Supplementary Material (ESI) for Organic & Biomolecular Chemistry

Supporting Information

Reactivity of *endo*-3-bromocamphor with Sulfur-Centered Nucleophiles by Electron Transfer Mechanism. Electrophilic behaviour of 3-camphoryl radical

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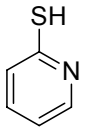
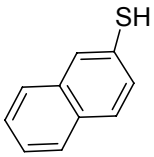
1. Computational Analysis

Computational Procedures. These calculations were performed with Gaussian 03.[1] The characterization of stationary points was performed by Hessian matrix calculations. The exploration of the potential surface was carried out within the functional B3LYP[2] at 6-31+G* level and LANL2DZ for sulfur atoms. The charge distribution was obtained by Mulliken Population Analysis from the anion optimized structures. The themochemical study was carried out with full optimization using acetonitrile solvent according to the polarized continuum model IEFPCM.[3]

1.a. Cartesian Coordinates for Neutral Molecules



C	0.001858	0.000000	0.053437
N	0.058013	0.000000	1.393887
C	1.265337	0.000000	1.965789
C	2.465158	0.000000	1.233887
C	2.385629	0.000000	-0.154889
C	1.128182	0.000000	-0.767871
S	1.345224	0.000000	3.748881
H	3.424743	0.000000	1.742625
H	3.293937	0.000000	-0.752043
H	1.022845	0.000000	-1.848447
H	-0.999012	0.000000	-0.373820
H	0.007612	0.000000	3.913394



C	0.009058	0.000000	0.021689
C	0.008467	0.000000	1.400579
C	1.228747	0.000000	2.128842
C	2.469613	0.000000	1.411359
C	2.436415	0.000000	-0.011427
C	1.236124	0.000000	-0.689492
C	1.270992	0.000000	3.549640
C	2.467057	0.000000	4.230679
C	3.699008	0.000000	3.518522
C	3.690825	0.000000	2.136339
S	5.274594	0.000000	4.361365
H	4.626312	0.000000	1.581032
H	0.335143	0.000000	4.104421
H	2.468759	0.000000	5.317578
H	3.376702	0.000000	-0.558438
H	1.226815	0.000000	-1.776496
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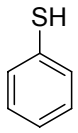
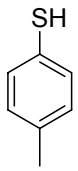
H	4.783906	0.000000	5.617477



C	-0.013673	0.000000	-0.026327
C	0.017227	0.000000	1.376298
C	1.253421	0.000000	2.037666
C	2.440805	0.000000	1.301901
C	2.411365	0.000000	-0.094969
C	1.178050	0.000000	-0.753061
S	-1.546441	0.000000	2.242371
H	1.294665	0.000000	3.124088
H	3.392106	0.000000	1.828240
H	3.337314	0.000000	-0.663304
H	1.138835	0.000000	-1.839443
H	-0.966672	0.000000	-0.549539
H	-1.039790	0.000000	3.491571



C	-0.008438	0.000000	0.026185
C	0.056040	0.000000	1.424017
C	1.314627	0.000000	2.044295

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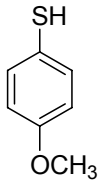
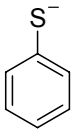
C	2.429066	0.000000	-0.127784
C	1.166033	0.000000	-0.731549
S	-1.393936	0.000000	2.470623
C	3.698269	0.000000	-0.949287
H	1.387537	0.000000	3.129158
H	3.441576	0.000000	1.779074
H	1.090554	0.000000	-1.817060
H	-0.970183	0.000000	-0.481087
H	3.478093	0.000000	-2.021971
H	4.314396	0.882917	-0.735836
H	4.314396	-0.882917	-0.735836
H	-2.307968	0.000000	1.479612



C	0.003690	0.000000	0.020492
C	0.014701	0.000000	1.421311
C	1.217943	0.000000	2.130179
C	2.424972	0.000000	1.410339
C	2.421640	0.000000	0.020743

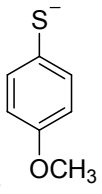
C	1.210139	0.000000	-0.687196
S	1.307807	0.000000	3.918523
O	1.315191	0.000000	-2.051699
C	0.121912	0.000000	-2.822391
H	3.374716	0.000000	1.939289
H	3.353275	0.000000	-0.537272
H	-0.950526	0.000000	-0.494658
H	-0.935596	0.000000	1.949474
H	0.442300	0.000000	-3.865696
H	-0.480844	-0.896884	-2.626113
H	-0.480844	0.896884	-2.626113
H	-0.021647	0.000000	4.145659

