# MAGNETIC ISOTOPE EFFECTS IN BIRADICALS:
SUBSTANTIAL ^{13}C ENRICHMENT AND A NOVEL MECHANISTIC PROBE

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Summary. Photolysis of 2,n-diphenylcycloalkanones (n-membered ring, n = 10, 11, 12, 15) produces products that are significantly enriched in ^{13}C. The enrichments are different for each product, and this allows assignment of the dynamic pathways through which each product is formed.

Published studies of magnetic isotope effects have been confined almost exclusively to reactions involving radical pairs.[1] Experiments in this laboratory have demonstrated substantial isotope enrichment in dibenzyl ketone (DBK) by photolyzing the sample in "microscopic reactors"[1d] such as micellar and porous solid[2] systems and in solutions of high viscosity.[3] Flexible biradicals are excellent examples of microscopic reactors because of the restrictions imposed by the chain, but no report of isotope enrichment comparable to DBK has yet appeared for these species.[4] We have recently shown by nanosecond laser techniques that biradicals derived from 2-phenylcycloalkanones exhibit a rich variety of dynamics[5] that could in principle be exploited for ^{13}C enrichment. Our goal was to exploit the relationships that we had discovered[5] among factors such as intersystem crossing (ISC) rates, chain dynamics, chain length, solvent viscosity, applied magnetic fields and temperature to control the biradical reactions and to optimize the efficiency of isotope separation. In this paper we report two novel findings: (1) that the cycloalkanones **1** lead to ^{13}C enrichment which is, in the best case, equal to the highest enrichment ever observed for DBK; (2) that different products of photolysis are enriched to different extents. This latter result furnishes a powerful new mechanistic probe into the dynamics of triplet-derived biradicals.
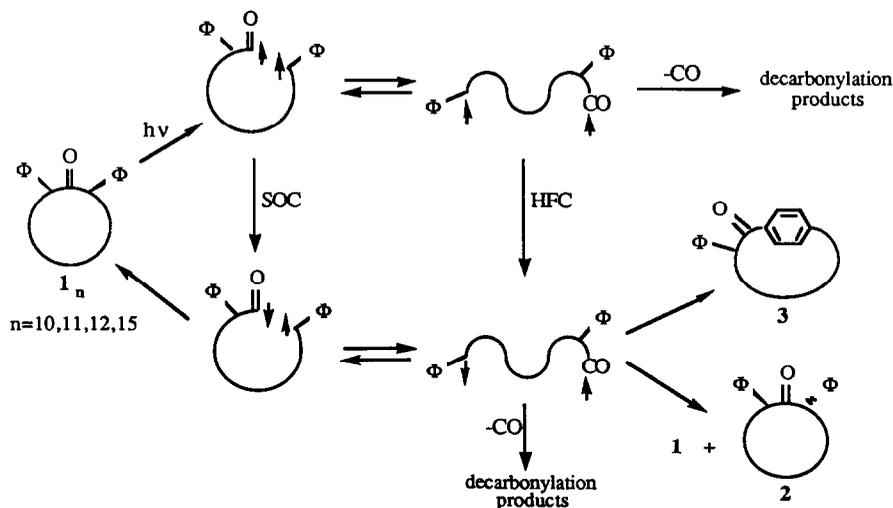
Scheme 1. Major kinetic processes in biradicals produced by photolysis of **1**. Not shown explicitly is biradical formation by secondary photolysis of **2**, and decarbonylation of the compact biradical conformers.

Our starting materials were the cis-cycloalkanones 1_n (n=6,10,11,12,15),[6] and the trans ketone 2_{12}. The parameter[7] evaluated to measure the extent of isotopic separation was the % increase (β) in ^{13}C content as a function of the extent of photolysis. For simplicity β was calculated assuming all of the enrichment was in the carbonyl position. The determination of β was made by mass spectrometric analysis and was investigated as a function of ring size, temperature, solvent and magnetic field. Our results for 1_{12} and 2_{12} are summarized in Table 1. The salient results for 1_{12} are as follows: (1) The β values for the recovered starting material in all cases are smaller than those for the isomeric products 2 and 3;   (2) the values of β for 2 and 3 generally increase with increasing temperature; (3) the values of β for 3 are much larger than for the corresponding *para*-methylacetophenone formed in the DBK micellar systems;[8] (4) in DMF 60% of 1_{12} was decarbonylated and the carbonyl-containing products have 40% overall enrichment, similar to the best DBK results.[8]

We suggest the following qualitative interpretation of the data. We assume that the initially formed triplet biradicals must undergo ISC to singlet biradicals before ring closure can take place and that the ISC mechanism responsible for isotope selection is electron-nuclear hyperfine coupling (HFC).[5] Efficient isotope selection poses two additional requirements: (1) a competitive chemical process (decarbonylation) that is faster than HFC-induced ISC, and (2) chain motions that are fast enough to allow both separation of the two radical centers and return to a reactive conformation before decarbonylation or ISC takes place. Singlet biradicals form products rapidly,[5,9] with the carbonyl containing products, 2 and 3, becoming enriched in ^{13}C and the CO becoming enriched in ^{12}C.

