Experimental Detection of the Pentaazacyclopentadienide (Pentazolate) Anion, *cyclo*-N_5^-**

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Dedicated to Professor George Olah
on the occasion of his 75th birthday

Nitrogen and oxygen are unique among the chemical elements. In contrast to the other elements, their homonuclear single-bond energies are significantly less than one third of their triple- or one half of their double-bond energies. Consequently, homonuclear polynitrogen and polyoxygen species are thermodynamically highly unstable and the number of known compounds is very limited. Owing to the highly endothermic heats of formation, their syntheses and handling present great challenges. It is, therefore, no surprise that for oxygen only one metastable allotrope, that is, ozone, is known and for nitrogen none are known that can be isolated in bulk, while most other elements can exist in the form of many stable allotropes.

Polynitrogen compounds have been studied extensively for the last two decades. In view of the great experimental difficulties, most of the efforts have been limited to theoretical studies.[1–9] The first major breakthrough in the synthesis area was achieved in 1999 with the synthesis of the N_5^+ ion in the form of a marginally stable AsF_6^- salt.[10] Subsequently, the thermally more stable $N_5^+SbF_6^-$ was synthesized, and the crystal structure of $N_5^+Sb_2F_{11}^-$ was determined.[11]

Based on Born–Haber cycle considerations, the stability of an ionic salt is governed by three factors: the lattice energy, the electron affinity of the cation, and the first ionization potential of the anion. Furthermore, each ion must possess a sufficiently high activation energy barrier toward decomposition. For the successful combination of N_5^+ with a polynitrogen anion in the form of a stable salt, an anion with a high first ionization potential is required. Theoretical calculations from our and other[1,5,8,12–18] research groups predict that the unknown pentazolate anion (see Figure 1) has a first ionization potential and activation energy barrier toward decomposition that might be high enough for the formation of stable $N_5^+N_5^-$. As a result, the synthesis of the N_5^- ion is hotly pursued in numerous laboratories.

Although the existence and stability of substituted pentazole ring compounds have been demonstrated successfully more than 40 years ago by Huisgen and Ugi[19–22] and substituted pentazoles have been well characterized,[23–28] all attempts to prepare either the parent HN_5 molecule[29,30] or its anion, N_5^-, have so far been unsuccessful. Herein, we report the first experimental detection of this important anion.

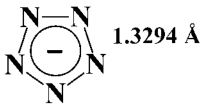

Figure 1. Minimum energy structure of the planar D_{5h} pentazolate anion from ref. [1], calculated at the CCSD(T)/aug-cc-pVTZ level of theory.

In our pursuit of the N_5^- ion, the following strategy was employed: a) the use of Ugi–Huisgen-type, substituted phenylpentazoles as starting materials; b) the transfer of maximum negative charge to the pentazole ring by the use of highly electron-donating substituents on the phenyl ring in *para*-position to the pentazolyl substituent to increase the aromaticity and stability of the pentazole ring, while at the same time weakening the connecting C–N bond; c) the selective cleavage of the C–N bond, while keeping the N–N bonds of the pentazole ring intact; and d) the use of an analytical method that is ideally suited for the generation and detection of anions. Similar approaches have been described, but attempts to cleave the C–N bond by ozonolysis were unsuccessful.[22,31] The reasons, outlined above, prompted us to choose *para*-hydroxy-[31] and *para*-dimethylamino-substituted phenylpentazoles[21] as starting materials and negative-ion electrospray ionization mass spectrometry (ESI-MS)[32–34] as the analytical tool.

The arylpentazoles and the corresponding diazonium salt precursors were prepared and characterized by multinuclear NMR spectroscopy.[24–28] For the cleavage experiments, these pentazoles were dissolved in strongly polar solvents, such as CH_3CN or a mixture of CH_3OH and CH_2Cl_2, and infused into the spectrometer's ion source at $10\,\mu L\,min^{-1}$ with a syringe pump.[35] In tandem mass spectrometry (MS-MS) experiments, the desired negative-ion peaks are mass-selected and subjected to product ion mass analysis following collision-induced dissociation (CID) at variable collision voltages using N_2 or Ar as the collision gas.

