report full details of this study and a comparison with modified substrates and *β*-keto esters **4**.

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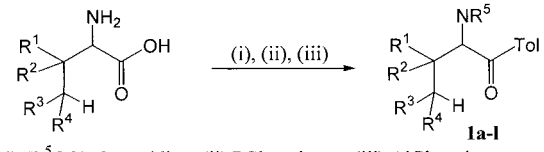
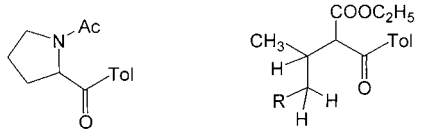
Scheme 2. Synthesis of Starting Materials

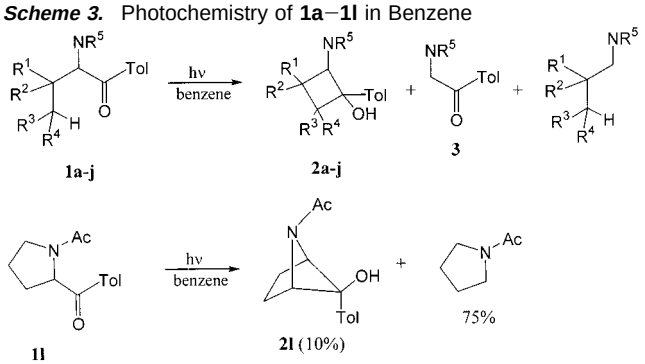


(i) $(R^5CO)_2O$, pyridine; (ii) PCl_5, toluene; (iii) $AlCl_3$, toluene. for **1g** and *allo*-**1g**: (ii) $(COCl)_2$, pyridine, 0°C

	R^1=	R^2=	R^3=	R^4=	R^5=	yield (%)
a	H	H	H	H	HAc	45
b	H	H	Me	H	HAc	40
c	H	H	Et	H	HAc	37
d	H	H	Me	Me	HAc	51
e	Me	H	H	H	HAc	48
f	Me	Me	H	H	HAc	46
g	Me	H	Me	H	HAc	12/10
h	Me	H	H	H	HBz	60
i	Me	H	H	H	Succ	42
j	Me	H	H	H	HTfAc	66
k	H	H	SMe	H	HAc	58



Scheme 3. Photochemistry of **1a**−**1l** in Benzene



Results and Discussion

The substrates **1a**−**1f** and **1h**−**1l** were synthesized by a two-step one-pot procedure from *N*-acyl α-amino acids via the corresponding acyl chlorides. Because of the harsh reaction conditions (PCl_5 chlorination), racemic material was produced in all cases. This was easily recognized from the reaction of isoleucine where a 1:1 mixture of **1g** and its diastereoisomer *allo*-**1g** was produced. To obtain the pure diastereoisomers, a milder method using oxalyl chloride for the primary chlorination step was applied for the synthesis of these two derivatives (Scheme 2).

Photochemical reactions were studied by irradiating 4 mM solutions in benzene with phosphor-coated mercury low-pressure lamps emitting at $\lambda = 350 \pm 20$ nm under a nitrogen atmosphere at 15 °C. The crude reaction mixtures were analyzed by NMR as well as gas chromatography (GC) and subsequently separated by flash chromatography. The cyclobutanols **2** were isolated (when formed) from the slow eluting fractions. In all cases except for the proline derivative **1l**, the acetylamino acetophenone **3** was detected as the Norrish II fragmentation product (Scheme 3). The corresponding alkenes were detected by GC. The degree of conversion was >95% for all substrates **1**, with a mass balance after chromatography of 75−80%

Table 1. Product Composition from Substrates **1a**−**1k**[a]

substrate	Yang (**2**)	Norrish II cleavage (**3**)	cyclization/ fragmentation-ratio	Norrish I cleavage
1a		33	0	67
1b	33	40	0.8	22
1c	48	35	1.4	12
1d	49	35	1.4	15
1e	74	8	9.3	18
1f	50	30	1.7	20
allo-**1g**	>95		>95	<5
1g		>95	0	<5
1h	65	13	5.0	22
1i	65	30	2.2	5
1j		20	0	40[b]
1k		65[b]	0	

[a] From ^{1}H NMR analysis of the crude reaction mixture, ±2%, ca. 5% detection limit. [b] Further products could not be characterized.

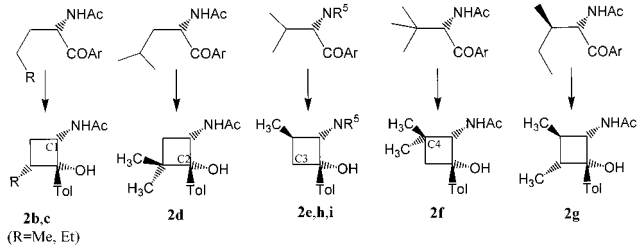


Figure 1. Yang cyclization products from amino acid derivatives: stereoselectivity.

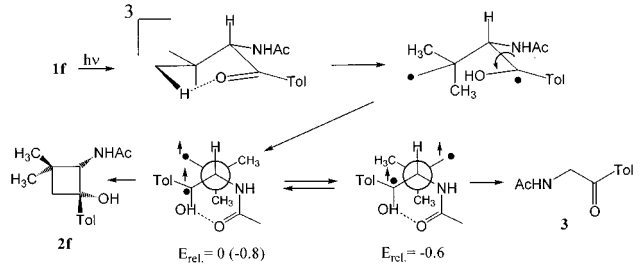
(besides the methionine derivative **1k** which gave mainly **3** and ca. 30% decomposition products).

The relative product composition is summarized in Table 1. Norrish type I cleavage was observed for all substrates except for the isoleucine derivatives **1g** and *allo*-**1g**. The Norrish I cleavage products (*N*-alkyl acetamides) were detected by NMR and GC and compared with authentic samples. The product from the Norrish type I cleavage of the methionine derivative **1k** was not detected probably due to secondary electron-transfer reactions which have also been detected for triplet-excited phthalimide derivatives of methionine[25] and cysteine derivatives.[26] The proline derivative **1l** resulted in Norrish II cleavage and gave minor amounts of the bicyclic Yang product **2l**. All cyclobutanes **2b**−**2j** were formed with diastereoselectivities >95%. The relative configurations of these products were established by NMR methods (NOE effects and coupling constants) and X-ray structure analyses of the cyclo-butanols **2e**,**f** as well as **2g**.[24] By comparison between the NMR spectral data for these compounds and for the norvaline- and norleucine-derived products **2b** and **2c**, respectively, as well as the leucine-derived product **2d**, the relative configuration of these cyclobutanols was unambiguously proven (Figure 1). The acylamino substituent (C-1) is always located cis, a methyl group at C-4 (in **2e** and **2g**) is located trans, and a substituent at C-3 (in **2b**,**c**,**g**) is located cis with respect to the hydroxy substituent at C-2.