1.b. Cartesian Coordinates for Anions

Anion 2 

S	0.000000	0.000000	-0.142212
C	0.000000	0.000000	1.655222
C	1.212174	0.000000	2.422370
C	1.211805	0.000000	3.828281

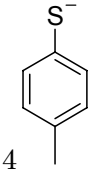
C	0.000000	0.000000	4.557385
C	-1.211805	0.000000	3.828281
C	-1.212174	0.000000	2.422370
H	2.155446	0.000000	1.878300
H	2.164771	0.000000	4.361794
H	0.000000	0.000000	5.647115
H	-2.164771	0.000000	4.361794
H	-2.155446	0.000000	1.878300



Anion 3

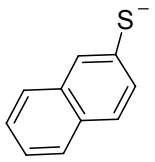
C	-0.101671	0.000000	0.083723
C	-0.040333	0.000000	1.511478
C	1.284929	0.000000	2.060701
C	2.438590	0.000000	1.260345
C	2.327050	0.000000	-0.143989
C	1.047611	0.000000	-0.734311
S	-1.514367	0.000000	2.548326
H	1.385098	0.000000	3.144289
H	3.431261	0.000000	1.707617
O	3.557157	0.000000	-0.872785
H	0.925862	0.000000	-1.816271

H	-1.085252	0.000000	-0.382030
C	3.466157	0.000000	-2.312935
H	4.498270	0.000000	-2.680191
H	2.943290	-0.894222	-2.691123
H	2.943290	0.894222	-2.691123

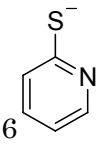


Anion 4

S	0.002125	0.000000	-0.188645
C	-0.001872	0.000000	1.610064
C	1.207109	0.000000	2.381381
C	1.205271	0.000000	3.785931
C	-0.001215	0.000000	4.529171
C	-1.205555	0.000000	3.787277
C	-1.208965	0.000000	2.379945
H	2.152039	0.000000	1.840240
H	2.160066	0.000000	4.318413
C	0.002303	0.000000	6.050961
H	-2.159330	0.000000	4.320690
H	-2.154885	0.000000	1.840730
H	-1.023834	0.000000	6.444451
H	0.513371	-0.885194	6.464196
H	0.513371	0.885194	6.464196

Anion 5 

C	-0.094955	0.000000	-0.048992
C	-0.003586	0.000000	1.364463
C	1.237605	0.000000	2.058750
C	2.482193	0.000000	1.314839
C	2.395755	0.000000	-0.117618
C	1.170548	0.000000	-0.763160
H	-0.928084	0.000000	1.939379
C	1.319820	0.000000	3.495014
C	3.721863	0.000000	2.015978
H	3.319063	0.000000	-0.699627
H	1.121712	0.000000	-1.850361
S	-1.641826	0.000000	-0.946806
C	2.546023	0.000000	4.152553
H	0.391762	0.000000	4.066480
H	2.580125	0.000000	5.242039
H	4.647420	0.000000	1.438295
C	3.767792	0.000000	3.411777
H	4.722788	0.000000	3.934984

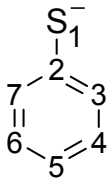
Anion 6 

C	-0.009277	0.000000	-0.016902
N	-0.001674	0.000000	1.337546
C	1.213802	0.000000	2.013277
C	2.427479	0.000000	1.230912
C	2.391372	0.000000	-0.165388
C	1.139097	0.000000	-0.832424
S	1.282133	0.000000	3.788946
H	3.371898	0.000000	1.768441
H	3.321856	0.000000	-0.735369
H	1.058611	0.000000	-1.917553
H	-1.001637	0.000000	-0.475495

1.c. Charges analysis for Anions

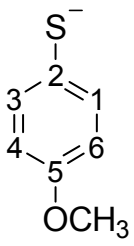
Charges Anion 2

1	S	-0.444346
2	C	-0.206378
3	C	-0.274437
4	C	-0.222203
5	C	-0.301895
6	C	-0.222203
7	C	-0.274437
8	H	0.212682
9	H	0.170846
10	H	0.178841
11	H	0.170846
12	H	0.212682



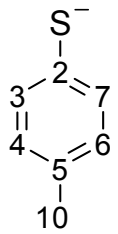
Charges Anion 3

1	C	-0.263954
2	C	-0.226327
3	C	-0.232098
4	C	-0.352413
5	C	0.282603
6	C	-0.340149
7	S	-0.451163
8	H	0.217983
9	H	0.201714
10	O	-0.337777
11	H	0.190517
12	H	0.213905
13	C	-0.480464
14	H	0.199867
15	H	0.188877
16	H	0.188877