The most interesting results were obtained with *para*-hydroxyphenylpentazole in CH_3CN. An intense $[parent-H]^-$ base peak was observed at *m*/*z* 162 and mass-selected for subsequent MS-MS studies (Figure 2). It was found advantageous to add a base, such as pyridine, to the CH_3CN solutions to increase significantly the concentration of this *para*-pentazolylphenolate anion. Using a low collision voltage of −10 V, the *m*/*z* 162 ion $[OC_6H_4N_5]^-$ underwent stepwise N_2, N_2, and CO loss (see Scheme 1), giving rise to intense peaks with *m*/*z* values of 134 $[OC_6H_4N_3]^-$, 106 $[OC_6H_4N]^-$, and 78 $[C_5H_4N]^-$, respectively. The loss of the first N_2 molecule is due

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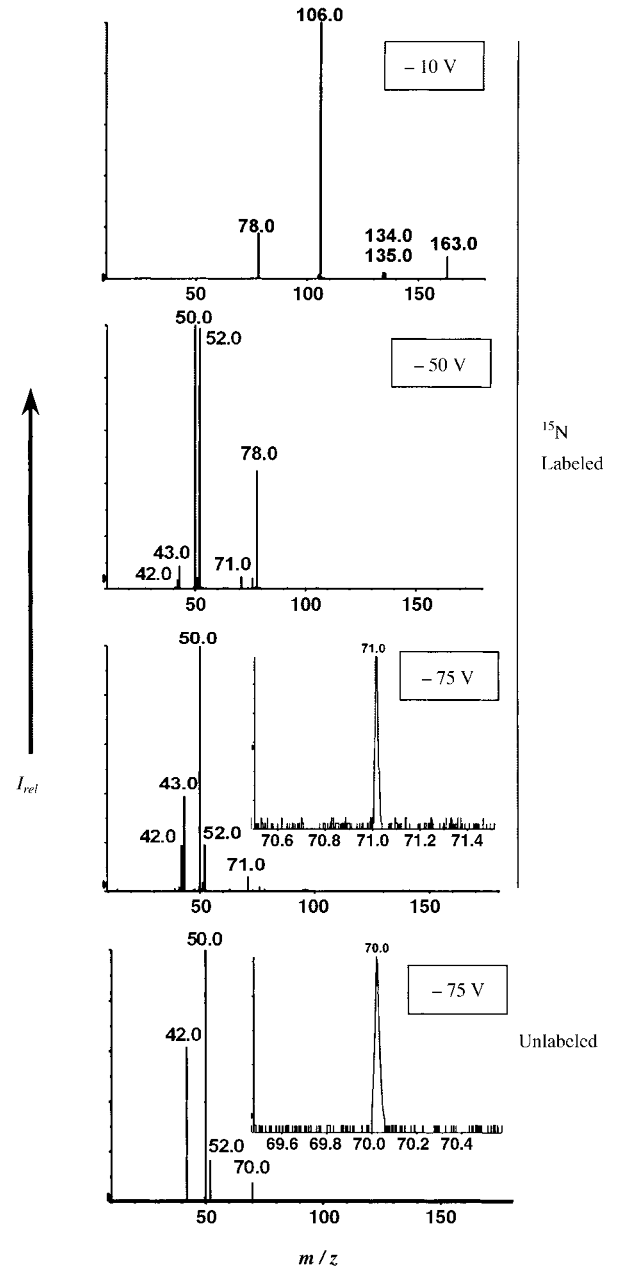
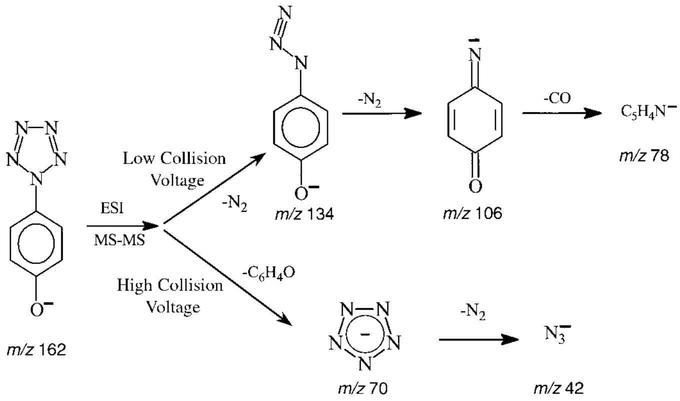