To interpret the stereochemical results mechanistically, the different selectivity-directing effects are discussed separately.

(A) Selectivity Connected with Hydrogen-Bonding Interactions. The Norrish II/Yang products **2** were always formed cis selective with respect to the acylamino and the hydroxy group. This accounts for the assumption that after primary hydrogen transfer from the γ-CH position, the *skew* triplet biradical rearranges to a hydrogen-bonded structure that is conformationally flexible with respect to rotation about the central C2−C3 bond but not about the C1−C2 single bond. In Scheme 4, the reaction pathway for the *tert*-leucine derivative **1f** is shown.

Scheme 4. Three-Step Reaction Protocol of the *tert*-Leucine Derivative **1f**



In this case, the cyclization/fragmentation ratio is 1.7, similar to that for the leucine derivative **1d** (1.4). Modification of the hydrogen-bond interaction was investigated by application of the four *N*-acyl derivatives of valine: *N*-acetyl (**1e**), *N*-benzoyl (**1h**), *N*,*N*-succinimidyl (**1i**), and *N*-trifluoroacetyl (**1j**). The first three substrates were expected to exhibit similar hydrogen-bonding efficiency between the acyl substituent and the newly formed hydroxy group, whereas the trifluoroacetyl group should be less active in hydrogen-bonding interactions. This presumption correlates with hydrogen-bond basicity values β_2H reported by Abraham and Platts for the groups $CH_3(CO)OR = 0.45$, $CF_3(CO)OR = 0.25$, and $CH_3(CO)NHR = 0.73$.[27] Thus, strong hydrogen-bond activity was expected for substrates **1a**−**1i**, a weaker hydrogen-bond activity was expected for the ester derivatives **4a**,**b** (vide infra), and the weakest hydrogen-bond activity was expected for **1j**. The idea that hydrogen bonding can function as a highly relevant tool in directing the stereochemistry of carbon−carbon-bond-forming steps has already been widely discussed for photochemical reactions involving triplet biradicals[28−30] and also established on theoretical grounds.[31] As expected, the cyclization reaction dominated the photochemistry of the substrates **1e**,**h**,**i**, whereas no Yang product was observed from the trifluoroacetyl derivative **1j**. Thus, not only is the stereoselectivity of the product formation influenced by hydrogen bonding but also the chemoselectivity of the reaction, that is, the cyclization/fragmentation ratio. This concept is also reflected in the quantum yields for H-transfer-initiated processes of **1b**,**e**,**f** (vide infra).

(B) Selectivity Connected with the Hydrogen-Transfer Step. After electronic excitation and intersystem crossing to the triplet $n\pi^*$ state of the carbonyl compound, a chairlike conformation initiates the hydrogen-transfer process.[32,33] The geometrical prerequisites for step **A** (Scheme 1) have been extensively investigated by Scheffer and co-workers for liquid-

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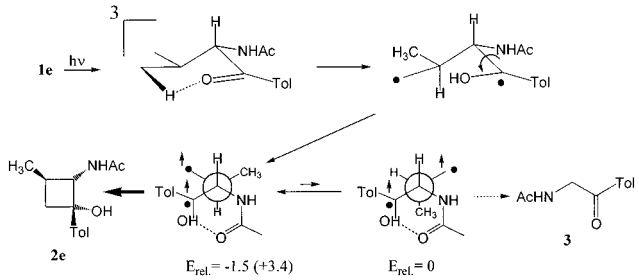
Scheme 5. Three-Step Reaction Protocol of the Valine Derivative **1e**



and solid-phase photolyses.[8] Following the classical assumption of an interaction between the reactive CH bond and the py orbital at the carbonyl oxygen,[34] the terminal carbonyl substituent (the tolyl group in substrates **1**) can adopt a pseudoequatorial position. The optimal conformation for efficient hydrogen transfer overrides substantial differences in γ-CH dissociation energies; for example, primary, secondary, and tertiary γ-CH (**1f**/**1b**/**1d**) were activated in a similar fashion and with similar quantum yields (vide infra). Additionally, as exemplified for the valine derivative **1e**, diastereotopic methyl groups are perfectly differentiated, and the chairlike transition state with one methyl group in an equatorial position is preferred (Scheme 5). This selectivity in hydrogen transfer is reflected in the relative configuration at C-4 of the cyclobutanol **2e**.

(C) Selectivity Connected with Triplet 1,4-Biradical Conformational Equilibration. The lifetimes of 1-hydroxytetramethylenes reported in the literature[3] are in the 50 ns region and thus long enough to enable conformational flexibility at room temperature. The syn biradical, which is formed after rearrangement of the primarily formed *skew* biradical, is in equilibrium with the anti conformer by rotation about the C2−C3 bond. The equilibrium constant, the hydrogen-back-transfer efficiency (from the syn structure), and the orbital orientation (p,p relative to the central C−C single bond) control the cyclization/cleavage ratio. The assumption is widely accepted that, after intersystem crossing, the singlet biradicals maintain conformational memory of their triplet precursors;[35,36] that is, the anti 1,4-biradical conformer gives exclusively cleavage products, whereas the syn 1,4-biradicals can cleave as well as cyclize. The assumption of triplet biradical equilibration and subsequent ring closure versus bond cleavage reflects nicely the experimental as well as the theoretical results. We observed three types of reaction modes concerning the Yang cyclization/cleavage ratios: (a) preferred cleavage (**1a** and **1g**), (b) nearly equal amounts of cleavage and cyclization (**1f**), and (c) preferred cyclization (**1e** and *allo*-**1g**). Semiempirical calculations (PM3)[37,38] of the three relevant 1,4-biradical conformers syn, syn(2), and anti (Table 2) resulted in absolute differences of less than 3 kcal/mol. For **1a** and **1g**, the anti biradicals are more stable with approximately 1.6 kcal; for **1e** and *allo*-**1g**, the syn biradicals are more stable with approximately 1−1.5 kcal. In the case of the biradicals from the *tert*-leucine derivative **1f**, the energies of the possible three conformers are identical within ±0.3 kcal/mol (Scheme 4). Hydrogen bond distances CO···HO were between 1.80 and 1.85 Å (Figure 2).