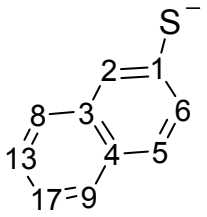
Charges Anion 4

1	S	-0.446660
2	C	-0.224637
3	C	-0.048183
4	C	-0.200248
5	C	0.436732
6	C	-0.252248
7	C	-0.042699
8	H	0.000000
9	H	0.000000
10	C	-0.222058
11	H	0.000000
12	H	0.000000
13	H	0.000000
14	H	0.000000
15	H	0.000000



Charges Anion 5

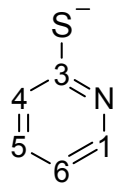
1	C	-0.233988
2	C	-0.240198
3	C	0.360897
4	C	0.369687
5	C	-0.233890
6	C	-0.020406
7	H	0.000000
8	C	-0.227526
9	C	-0.223494
10	H	0.000000
11	H	0.000000
12	S	-0.401439



13 C -0.059744
14 H 0.000000
15 H 0.000000
16 H 0.000000
17 C -0.089899
18 H 0.000000

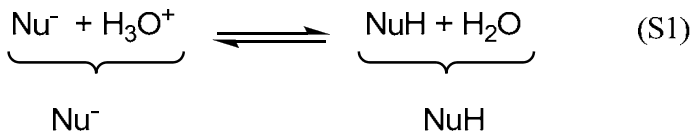
Charges Anion 6

1 C -0.175667
2 N -0.017191
3 C -0.361259
4 C 0.019216
5 C -0.012059
6 C -0.077347
7 S -0.375694
8 H 0.000000
9 H 0.000000
10 H 0.000000
11 H 0.000000



1.d. Proton Affinities Data

The thermochemical data concerning proton affinities were obtained by eq. S1.



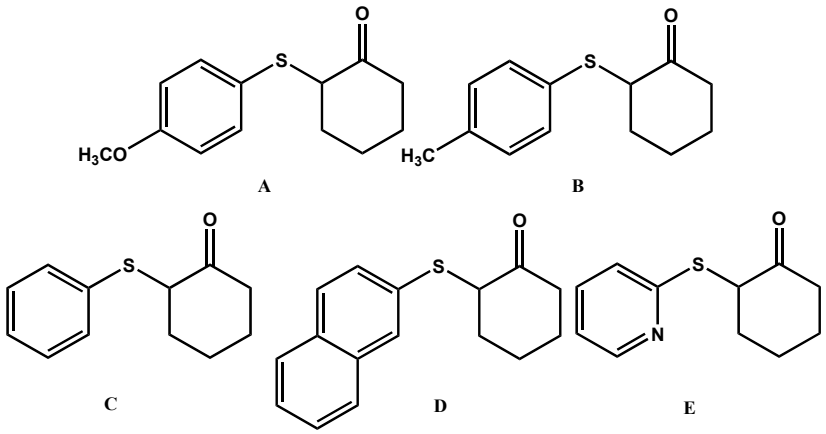
(S1)

Table S1: Proton Affinities

Compound	E_{NuH}	E_{Nu-}	PA
6 E_e[a]	-722.93571	-646.04121	-41.71417
6 ZPE[b]	0.10639	0.10996	
6 E_e+ZPE[c]	-722.82932	-722.76285	
5	-860.54290	-860.47863	-42.91725
5	0.16410	0.16822	
5	-860.378801	-860.31041	
2	-706.89243	-706.82716	-43.29291
2	0.11797	0.12169	
2	-706.77447	-706.70548	
4	-746.20992	-746.14395	-43.75467
4	0.14538	0.14914	
4	-746.06454	-745.99481	
3	-821.41919	-821.35303	-43.99533
3	0.15047	0.15443	
3	-821.26871	-821.19860	

B3LYP/6-31+G*//6-31+G* calculated PA form S-centered anions in acetonitrile. a)Electronic Energy b)Zero Point Energy c) Total Energy.