Figure 2. Negative ion, full-range CID mass spectra of the mass selected, ^{15}N labeled (*m/z* 163) and unlabeled (*m/z* 162) peaks due to $[OC_6H_4N_5]^-$ recorded at collision voltages of −75, −50, and −10 V. All spectra are multichannel spectra and the typical mass resolution and noise level are shown for the *m/z* 70 and 71 peaks in the inserts.

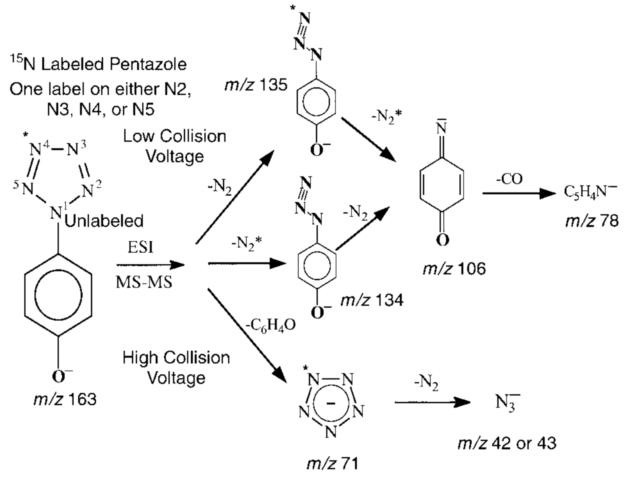
to the opening of the pentazole ring and produces the 4-azidophenolate ion. The second N_2 loss occurs from the azido group and generates the deprotonated quinone–imide, $[N{=}C_6H_4{=}O]^-$. This ion then undergoes CO extrusion giving a $[C_5H_4N]^-$ ion. Secondary fragmentation of the *m/z* 134 ion at a collision voltage of −30 V gave rise to intense peaks at *m/z* 78 $[C_5H_4N]^-$, 52 $[C_3H_2N]^-$, and 50 $[C_3N]^-$. The product ion spectra of the *m/z* 106 and 78 ions at collision voltages of −75 V gave only a very intense *m/z* peak at 50 $[C_3N]^-$.

Using high collision voltages of about −75 V for the CID of the *m/z* 162 ion, however, gave a very different fragmentation pattern. The only peaks observed were *m/z* 70, 52, 50, and 42. The *m/z* 70 peak can only be due to N_5^-, and the *m/z* 52 and 50 peaks are due to $[C_3H_2N]^-$ and $[C_3N]^-$, respectively, and, as shown above, result from the fragmentation of the $[C_5H_4N]^-$ ion. The *m/z* 42 peak is attributed to the azide anion, N_3^-. Since the 4-azidophenolate ion does not eliminate N_3^- but only N_2 (see above results for the MS-MS of the *m/z* 134 peak), the N_3^- ion can only come from the decomposition of an N_5^- ion. These results clearly demonstrate that at high collision voltages the pentazolate anion is formed. The fragmentation of the *m/z* 70 ion to N_3^- by loss of dinitrogen is in accord with the theoretically predicted decomposition pathway of N_5^-[8] and further supports its identification as N_5^-.



Scheme 1. ESI-MS-MS fragmentation of the mass-selected unlabeled 4-pentazolylphenolate anion at low and high collision voltages.

Additional evidence for the formation of the pentazolate anion was obtained by studies using ^{15}N labeled 4-hydroxyphenylpentazole. In these experiments, the 4-hydroxyphenyldiazonium salt was reacted with azide that was ^{15}N labeled in one terminal position. This resulted in a pentazole ring containing one ^{15}N label either in the N2, N3, N4, or N5 positions. Its ESI-MS spectrum (see Figure 2 and Scheme 2) at high collision voltages gave the *m/z* 71 peak expected for a singly labeled pentazolate anion. Furthermore, the observation of both an *m/z* 135 peak and an *m/z* 134 peak for the ^{15}N-labeled and unlabeled $[OC_6H_4N_3]^-$ ions, respectively, and of single *m/z* 106 and 78 peaks provides proof that the first two steps of the low collision voltage decomposition must involve



Scheme 2. ESI-MS-MS fragmentation observed for the mass-selected ^{15}N singly labeled 4-pentazolylphenolate anion at low and high collision voltages.