Table 2. Relative Energies[a] and C1···C4 Distances[b] of Triplet 1,4-Biradical from **1a**−**1g**

substrate	syn	anti	syn(2)
1a	1.7 (3.17)	0.0 (3.81)	5.7 (3.25)
1b	0.1 (3.10)	0.0 (3.81)	3.0 (3.18)
1e	0.0 (2.92)	1.5 (3.80)	4.9 (3.19)
1f	0.8 (2.94)	0.2 (3.83)	0.0 (3.10)
allo-**1g**	0.0 (2.91)	1.8 (3.77)	2.4 (3.17)
1g	1.7 (3.28)	0.0 (3.85)	1.0 (3.20)

[a] In kcal/mol, PM3-UHF, AMBER[52] preoptimized, para-methyl was omitted. [b] In brackets, in Å.

The stereospecificity detected for the Yang cyclization of the isoleucine derivatives (2*S*,3*S*)-**1g** and (2*S*,3*R*)-*allo*-**1g** is also in agreement with the photoenol generation and spectroscopy from **1g** and **1b**, respectively.[39] Whereas from **1g** the photoenol (deriving from the Norrish II cleavage) could be easily detected, the amount of enol transient formed from photolysis of **1b** was significantly smaller. The diastereoisomeric starting materials **1g** and *allo*-**1g** already exhibit two stereogenic centers and *two chemically different* γ-CH positions [in contrast to **1e**,**f** where only homotopic (for **1f**) or diastereotopic (for **1e**) methyl groups delivered the γ-hydrogens]. The biradical situation is depicted for *allo*-**1g** in Scheme 6; in this case, the two different γ-CH positions available for H transfer are clearly differentiated in bond dissociation energies, and the H transfer is favored from the methylene group *independently* of the position of the less reactive methyl group (equatorial/axial).

The biradical conformers relevant for the chemoselectivity of the Norrish II reaction of *allo*-**1g** are the syn and the anti isomer [syn(2) has one gauche interaction more than syn], with the syn isomer approximately 1 kcal/mol more stable than the anti.[40] The situation for the isoleucine system **1g** was like a mirror image; the anti isomer is approximately 1−1.7 kcal/mol more stable than both possible syn conformers (Scheme 7). These numbers nicely reflect chemical intuition with respect to the gauche interaction heat of formation increments.[41]

Further evidence for the role of geometrical factors came from an analysis of the C1−C4 distance in the triplet biradical which resulted from the PM3 calculations (Table 2). In most cases where cyclobutane formation was observed, this distance in one of the syn biradicals was between 3.1 and 2.9 Å. The intermediates from amino butyric acid (**1a**) and isoleucine (**1g**), however, that reacted solely in photofragmentation, showed reduced C1−C4 interactions with shortest C−C distances of 3.17 and 3.28 Å, respectively.[42]

(D) Selectivity Connected with the Terminal Carbon−Carbon Bond-Forming Step. After primary hydrogen transfer and conformational rearrangement, the terminal C−C-bond-forming step leads to the cyclobutanols **2**. Prior to this step as well as the C2−C3 fragmentation step, the triplet biradicals have to undergo spin inversion to cross into the singlet energy surface. In singlet photochemical reactions, stereoselectivity is often

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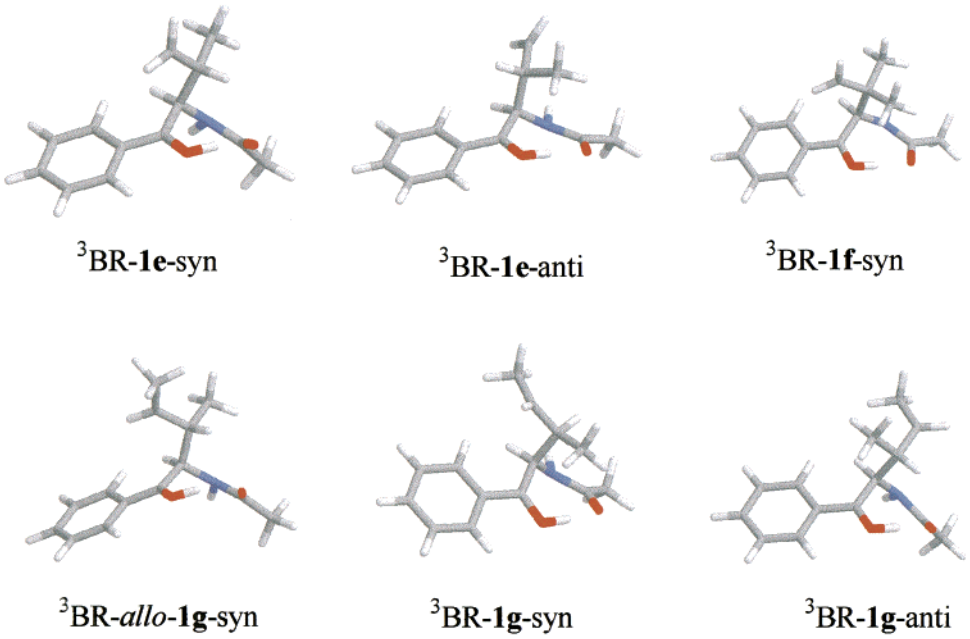
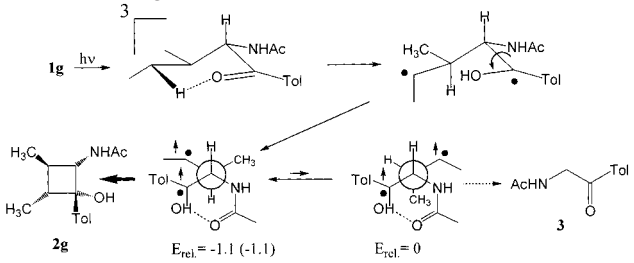
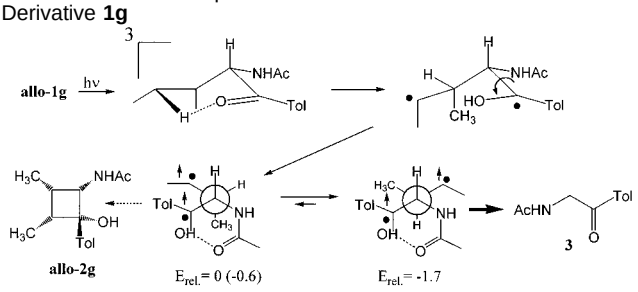


Figure 2. PM3 calculated triplet biradicals (^{3}BR) from substrates **1e**, **1f**, **1g**, and *allo*-**1g**. Low energy conformers: **1e**-syn, *allo*-**1g**-syn, and **1g**-anti. High energy conformers: **1e**-anti and **1g**-syn.