1.e. Cartesian Coordinates for Substitution Products (13-17)



A

C	0.000000	0.000000	0.000000
C	0.000000	0.000000	1.538513
C	1.431212	0.000000	2.032521
C	2.179228	1.247233	1.616362
C	2.200383	1.324399	0.068751
C	0.783162	1.223870	-0.521884
S	-0.990492	-1.410314	2.305991
C	-2.670445	-0.919003	1.989703
C	-3.389760	-0.127578	2.927688
C	-4.722900	0.204320	2.716315
C	-5.407205	-0.243175	1.565330
C	-4.719083	-1.073006	0.654957
C	-3.384750	-1.405977	0.860179
O	1.961559	-0.943029	2.652738
H	1.676604	2.157025	2.000458
H	3.197906	1.221295	2.025863
H	2.676093	2.266492	-0.257530
H	2.821275	0.501543	-0.313753
H	0.223653	2.136687	-0.261986
H	0.835616	1.194144	-1.620758

H	-1.034093	0.030983	-0.375996
H	0.457858	-0.932220	-0.358649
H	-0.488002	0.939214	1.859293
H	-2.867091	-2.046153	0.149486
H	-5.234502	-1.454078	-0.226356
O	-6.747008	0.100846	1.349513
H	-5.241846	0.821817	3.449005
H	-2.875354	0.222601	3.820023
C	-7.190409	0.925879	2.390050
H	-8.232584	1.193478	2.222176
H	-7.099693	0.396100	3.337165
H	-6.583852	1.829815	2.420199

B

C	-0.015309	-0.034774	-0.000858
C	-0.026477	-0.005344	1.400576
C	1.199190	0.022862	2.082949
C	2.403030	0.032868	1.376262
C	2.423127	0.021701	-0.026676
C	1.193747	-0.011403	-0.700187
S	-1.573047	-0.098048	2.314569
C	-2.157547	1.646085	2.118126
C	-3.600599	1.758351	2.609069
C	-4.198328	3.153953	2.489797
C	-3.295106	4.207833	3.168526
C	-1.848280	4.113983	2.664967
C	-1.283068	2.695121	2.842964
O	-4.211788	0.821234	3.088112
H	-4.294596	3.397136	1.420666
H	-5.202917	3.135736	2.923104
H	-3.704886	5.209700	2.990264

H	-3.315169	4.048345	4.255768
H	-1.807488	4.395479	1.601940
H	-1.214650	4.831440	3.201993
H	-0.259311	2.636418	2.457621
H	-1.238774	2.438531	3.910139
H	-2.159114	1.879973	1.043685
H	1.205340	0.031743	3.169373
H	3.342365	0.050537	1.926275
C	3.732753	0.035971	-0.781269
H	1.180155	-0.033572	-1.788110
H	-0.954723	-0.089615	-0.545098
H	3.571225	0.007634	-1.863960
H	4.314882	0.938396	-0.553947
H	4.357006	-0.826162	-0.513869

C

C	0.112031	0.065774	-0.103752
C	0.311690	0.410446	1.371962
C	1.683260	0.043937	1.922224
C	2.016876	-1.439433	1.647942
C	1.836729	-1.788800	0.164244
C	0.425205	-1.431042	-0.330456
O	-0.562601	0.902929	2.060585
S	-1.587151	0.575781	-0.628335
H	2.433379	0.679145	1.427002
H	1.698053	0.275867	2.991441
H	3.042439	-1.649902	1.975422
H	1.355813	-2.072632	2.256101
H	2.584770	-1.249690	-0.436296
H	2.020482	-2.858802	0.003508
H	0.320250	-1.661971	-1.396162

H	-0.324369	-2.031706	0.202453
H	0.835448	0.661290	-0.679072
C	-1.435136	0.348738	-2.407249
C	-2.077885	-0.728706	-3.034107
C	-2.018140	-0.874789	-4.423800
C	-1.309682	0.047913	-5.197578
C	-0.669716	1.126546	-4.578167
C	-0.740424	1.282941	-3.191895
H	-2.625894	-1.446557	-2.430355
H	-2.523592	-1.711851	-4.899110
H	-1.262249	-0.067250	-6.277416
H	-0.127897	1.855622	-5.175694
H	-0.269670	2.138875	-2.715174

D

C	-0.021678	-0.028662	0.017568
C	-0.017422	-0.018389	1.401007
C	1.224113	-0.000606	2.096167
C	2.415428	0.022981	1.403254
C	2.437914	0.034900	-0.017858
C	1.189814	0.008151	-0.724083
S	-1.558323	-0.104814	2.327529
C	-2.141226	1.639052	2.120860
C	-3.586842	1.753039	2.603694
C	-4.184148	3.147321	2.471744
C	-3.285959	4.206066	3.149774
C	-1.835844	4.109621	2.656118
C	-1.271327	2.691770	2.845782
O	-4.196296	0.820372	3.093481
H	-4.273039	3.383363	1.400404
H	-5.191683	3.131564	2.898220