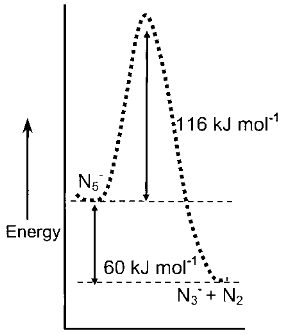


Figure 3. Activation energy barrier and decomposition enthalpy of the pentazolate anion calculated at the CCSD(T)/aug-cc-pVTZ level of theory.[8]

N_2 elimination, while the third step is the CO extrusion from the $[N{=}C_6H_4{=}O]^-$ ion.

The N_3^- and N_2 fragments have been calculated at the CCSD(T)/aug-cc-pVTZ level of theory to be 60 kJ mol^{-1} lower in energy than N_5^-, with an energy barrier of 116 kJ mol^{-1} to the cycloreversion (Figure 3).[8] These values indicate that bulk N_5^- salts should be manageable on a preparative scale. Furthermore, the formation of the N_5^- ion from a starting material containing a pentazole ring and the vibrational instability of open-chain N_5^-[8] establish beyond doubt that the observed N_5^- species must be the long-sought pentazolate anion.

In summary, our results constitute the first experimental detection of the pentazolate anion and demonstrate that in suitably substituted phenylpentazoles the C–N bond can be cleaved while leaving the pentazole ring intact. Since the substituted phenylpentazoles are easily accessible, this approach holds great promise for the bulk synthesis of N_5^- salts, and experiments in this direction are in progress in our laboratories. The pentazolate anion is the polynitrogen counterpart to the cyclopentadienide anion. It, therefore, has great potential as a pentahapto ligand for transition metals[13,36] and could lay the foundation for a field of purely inorganic metallocene-type chemistry. Our results on N_5^+[10,11] and N_5^-, together with the recent observations of the N_4 molecule as a metastable species with a lifetime exceeding one microsecond,[37] the observation of a new but ill-characterized polynitrogen species from a discharge generated nitrogen plasma,[38] and exciting progress in high nitrogen compounds,[28,39] indicate a bright future for experimental polynitrogen chemistry.

Experimental Section

Caution! Although no explosions were encountered in the course of this work, pentazoles can spontaneously lose nitrogen and should be handled by using appropriate safety precautions (small scale, face shield, leather gloves, protective clothing, and blast shields) until reliable safety data for these compounds become available.

The NMR spectra were recorded at 400.13 MHz (^1H), 100.62 MHz (^{13}C), 29.91 MHz (^{14}N), and 40.56 MHz (^{15}N) on a Bruker Avance 400 NMR spectrometer using solutions in a standard glass precision 5 mm tube at -10 ± 1 °C. The pentazoles are more stable in 1:1 mixtures of CD_2Cl_2 and CD_3CN than in other solvent mixtures that contain some CD_3OD. The following external references were used: ^1H, TMS (0 ppm), ^{13}C (CD_2Cl_2) 54.00 ppm or (CD_3CN) 1.39 ppm referenced to $(CH_3)_4Si$ (0 ppm); $^{14/15}N$, 1:1 mixture of 50 % ^{15}N labeled CD_3NO_2 and CH_3NO_2 (0 ppm).