Scheme 6. Three-Step Reaction Protocol of the Isoleucine Derivative *allo*-**1g**



Scheme 7. Three-Step Reaction Protocol of the Isoleucine Derivative **1g**



controlled by the optimal geometries for radical−radical combinations, whereas in triplet photoreactions, the geometries most favorable for intersystem crossing (ISC) are considered to be of similar relevance. These geometries can be quite different from the former ones due to differences in spin−orbit coupling (SOC) values. We have described this phenomenon for [2 + 2]-photocycloadditions.[16−18] The situation is very much the same for the terminal step of the Yang reaction. Calculations resulted in large SOC values for syn geometries and lower values for anti geometries.[43] Assuming that in the syn conformer the hydroxy group localized at the benzylic radical is strongly hydrogen bonded and thus the radical geometry at C-1 is largely fixed, bond rotation about the C3−C4 single bond makes the

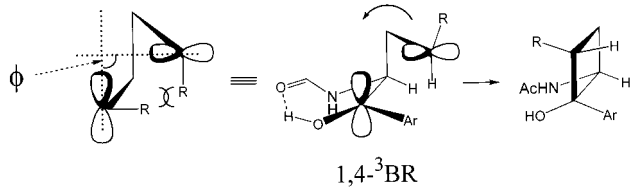
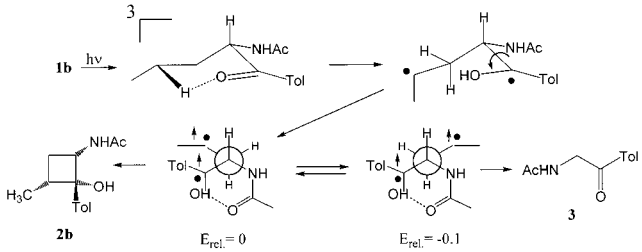


Figure 3. 90° conformational situation for the triplet 1,4-biradical: stereoselectivity of the C2−C4 bond formation.

Scheme 8. Three-Step Reaction Protocol of the Norvaline Derivative **1b**



important contribution for SOC modulation. Already the unbranched substrates **1b** and **1c** gave the corresponding cyclobutanols **2b** and **2c** with high simple diasteroselectivity but low cyclization/fragmentation ratios (shown for the isovaline derivative **1b** in Scheme 8).

Optimal ϕ values for strong SOC are in the range of 90° ± 10°.[20,44] This model presupposes conformational mobility at this intermediate stage in contrast to the reaction of singlet excited carbonyl states where conical intersections guide the substrates to the cycloaddition products nearly barrier-free. A view along the central C−C bond of the intermediate triplet 1,4-biradical (Figure 3) shows the important contribution to this high degree of stereocontrol: increasing gauche interactions are expected for a biradical approach from the same *half space* as the

(43) Klessinger, M. *Pure Appl. Chem.* **1997**, *69*, 773−778.

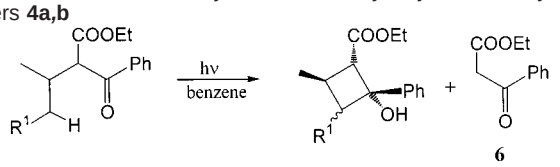
(44) A more sophisticated and theoretically more advanced description of the conformational dependence of SOC in 2-oxatetramethylenes: Kutateladze, A. G. *J. Am. Chem. Soc.* **2001**, *123*, 9279−9282.

Table 3. Quantum Yields for Photoprocesses of **1b**,**e**,**f**[a]

substrate	Φ_T	Φ_C	Φ_F
1b	0.12	0.04	0.05
1e	0.26	0.19	0.02
1f	0.23	0.11	0.08

[a] In benzene, ±0.02, by valerophenone actinometry.

Scheme 9. Photochemistry of the 2-Benzoylbutyric Acid Ethyl Esters **4a,b**



4a (R^1=H)
4b (R^1=Me)

4a (26%)
4b (15%) **d.r.=2:1**

hydroxymethyl or acetoxymethyl group, respectively (vide supra). The aryl substituent at C-1 repulses a large substituent at C-4 when oriented orthogonal with respect to each other, and thus the preferred geometry for ISC is expected to be such as depicted in Figure 2 which leads to the correct product configuration.

Quantum Yield Studies. The quantum yields for the photodecomposition of substrates **1b**, **1e**, and **1f** were determined using a merry-go-round apparatus[45] with valerophenone as the actinometer.[46] The product composition was measured as a function of time by GC, and the total quantum yields Φ_T for substrate photodecomposition are separated into quantum yields for cyclization Φ_C and quantum yields for Norrish II fragmentation Φ_F (Table 3).

The trend in quantum yields is in agreement with literature values for α-branched alkylaryl ketones. In our cases, the quantum yields for H-transfer-initiated reactions, that is, the Norrish II cleavage and the Yang cyclization, are much higher than for simple butyrophenones. For substrates without a further α-substituent, Φ_c of 4−7% was reported, whereas α-methylated compounds show increased cyclization efficiences with Φ_C of 9−12%.[47] The increased Φ_c and Φ_F values for **1b**,**e**,**f** account for the hydrogen-bonding interaction at the stage of the triplet 1,4-biradical which slows down the hydrogen back-transfer. The valine derivative **1e** has one of the largest quantum yields known for the Norrish/Yang reaction with Φ_c = 19% and also a synthetically useful chemical yield of 52% for the 2-aminocyclobutanol **2e** which is formed in diastereomerically pure form.

Photochemistry of *β*-Keto Esters 4a,b. Also, aromatic *β*-keto esters **4a**,**b** gave the Yang cyclization products **5a**,**b** in low yields (Scheme 9). The isopropyl derivative (by alkylation of benzoyl ethyl acetate) **4a** gave upon photolysis in benzene mainly Norrish II cleavage (**6**), in contrast to the analogous substrate **1e**. Similar to **1e**, the cyclobutanol **5a** was formed with high diastereoselectivity. The selectivity also vanished in the case of the isoleucine derivative **4b** where a 2:1 mixture of diastereoisomers (trans/cis with respect to the C3, C4-dimethyl substitution pattern) was isolated. Both trends account for a reduced influence of the intermediary hydrogen-bond stabilization;[27] the diastereoselectivity connected with hydrogen transfer from one of the diastereotopic methyl groups in **4a** (which is independent of hydrogen-bonding effects) still prevails, whereas the efficiency of the cyclobutanol formation decreases and also the stereoselectivity of the terminal C−C bond formation step with **4b** (which are both depending on hydrogen-bonding effects). These results are corroborated by the results reported by Hasegawa et al. for the Yang cyclization reactions of α-alkylated benzoyl ethyl acetates.[48]