H	-3.695317	5.206361	2.962322
H	-3.313184	4.053271	4.237769
H	-1.788075	4.385206	1.591913
H	-1.205595	4.829667	3.193455
H	-0.245285	2.632062	2.466552
H	-1.233267	2.441322	3.914657
H	-2.135026	1.867539	1.045529
H	1.219443	-0.007909	3.182271
H	3.359216	0.035415	1.944446
C	3.649107	0.065830	-0.762856
C	1.204639	0.006181	-2.147485
H	-0.965626	-0.078008	-0.520703
C	2.395500	0.036150	-2.840429
H	0.256913	-0.020640	-2.680908
H	2.394223	0.034322	-3.927407
C	3.630095	0.068256	-2.141195
H	4.594346	0.086753	-0.224779
H	4.562533	0.091674	-2.699347

E

C	-0.031710	0.448720	-0.115555
C	-0.067400	-0.095785	1.332815
C	1.356412	-0.271342	1.855628
C	2.209863	0.985728	1.763696
C	2.212628	1.551671	0.326003
C	0.784117	1.749051	-0.199134
S	-0.988768	-1.675987	1.503858
C	-2.675607	-1.093296	1.467485
N	-2.938115	0.216862	1.488001
C	-4.225116	0.602993	1.496002

C	-5.298397	-0.282926	1.484255
C	-5.013551	-1.654590	1.459424
C	-3.689574	-2.072454	1.448376
O	1.790207	-1.330566	2.271076
H	1.787811	1.738953	2.446080
H	3.218928	0.742457	2.109882
H	2.768852	2.497045	0.306945
H	2.752362	0.855120	-0.330911
H	0.280780	2.534791	0.383521
H	0.809498	2.098697	-1.239225
H	-1.060210	0.616899	-0.449231
H	0.407172	-0.314139	-0.772763
H	-0.583661	0.641329	1.960734
H	-3.432143	-3.127636	1.426441
H	-5.816490	-2.387355	1.446560
H	-6.319591	0.085708	1.491836
H	-4.391901	1.678605	1.512122

1.f. Molecular Orbital Calculation

The LUMOs molecular orbitals of neutral products were evaluated by theoretical calculations, assuming that the order of energies would be qualitatively parallel to the energies of the SOMOs of the corresponding radical anions.[4] According to our calculations (Figure S1), when an electron withdrawing group is present in an aromatic compound, the unpaired spin distribution, corresponding to the radical anion, is located mainly on the π aromatic ring (compounds $\mathbf{11}^{\bullet-}$ and $\mathbf{12}^{\bullet-}$). Conversely, when an electron donor group is present in an aromatic compound, the unpaired spin distribution of the radical anion is distributed between the aromatic ring and the carbonyl group (compounds $\mathbf{9}^{\bullet-}$ and $\mathbf{10}^{\bullet-}$). This latter situation promotes both a higher charge distribution and a higher spin distribution, favouring the formation of substitution products. Thus, the electronic distribution of SOMOs molecular orbital qualitatively predicts that, for anions **3** and **4** (when electron donor group is present), the coupling step is more favoured than that corresponding to **2** toward $\mathbf{7}^{\bullet}$, whereas the coupling reactions for anions **5** and **6** is lower (when electron acceptor group is present).

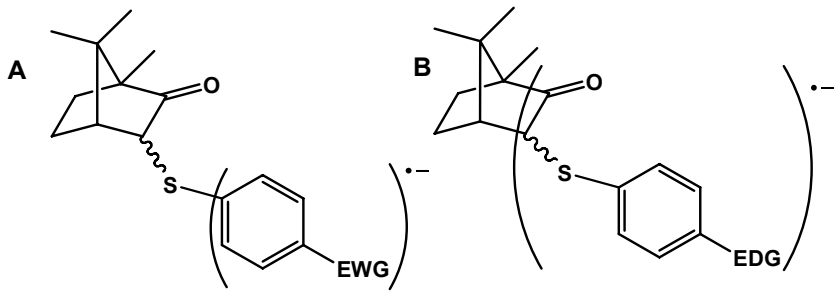


Figure S1. SOMO molecular orbital of radical anions corresponding to substitution products. A. With electron-withdrawing group. B. With electron-donating group.

Figure S2 shows the SOMOs for the substitution products from the coupling of anions **2**-**6** with cyclohexanone-derived radicals.