In addition to HFC, another ISC mechanism, spin-orbit coupling (SOC), also causes triplet to singlet biradical interconversion,[5,10] but does not lead to isotope selection. The ISC mechanism which operates depends strongly on the biradical chain conformation.[5] HFC dominates ISC in conformers with large end-to-end distances (R), whereas SOC dominates ISC in conformers with small (<4 Å) values of R.[5] Carbonyl containing products formed via ISC at large R will have a higher β than products formed via ISC at small R, since ISC at large R is

Table 1. Yields and enrichment in the photolysis of 1_{12} and 2_{12} in hexane and DMF under various conditions.

T (°C)	Starting Ketone[a]	Solvent	1_{12} Yield[b]	β[c]	2_{12} Yield[b]	β[c]	3_{12} Yield[b]	β[c]
23	1_{12}	DMF	29	12	1.8	133	8.6	110
23	1_{12}	Hexane	7	41	1.1	151	.4	179
23	1_{12}	Hexane[d]	25	7	1.5	96	.9	158
10	1_{12}	Hexane	44	0	2.2	90	1.8	128
0	1_{12}	Hexane	21	12	2.8	113	1.7	140
-10	1_{12}	Hexane	30	5	3.8	66	3.0	97
-20	1_{12}	Hexane	40	6	4.8	74	4.3	72
10	2_{12}	Hexane	2.3	68	23	2	2.8	131
0	2_{12}	Hexane	2.3	115	38	10	3.0	97

a) Starting material was 98% of the isomer listed, plus 2% of the cis/trans isomer.
b) Percent of compound in the product mixture (±1%).
c) Percent increase in ^{13}C content (±30% uncertainty, mainly from the mass spectrometer).
d) Photolyzed in a 1.2 kG magnetic field (all other runs in the earth's magnetic field).

dominated by the isotope selective HFC process. The differences in β among **1, 2,** and **3** can be understood in these terms. Triplet cycloalkanone cleavage intially produces a biradical in a conformation with small R. SOC-dominated ISC in this conformation (probably fast enough at small R to compete with chain isomerization) yields mainly recyclization to generate unenriched **1**. Formation of **2** and **3** requires conformations in which R is larger than that adequate for formation of **1**. These extended conformations allow HFC to contribute significantly to ISC and to lead to **2** and **3** enriched in ^{13}C. This interpretation requires that photolysis of 2_{12} must lead to enriched 1_{12} and unenriched 2_{12}, *opposite to the results when 1_{12} is photolyzed.* Table 1 confirms this prediction.

The differences in β among **1, 2,** and **3** are seen to result from *the inherent tendency of HFC and SOC to produce different products,* and this in turn results from the R-dependence of the ISC mechanism. The dependence of product distribution on the ISC mechanism was previously demonstrated by the CIDNP of products derived from photolysis of 2-norbornanone.[11] The CIDNP spectra showed that the ratio of cyclization to disproportionation produced via SOC was greater than that produced via HFC. Just as in the present case, the process favored by HFC (disproportationation) required a larger R than the SOC favored process (cyclization).

In hexane the increase in β with temperature may arise from the rapid increase in the decarbonylation rate constant, k_{-CO}, relative to the HFC rate constant k_{HFC}. In DMF, on the other hand, the ratio of k_{-CO} to k_{HFC} is smaller than the ratio in hexane, but the enrichments do not decrease correspondingly. The marked increase of both the chemical yield of **3** and the total enrichment in DMF solvent is not understood and is being investigated.

The data in Table 2 demonstrate the effect of ring size on enrichment. In 1_6 the maxium value of R is too small for either HFC or cyclophane formation to take place. β is largest for n=10-12, then appears to decrease for n=15. The decrease at large n could be due to a number of factors and is under investigation.

Table 2. Yields and enrichments for the photolyisis of various sized cycloalkanones in hexane at 0°.[a]

Starting Ketone	1_n Yield[b]	β[c]	2_n Yield[b]	β[c]	3_n Yield[b]	β[c]
$1_6 + 2_6$[d]	35	-3	21	-3	0	0
1_{10}	11	22	1.2	120	.4	124
1_{11}	15	-9	2.1	102	2.2	108
1_{12}	21	12	2.8	113	1.7	140
1_{15}	43	35	12	36	.6	80

a) Starting materials are >98% of the isomer listed except 1_{15}, which contains 13% trans. The ratio of $1_6/2_6$ is 38/62.
b) Percent of compound in the product mixture (±1%).
c) Percent increase in ^{13}C content (±30% uncertainty, mainly from the mass spectrometer)
d) Photolyzed at 23° C.

Some other observations that are pertinent to the proposed mechanism are: (1) 2,n-dialkylcycloalkanones[4] do not possess a competitive decarbonylation process and do not show significant isotopic enrichment upon photolysis under conditions comparable to those reported here; (2) the values of β decrease with the application of an external 1.2 kG magnetic field; (3) from mass spectrometric analysis of the M-28 peak, about half of the

enrichment accumulates in the carbonyl carbon of **2**, a result consistent with earlier findings for DBK.[2,12] In the DBK system, the rest of the enrichment is in the benzylic carbons.[12]

In summary, substantial isotopic enrichment has been demonstrated in biradical reactions, and a valuable new mechanistic probe has emerged. Because ^{13}C enrichment depends on the HFC mechanism of ISC, β is sensitive to the competition between HFC and the other important dynamical processes such as decarbonylation, SOC, and chain dynamics. In the reactions of **1**, we are led to conclude that **2** and **3** are formed mainly from extended chain biradical conformers via the HFC mechanism, and **1** is reformed from the biradical mainly from the nearly cyclic conformers via the SOC mechanism.

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(Received in USA 3 March 1987)