Conclusion

The set of alkyl-substituted α-amino *p*-methylbutyrophenone derivatives **1a**−**1g** was highly useful to describe the different chemo- and stereoselection stages in the Norrish/Yang reaction sequence. The three decisive steps (a) hydrogen transfer, (b) biradical equilibration and hydrogen-bond stabilization, and (c) ISC-coupled bond formation versus bond cleavage became visible in (a) selective hydrogen transfer from diastereotopic *γ*-CH, (b) asymmetric 1,2-induction at the stage of the biradical connected with intramolecular hydrogen bonding, and (c) asymmetric induction coupled with selective biradical cyclization due to SOC-determined ISC geometries.[49] The comparison of the diastereoisomeric isoleucine derivatives[50] **1g** and *allo*-**1g** is a useful method for evaluation of the reactivity modulation at the stage of the triplet 1,4-biradicals.

Experimental Section

General Remarks. ^{1}H NMR: Bruker AC 250 (250 MHz), Bruker AC 300 (300 MHz). ^{13}C NMR: Bruker AC 250 (63.4 MHz), Bruker AC 300 (75.5 MHz), carbon multiplicities were determined by distortionless enhancement by polarization transfer (DEPT). UV−vis: Hitachi U-3200. Mass spectroscopy (EI or CI): Finnigan Incos 500; *m*/*z* (rel. %). HR-mass spectroscopy (FAB): Finnigan MAT H-SQ 30. Column chromatography: silica gel (Merck) 60−230 mesh; petroleum ether (PE, 40−60 °C), ethyl acetate (EA). All melting points were determined with a Büchi melting point apparatus (type Nr. 535) and are uncorrected. Combustion analyses: Elementar Vario EL. Rayonet chamber photoreactors RPR-208 (8 × 3000 Å lamps, ca. 800 W, λ = 300 ± 10 nm) and RPR-100 (16 × 3500 Å lamps, ca. 400 W, λ = 350 ± 20 nm) were used for irradiations.

Substrates 1a−1l. General Procedure. ***N*-[1-(4-Methyl-benzoyl)-propyl]-acetamide (1a).** To a suspension of 6.25 g (15.0 mmol) of phosphorus pentachloride in 40 mL of toluene was added under external cooling a solution of 2.0 g (13.8 mmol) of *N*-acetyl 2-aminobuytric acid in 20 mL of toluene. After heating to 60 °C for 2 h and cooling to room temperature, 4.0 g (30 mmol) of aluminum chloride was added, and, after stirring overnight at room temperature, the yellow-orange mixture was poured into 100 mL of ice and extracted with 3 × 50 mL of methylene chloride. After washing the organic phase with 5% aqueous sodium bicarbonate and drying over magnesium sulfate, the solvent was evaporated, and the residue was purified by column chromatography (silica gel, chloroform/PE 2:1). **1b**−**1l** were synthesized likewise and characterized by ^{1}H NMR and ^{13}C NMR (Table 4), IR, and HR-MS.

(2*S*,3*S*)-*N*-[2-Methyl-1-(4-methyl-benzoyl)-butyl]-acetamide (1g) and (2*S*,3*R*)-*N*-[2-Methyl-1-(4-methyl-benzoyl)-butyl]-acetamide (*allo*-1g). To a solution of 1.0 g (5.8 mmol) of *N*-acetyl (L) isoleucine in 25 mL of dichloromethane under nitrogen cooled to 0 °C was added over 1 h a solution of 1 mL (11.6 mmol) of oxalyl chloride and 1 drop of pyridine in 5 mL of dichloromethane. After stirring at room temperature

(45) Moses, F. G.; Liu, R. S. H.; Monroe, B. H. *Mol. Photochem.* **1969**, *1*, 245.
(46) Wagner, P. J.; Kemppainen, A. E. *J. Am. Chem. Soc.* **1972**, *94*, 7495−7499.
(47) Lewis, F. D.; Hillard, T. A. *J. Am. Chem. Soc.* **1972**, *94*, 3852−3856.
(48) Hasegawa, T.; Arata, Y.; Endoh, M.; Yoshioka, M. *Tetrahedron* **1985**, *41*, 1667−1674.
(49) Griesbeck, A. G.; Heckroth, H. *Res. Chem. Intermed.* **1999**, *25*, 599−608.
(50) We have also used this stereochemical probe in phthalimide photochemistry: Griesbeck, A. G.; Mauder, H. *Angew. Chem.* **1992**, *103*, 97−99; *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 73−75.

Table 4. NMR Spectral Data for Substrates **1a**−**1l** and **4a**,**b**[a,b]