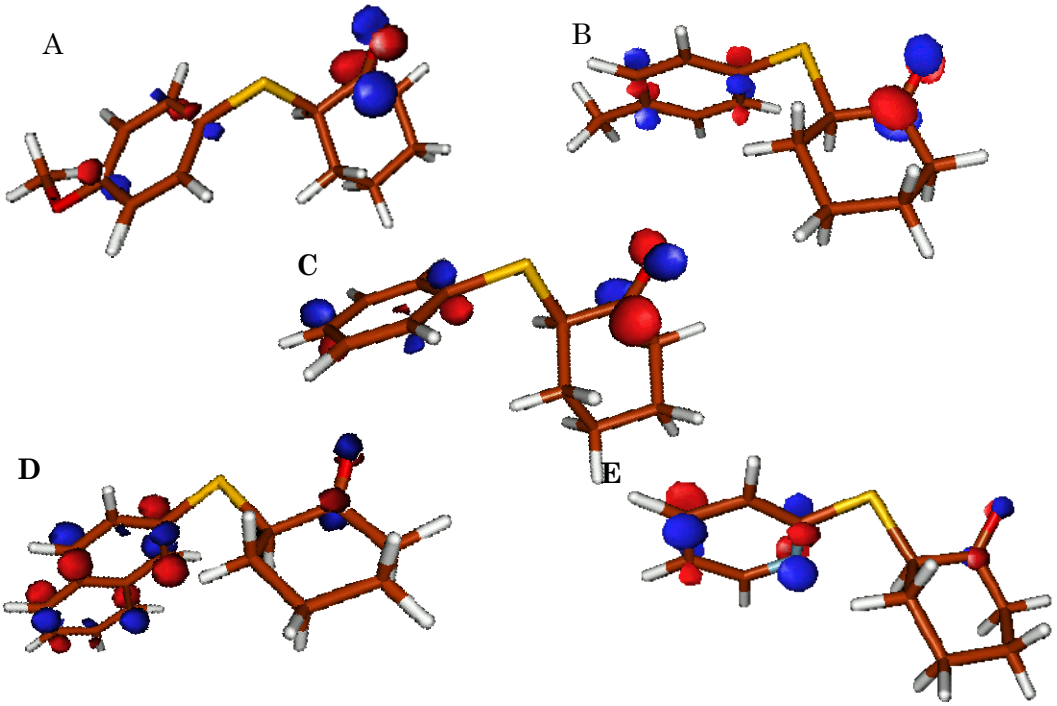


Figure S2: SOMOs corresponding to FCRA of S-aryl substituted cyclohexanone **A-E** employing B3LYP/6-31+G*. **A)** 2-(4-metoxyphenylthio)cyclohexanone. **B)** 2-(4-methylphenylthio)cyclohexanone. **C)** 2-(phenylthio)cyclohexanone. **D)** 2-(naphthalen-2-ylthio)cyclohexanone. **E)** 2-(2-pyridinthio)cyclohexanone.

On the other hand, the energy of the frontier orbitals largely depends on the aryl ring; as seen from **Table S2**, the reactivity trend is not in agreement with the calculated values of ΔE HOMO-LUMO or HOMO-SOMO in neutral molecules or Frank-Condon Radical Anions (FCRA), respectively.

Table S2: B3LYP/6-31+G* Frontier Orbital Analysis

	HOMO	LUMO	ΔE^a	HOMO	SOMO	ΔE^b
PhS-	-0.0103	0.08517	0.0955	-0.0103	-0.04435	-0.0340
AnS-	-0.0107	0.07559	0.0863	-0.0107	-0.03889	-0.0282
TolS-	-0.0065	0.0835	0.0900	-0.0065	-0.04002	-0.0335
NaphS-	-0.0201	0.06321	0.0833	-0.0201	-0.0639	-0.0438
2-PyS-	-0.0272	0.07923	0.1065	-0.0272	-0.04407	-0.0169

a- Calculated from LUMO corresponding to the neutral product b- Calculated from the SOMO of FCRA. The orbitals energies and ΔE values in eV.

Finally, we observe that the frontier orbital theory (ΔE HOMO-SOMO) used to explain the reactivity in the coupling step between phenyl radical for several nucleophiles cannot be applied to stable radicals such as α-keto. This mainly results from two factors, the small energy changes observed in the SOMO energies, and the fact that the alignment of the energy of anions with the HOMO energy is not fulfilled in cases where the charge distributions are markedly different.

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