The following arylpentazoles were prepared from the corresponding aryldiazonium salts and sodium azide in water at ice/salt-bath temperatures: *para*-R-C_6H_4-*cyclo*-N_5 (R = OH, O^- (for the counterions see below), OCH_3, OC_6H_5, $N(CH_3)_2$, O-C_6H_4-*cyclo*-N_5). For the preparation of ^{15}N-labeled pentazoles, singly labeled $Na^+[^{15}N{=}N{=}N]^-$ was used. In a typical preparation, 4-hydroxyaniline hydrochloride (2.4 mmol) was dissolved in water (≈ 15 mL) in a 50 mL beaker, cooled in an ice-salt bath, and slightly acidified with 1 N aqueous HCl. A cold solution of sodium nitrite (2.6 mmol) in water (~ 10 mL) was slowly added with vigorous stirring, resulting in the instant formation of 4-hydroxyphenyldiazonium chloride. A cold aqueous solution of sodium azide (2.5 mmol) was slowly added with stirring, resulting in spontaneous effervescence and the formation of a brownish solid. This solid was filtered off at 0 °C, washed with ice-cold water and then with cold methanol (−25 °C) twice, and finally dried in vacuo. 4-Hydroxyphenylpentazole was obtained in 20–35 % yield, contaminated with ≈ 10 % of 4-hydroxyphenylazide, and characterized by multinuclear NMR studies. For the preparation of the cesium or tetramethylammonium (TMA) salts, equivalent amounts of $N(CH_3)_4OH$ or $CsOCH_3$ in methanol, respectively, were added to the 4-hydroxyphenylpentazole solutions at −40 °C and these solutions were then allowed to warm slowly to −10 °C. Alternatively, the 4-pentazolylphenolate anion could be generated by adding pyridine to a solution of 4-hydroxyphenylpentazole in CH_3CN at −25 °C.

For the following ^1H NMR spectra, H_a and H_b correspond to the hydrogen atoms at the *ortho* and *meta* positions, respectively, relative to the pentazole-bearing carbon atom (C_{ipso}), and for the ^{13}C NMR spectra, the carbon in the *para* position, bearing the electron-releasing group, that is -OH or -O^-, is labeled as (C_p). In the case of the $^{14/15}N$ NMR spectra, N1 is the nitrogen atom in the pentazole ring that is bonded to the aryl group, N2/N5 are bonded directly to N1, and N3 and N4 are bonded to N2 and N5, respectively. In the corresponding azides, N1 refers to the nitrogen atom attached to the phenyl group and N3 is the terminal nitrogen atom. The ^{15}N-labeled azides were obtained by the thermal decomposition of the corresponding pentazoles at 25 °C, resulting in the 2 and 3 positions being labeled. Evolved N_2 gas can be observed at $\delta = -72$ ppm (literature value $\delta = -73$ ppm[25]). Spectral data, obtained for the compounds in either a 1:1 mixture of CD_2Cl_2 and CD_3CN or a mixture of other solvents are:

4-Hydroxyphenylpentazole: ^1H: $\delta = 7.02$ (H_b AB, 2H, $^3J_{H,H} = 9.2$ Hz), 7.95 ppm (H_a AB, 2H, $^3J_{H,H} = 9.2$ Hz); ^{13}C: $\delta = 126.4$ (s, C_i), 123.2 (s, C_o), 117.0 (s, C_m), 161.2 ppm (s, C_p); ^{14}N: $\delta = -81.6$ ppm (br, N1); ^{15}N: $\delta = 4.2$ (s, N2/N5), −27.6 ppm (s, N3/N4). Literature values[31]: ^1H: $\delta = 7.04$ (d, H_b, $J =$ 6.4 Hz), 8.01 ppm (d, 2H, $J = 6.5$ Hz). The previously reported coupling constant of about 6.4 Hz appears to be incorrect.

4-Hydroxyphenylazide: ^1H: $\delta = 6.75$ (H_b AB, 2H, $^3J_{H,H} = 8.8$ Hz), 6.83 ppm (H_a AB, 2H, $^3J_{H,H} = 8.8$ Hz); ^{13}C: $\delta = 131.5$ (s, C_i), 120.4 (s, C_o), 116.9 (s, C_m), 155.3 ppm (s, C_p), ^{15}N: $\delta = -136.6$ (s, N2), −149.1 ppm (s, N3); ^{15}N: $\delta =$ −141.2 (s, N2), −152.5 ppm (s, N3). Literature values [40]: ^1H: $\delta = 6.83$ (H_b d, 2H, $J = 9$ Hz), 6.92 ppm (H_a d, 2H, $J = 9$ Hz).