	^{1}H NMR ($CDCl_3$, 300 MHz)	^{13}C NMR ($CDCl_3$, 75.5 MHz)
1a	0.81 (t, 3H, *J* 7.5), 1.66 (m, 1H), 2.01 (m, 1H), 2.07 (s, 3H), 2.40 (s, 3H), 5.56 (m, 1H), 6.57 (d, 1H, *J* 8.3), 7.28 (d, 2H, *J* 8.4), 7.47 (d, 2H, *J* 8.4)	CH_3: 8.8, 21.6, 23.2 CH_2: 26.3 CH: 54.5, 128.7, 129.4 C_q: 131.8, 144.8, 169.7, 198.5
1b	0.84 (t, 3H, *J* 7.5), 1.30 (m, 2H), 1.54 (m, 1H), 1.90 (m, 1H), 2.04 (s, 3H), 2.40 (s, 3H), 5.59 (m, 1H), 6.49 (d, 1H, *J* 8.7), 7.28 (d, 2H, *J* 8.4), 7.47 (d, 2H, *J* 8.4)	CH_3: 13.8, 21.7, 23.4 CH_2: 18.2, 35.7 CH: 53.5, 128.7, 129.6 C_q: 131.9, 144.9, 169.7, 198.7
1c	0.80 (t, 3H, *J* 6.9), 1.24 (m, 4H), 1.54 (m, 1H), 1.90 (m, 1H), 2.03 (s, 3H), 2.40 (s, 3H), 5.57 (m, 1H), 6.49 (d, 1H, *J* 8.1), 7.28 (d, 2H, *J* 8.4), 7.47 (d, 2H, *J* 8.4)	CH_3: 13.8, 21.7, 23.3 CH_2: 22.4, 26.9, 33.3 CH: 53.6, 128.7, 129.6 C_q: 131.9, 144.9, 169.6, 198.7
1d	0.88 (t, 3H, *J* 6.9), 1.24 (m, 4H), 1.54 (m, 1H), 1.90 (m, 1H), 2.03 (s, 3H), 2.40 (s, 3H), 5.57 (m, 1H), 6.49 (d, 1H, *J* 8.1), 7.28 (d, 2H, *J* 8.4), 7.47 (d, 2H, *J* 8.4)	CH_3: 21.7, 21.8, 23.3, 23.4 CH_2: 25.0 CH: 43.1, 51.9, 128.7, 129.5 C_q: 131.9, 144.8, 169.7, 199.3
1e	0.72 (d, 3H, *J* 6.1), 0.98 (d, 3H, *J* 6.0), 2.02 (s, 3H), 2.11 (m, 1H), 2.34 (s, 3H), 5.50 (dd, 1H, *J* 4.4, 9.0), 6.40 (d, 1H, *J* 9.0), 7.23 (d, 2H, *J* 8.2), 7.82 (d, 2H, 8.2)	CH_3: 16.7, 19.9, 21.6, 23.4 CH: 31.9, 57.7, 128.7, 129.5 C_q: 132.6, 144.7, 170.1, 199.1
1f	0.91 (s, 9H), 2.01 (s, 3H), 2.41 (s, 3H), 5.52 (d, 1H, *J* 9.4), 6.35 (d, 1H, *J* 9.4), 7.26 (d, 2H, *J* 8.2), 7.89 (d, 2H, *J* 8.2)	CH_3: 21.6, 23.4, 26.9 CH: 58.5, 128.7, 129.4 C_q: 35.6, 135.0, 144.6, 169.6, 200.6
allo-**1g**	0.94 (d, 3H, *J* 6.8), 0.99 (d, 3H, *J* 7.3), 1.17 (m, 1H), 1.46 (m, 1H), 1.81 (m, 1H), 1.99 (s, 3H), 2.43 (s, 3H), 5.68 (dd, 1H, *J* 3.4, 8.9), 6.40 (d, 1H, *J* 8.9), 7.38 (d, 2H, *J* 8.2), 7.88 (d, 2H, *J* 8.2)	CH_3: 11.9, 16.1, 21.6, 23.8 CH_2: 38.6 CH: 27.1, 57.5, 128.6, 129.4 C_q: 132.2, 144.7, 170.1, 199.0
1g	0.78 (t, 3H, *J* 7.5), 0.92 (d, 3H, *J* 6.8), 1.0 (m, 1H), 1.30 (m, 1H), 1.89 (m, 1H), 2.01 (s, 3H), 2.39 (s, 3H), 5.56 (dd, 1H, *J* 5.1, 8.9), 6.53 (d, 1H, *J* 8.9), 7.24 (d, 2H, *J* 7.9), 7.89 (d, 2H, *J* 7.9)	CH_3: 11.5, 13.6, 21.6, 23.2 CH_2: 38.4 CH: 27.0, 56.3, 128.7, 129.5 C_q: 132.2, 144.6, 169.9, 198.9
1h	0.80 (d, 3H, *J* 7.0), 1.04 (d, 3H, *J* 6.8), 2.29 (m, 1H), 2.36 (s, 3H), 5.74 (dd, 1H, *J* 4.4, 8.7), 7.01 (d, 1H, *J* 8.7), 7.22−7.93 (m, 9 H)	CH_3: 16.7, 19.9, 21.5 CH: 32.1, 58.1, 126.9, 128.0, 128.4, 129.4, 131.4 C_q: 132.5, 134.2, 144.7, 167.3, 198.8
1i	0.82 (d, 3H, *J* 6.8), 1.06 (d, 3H, *J* 6.6), 2.37 (s, 3H), 2.60 (br s, 4H), 2.88 (m, 1H), 5.01 (d, 1H, *J* 9.0), 7.19 (d, 2H, *J* 8.4), 7.67 (d, 2H, *J* 8.4)	CH_3: 18.7, 20.8, 21.5 CH_2: 27.6 CH: 26.1, 59.9, 127.7, 129.2 C_q: 133.4, 143.7, 176.3, 194.1
1j	0.78 (d, 3H, *J* 6.9), 1.04 (d, 3H, *J* 6.8), 2.30 (m, 1H), 2.36 (s, 3H), 5.57 (dd, 1H, *J* 4.5, 8.8), 7.23 (d, 2H, *J* 8.2), 7.85 (d, 2H, *J* 8.2)	CH_3: 17.1, 19.4, 21.4, 115.1 (CF_3) CH: 32.3, 59.4, 128.4, 129.7 C_q: 133.1, 144.9, 157.6, 200.1
1k	1.81 (m, 1H), 2.01 (s, 3H), 2.08 (s, 3H), 2.20 (m, 1H), 2.41 (s, 3H), 2.50 (m, 2H), 5.71 (m, 1H), 7.28 (d, 1H, *J* 8.2), 7.91 (d, 2H, *J* 8.2)	CH_3: 15.4, 21.6, 23.3 CH_2: 29.9, 33.3 CH: 52.8, 128.8, 129.5 C_q: 131.5, 145.1, 169.7, 197.8
1l	2.10 (m, 3H), 2.13 (s, 3H), 2.31 (m, 1H), 2.41 (s, 3H), 3.58 (m, 1H), 3.76 (m, 1H), 5.50 (dd, 1H, *J* 3.5, 8.9), 7.26 (d, 3H, *J* 8.2), 7.89 (d, 2H, *J* 8.2)	CH_3: 21.6, 24.5 CH_2: 21.9, 29.4, 48.2 CH: 60.9, 128.5, 129.6 C_q: 131.9, 144.1, 169.3, 196.8
4a	0.92 (d, 3H, *J* 6.6), 1.03 (d, 3H, *J* 6.8), 1.15 (t, 3H, *J* 7.2), 2.64 (m, 1H), 4.07 (d, 1H, *J* 9.4), 4.11 (q, 2H, *J* 7.2), 7.46 (m, 2H), 7.56 (m, 1H), 8.01 (m, 2H)	CH_3: 14.0, 20.4, 21.0 CH_2: 61.2 CH: 61.6, 128.6, 128.8, 133.4 C_q: 136.9, 169.1, 194.7
4b	0.91 (t, 3H, *J* 6.8), 1.03 (d, 3H, *J* 6.8), 1.16 (t, 3H, *J* 7.2), 1.31 (m, 2H), 2.46 (m, 1H), 4.11 (d, 1H, *J* 7.0), 4.16 (q, 2H, *J* 7.2), 7.46 (m, 2H), 7.56 (m, 1H), 8.04 (m, 2H)	CH_3: 11.0, 14.0, 16.4 CH_2: 26.9, 59.9 CH: 34.9, 61.2, 128.5, 128.7, 133.4 C_q: 137.1, 169.1, 194.8

[a] ^{13}C NMR, multiplicities determined by DEPT. [b] All compounds were characterized by correct combustion analysis.

for 2 h, the solvent was evaporated, and the residue was dissolved in 20 mL of toluene and treated with 1.59 g (12 mmol) of aluminum chloride. After stirring for 24 h at room temperature, the yellow-orange mixture was poured into 100 mL of ice and extracted with 3 × 50 mL of methylene chloride. After washing the organic phase with 5% aqueous sodium bicarbonate and drying over magnesium sulfate, the solvent was evaporated, and the residue was purified by column chromatography (silica gel, chloroform/PE 2:1). *Allo*-**1g** was synthesized likewise (Table 4).

2-Benzoyl-3-methyl-butyric Acid Ethyl Ester (4a). A solution of 5.55 g (28.9 mmol) of ethyl benzoyl acetate and 2.36 g (34.7 mmol) of sodium ethoxide in 50 mL of ethanol was heated to reflux for 3 h. After cooling to room temperature, 13.6 mL (144.5 mmol) of 2-bromopropane was added, and the solution was heated to reflux for an additional 2 h. After filtration and evaporation of 80% of the solvent, 100 mL of methylene chloride was added and extracted with 3 × 50 mL of water and 2 × 50 mL of 4 N HCl. After drying over magnesium sulfate, the solvent was evaporated, and the residue was purified by

column chromatography (silica gel, PE/EE 4:1) to give **4a** in 34%. 2-Benzoyl-3-methyl-pentanoic acid ethyl ester (**4b**) was synthesized likewise in 41% yield (Table 4).

Photolyses of 1a−1l and 4a,b. General Procedure. A solution of 0.2 mmol of the starting material in 50 mL of benzene was irradiated under a nitrogen atmosphere at 15 °C for 5 h (TLC- and GC-control) with phosphor-coated mercury low-pressure lamps emitting at 350 ± 20 nm. After evaporation of the solvent, the crude reaction mixture was separated and purified by column chromatography (silica gel, PE/EE 2:1). The Norrish I cleavage products are all literature-known and were compared with authentic samples or spectral data from the literature. As a Norrish II cleavage product, *N*-(4-methyl-benzoyl)-acetamide (**3**) was formed during the photolyses of **1a−1g**, and the corresponding amides were formed from **1h−1l**.

***N*-(2-Hydroxy-3-methyl-2-*p*-tolyl-cyclobutyl)-acetamide (2b).** 22%, colorless oil. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.11 (d, 3H, *J* 6.6), 1.66 (m, 1H), 1.91 (s, 3H), 2.29 (s, 3H), 2.30 (m, 1H), 2.39 (m, 1H), 4.95 (m, 1H), 6.47 (d, 1H, *J* 8.6), 7.09 (d, 2H, *J* 7.9), 7.24 (d, 2H, *J* 7.9). ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 12.6 (CH_3), 20.9 (CH_3), 23.1 (CH_3), 35.0 (CH), 39.3 (CH_2), 55.7 (CH), 74.0 (C_q), 81.4 (C_q), 124.9 (CH), 129.2 (CH), 137.3 (C_q), 141.9 (C_q), 169.7 (C_q). Anal. Calcd for $C_{14}H_{19}NO_2$ (233.3): C, 72.07; H, 8.21; N, 6.00. Found: C, 71.83; H, 8.16; N, 5.75.

***N*-(2-Hydroxy-3-ethyl-2-*p*-tolyl-cyclobutyl)-acetamide (2c).** 41%, colorless oil. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 0.82 (t, 3H, *J* 7.3), 1.60 (m, 1H), 1.91 (s, 3H), 2.21 (m, 1H), 2.29 (s, 3H), 2.41 (m, 1H), 4.56 (m, 1H), 6.49 (d, 1H, *J* 8.8), 7.09 (d, 2H, *J* 7.9), 7.28 (d, 2H, *J* 7.9). ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 11.5 (CH_3), 21.0 (CH_2), 21.3 (CH_3), 23.2 (CH_3), 32.4 (CH_2), 42.1 (CH), 48.4 (CH), 81.4 (C_q), 124.8 (CH), 129.1 (CH), 137.1 (CH), 141.7 (C_q), 169.7 (C_q). Anal. Calcd for $C_{15}H_{21}NO_2$ (247.3): C, 72.84; H, 8.56; N, 5.66. Found: C, 71.72; H, 8.46; N, 5.56.

***N*-(2-Hydroxy-3,3-dimethyl-2-*p*-tolyl-cyclobutyl)-acetamide (2d).** 47%, mp 192−194 °C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 0.76 (s, 3H), 1.21 (s, 3H), 1.83 (m, 1H), 1.90 (s, 3H), 2.02 (m, 1H), 2.28 (s, 3H), 5.06 (m, 1H), 6.45 (d, 1H, *J* 8.3), 7.07 (d, 2H, *J* 7.9), 7.21 (d, 2H, *J* 7.9). ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 21.1 (CH_3), 21.2 (CH_3), 21.7 (CH_3), 23.4 (CH_3), 38.9 (CH_2), 42.6 (C_q), 52.6 (CH), 77.3 (C_q), 124.9 (CH), 129.1 (CH), 137.4 (C_q), 141.7 (C_q), 169.7 (C_q). Anal. Calcd for $C_{15}H_{21}NO_2$ (247.3): C, 72.84; H, 8.56; N, 5.66. Found: C, 72.16; H, 8.49; N, 5.98.

***N*-(2-Hydroxy-4-methyl-2-*p*-tolyl-cyclobutyl)-acetamide (2e).** 52%, mp 172−173 °C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.19 (d, 3H, *J* 6.6), 1.78 (dd, 1H, *J* 9.7, 11.8), 2.02 (s, 3H), 2.31 (s, 3H), 2.38 (m, 2H), 4.36 (t, 3H, *J* 8.9), 6.30 (d, 1H, *J* 8.4), 7.14 (d, 2H, *J* 7.9), 7.28 (d, 2H, *J* 7.9). ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 19.1 (CH_3), 21.0 (CH_3), 23.4 (CH_3), 35.2 (CH), 38.5 (CH_2), 56.9 (CH), 78.0 (C_q), 124.9 (CH), 129.1 (CH), 137.4 (C_q), 141.8 (C_q), 169.6 (C_q). Anal. Calcd for $C_{14}H_{19}NO_2$ (233.3): C, 72.07; H, 8.21; N, 6.00. Found: C, 71.09; H, 8.16; N, 5.79.

***N*-(2-Hydroxy-4,4-dimethyl-2-*p*-tolyl-cyclobutyl)-acetamide (2f).** 43%, colorless oil. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.19 (s, 3H), 1.21 (s, 3H), 2.01 (s, 3H), 2.06 (d, 1H, *J* 9.5), 2.33 (s, 3H), 3.04 (d, 1H, *J* 9.5), 4.49 (d, 1H, *J* 9.0), 6.22 (d, 1H, *J* 9.0), 7.15 (d, 2H, *J* 7.9), 7.25 (d, 2H, *J* 7.9). ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 21.0 (CH_3), 23.3 (CH_3), 23.4 (CH_3), 29.8 (CH_3), 36.6 (CH_2), 38.1 (C_q), 58.1 (CH), 75.9 (C_q), 124.8 (CH), 129.1 (CH), 130.1 (C_q), 137.2 (C_q), 169.9 (CH_q). Anal. Calcd for $C_{15}H_{21}NO_2$ (247.3): C, 72.84; H, 8.56; N, 5.66. Found: C, 72.34; H, 8.34; N, 5.39.

***N*-(2-Hydroxy-3,4-dimethyl-2-*p*-tolyl-cyclobutyl)-acetamide (2g).** 79%, mp 204−205 °C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.18 (d, 3H, *J* 6.1), 1.19 (d, 3H, *J* 6.1), 1.89 (m, 1H), 2.03 (s, 3H), 2.02−2.05 (m, 1H), 2.37 (s, 3H), 4.19 (d, 1H, *J* 8.8), 6.32 (d, 1H, *J* 8.8), 7.18 (d, 2H, *J* 7.9), 7.34 (d, 2H, *J* 7.9). ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 12.1 (CH_3), 18.0 (CH_3), 21.4 (CH_3), 23.0 (CH_3), 43.1 (CH), 44.8 (CH), 57.7 (CH), 80.6 (C_q), 126.6 (CH), 130.1 (CH), 138.0 (C_q), 144.4 (C_q), 173.1 (C_q). Anal. Calcd for $C_{15}H_{21}NO_2$ (247.3): C, 72.84; H, 8.56; N, 5.66. Found: C, 72.99; H, 8.40; N, 5.47.

***N*-(2-Hydroxy-4-methyl-2-*p*-tolyl-cyclobutyl)-benzamide (2h).** ca. 65% (from crude NMR), colorless oil. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.14 (d, 3H, *J* 6.8), 1.78 (dd, 1H, 1H, *J* 9.8, 11.9), 2.32 (s, 3H), 2.31 (m, 2H), 4.49 (t, 1H, *J* 8.8), 7.02−7.85 (m, 9H).

1-(2-Hydroxy-4-methyl-2-*p*-tolyl-cyclobutyl)-pyrrolidine-2,5-dione (2i). ca. 65% (from crude NMR). ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.15 (d, 3H, *J* 6.6), 1.96 (dd, 1H, *J* 9.2, 12.3), 2.30 (s, 3H), 2.57 (dd, 1H, *J* 12.3), 2.74 (s, 4H), 2.78 (m, 1H), 4.58 (d, 1H, *J* 9.4), 7.11 (d, 2H, *J* 7.9), 7.29 (d, 2H, *J* 7.9). ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 19.6 (CH_3), 20.9 (CH_3), 27.8 (CH_2), 41.7 (CH_2), 44.6 (CH), 60.7 (C_q), 80.5 (C_q), 124.8 (CH), 129.1 (CH), 136.9 (C_q), 141.1 (C_q), 179.2 (C_q).

1-(6-Hydroxy-6-phenyl-5-aza-bicyclo[2.1.1]hex-5-yl)-ethanone (2l). ^{1}H NMR ($CDCl_3$, 300 MHz, mixture with *N*-acetylpyrrolidine): δ 1.88 (m, 4H), 2.00 (s, 3H), 2.31 (s, 3H), 5.22 (m, 2H), 7.14 (d, 2H, *J* 7.9), 7.28 (d, 2H, *J* 7.9). ^{13}C NMR ($CDCl_3$, 75.5 MHz, mixture with *N*-acetylpyrrolidine): δ 20.6 (CH_3), 22.1 (CH_2), 24.3 (CH_3), 63.0 (CH), 77.2 (C_q), 125.4 (CH), 129.2 (CH), 137.6 (C_q), 144.0 (C_q), 169.1 (C_q).

***N*-(4-Methyl-benzoyl)-acetamide (3).** mp 142 °C (143 °C).[51]

Ethyl 2-Hydroxy-4-methyl-2-phenyl-cyclobutanoate (5a). ca. 26% (from crude NMR, mixture with the Norrish I cleavage product). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.21 (d, 3H, *J* 6.9), 1.22 (t, 3H, *J* 6.8), 1.99 (dd, 1H, *J* 9.1, 13.1), 2.48 (dd, 1H, *J* 8.2, 13.1), 2.92 (m, 1H), 3.21 (d, 1H, *J* 9.2), 4.21 (q, 2H, *J* 6.8), 7.23−7.49 (m, 5H). ^{13}C NMR ($CDCl_3$, 75.5 MHz): δ 14.2 (CH_3), 20.6 (CH_3), 29.4 (CH), 41.3 (CH_2), 54.1 (CH), 75.6 (C_q), 124.9 (CH), 127.3 (CH), 128.2 (CH), 146.1 (C_q), 173.2 (C_q).

Ethyl 2-Hydroxy-3,4-dimethyl-2-phenyl-cyclobutanoate (5b). ca. 15% (from crude NMR, mixture with the Norrish I cleavage product). 1. diastereoisomer, ^{1}H NMR ($CDCl_3$, 300 MHz): δ 0.55 (d, 3H, *J* 7.7), 1.01 (d, 3H, *J* 6.8), 1.22 (t, 3H, *J* 6.8), 2.45 (m, 1H), 3.02 (m, 1H), 3.20 (d, 1H, *J* 10.1), 4.21 (q, 2H, *J* 6.8), 7.23−7.49 (m, 5H). 2. diastereoisomer, ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.06 (d, 3H, *J* 6.8), 1.12 (d, 3H, *J* 6.8), 1.22 (t, 3H, *J* 6.8), 2.05 (m, 1H), 2.34 (m, 1H), 2.81 (d, 1H, *J* 9.4), 4.23 (q, 2H, *J* 6.8), 7.23−7.49 (m, 5H).

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