Cesium/TMA 4-pentazolylphenolate: ^1H: $\delta = 6.66$ (H_b AB, 2H, $^3J_{H,H} =$ 7.2 Hz), 6.74 ppm (H_a AB, 2H, $^3J_{H,H} = 7.2$ Hz); ^{13}C: $\delta = 122.8$ (s, C_i), 120.7 (s, C_o), 119.9 (s, C_m), 172.1 ppm (s, C_p); ^{14}N: $\delta = -81.1$ ppm (br, N1); ^{15}N: $\delta = 1.9$ (s, N2/N5), −29.7 ppm (s, N3/N4).

Cesium/TMA 4-azidophenolate: ^1H: $\delta = 6.61$ (H_b AB, 2H, $^3J_{H,H} = 6.8$ Hz), 7.95 ppm (H_a AB, 2H, $^3J_{H,H} = 6.8$ Hz); ^{13}C: $\delta = 125.1$ (s, C_i), 120.2 (s, C_o), 120.1 (s, C_m), 165.4 ppm (s, C_p); ^{15}N: $\delta = -135.7$ (s, N2), −150.9 ppm (s, N3). Literature values [31]: CD_3OD (CD_2Cl_2): ^1H: $\delta = 6.59$ (6.47) (d, 2H, $J = 9.0$ (8.8) Hz), 6.69 ppm (6.65) (d, 2H, $J = 9.0$ (8.8) Hz); ^{15}N (CD_2Cl_2): $\delta =$ −131.7 (s, 1N), −148.4 ppm (s, 1N). In the literature data,[31] no assignments to the individual nitrogen atoms were given, and due to the nuclear Overhauser effect, the ^{15}N signals cannot be integrated.

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[35] The MS and MS-MS experiments were carried out on a PE Sciex Qstar Pulsar quadrupole/time-of-flight tandem mass spectrometer (Applied Biosystems, Foster City, California) operated with a room temperature turbo-ionspray source and using Analyst QS data acquisition software. The samples were dissolved in a 1:10 mixture of pyridine and acetonitrile, and infused via a syringe pump at 5 $\mu L\,min^{-1}$. The instrument was run in the negative ion mode with the capillary voltage at -4500 V and the dissociation potential (source CID) at -20 V. The TOF Pulser frequency was set for 5 kHz with a 1 s accumulation time per spectrum. Data were aquired over the mass range of 10–600 *m*/*z* for MS acquisition. In the MS-MS mode, the quadrupole mass analyzer was set to pass the parent ion at unit mass resolution. N_2 or Ar was used as the collision gas. The gas settings were as follows: source nebulizer gas = 30, desolvation gas = 0, curtain gas = 25, collision gas = 5.

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First Synthesis of Optically Pure Propargylic *N*-Hydroxylamines by Direct, Highly Diastereoselective Addition of Terminal Alkynes to Nitrones**

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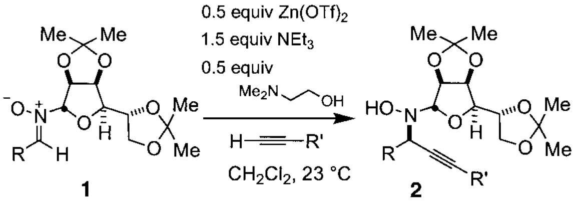
Dedicated to Professor Andrea Vasella

Optically active propargylic alcohols serve as versatile building blocks for asymmetric synthesis.[1] The corresponding propargylic amines or *N*-hydroxylamines could also serve in a similar capacity were it not for the fact that general, useful methods that provide access to such compounds are not available.[2] The latter are not only synthetic equivalents of the former, but also are amenable to further elaborations, such as cyclization to afford isoxazolines.[3] Herein, we document the first general method for the preparation of optically active propargylic *N*-hydroxylamines [Eq. (1), Tf = trifluoromethanesulfonyl]. The method prescribes the use of nitrones which are conveniently prepared through condensation of the corresponding aldehydes and a mannose-derived glycosidic *N*-hydroxylamine.[4] Reaction of the nitrones with a broad range of terminal acetylenes in the presence of Zn^{II} ions, 2-dimethylaminoethanol, and NEt_3 gives adducts in high diastereoselectivity and yield. Following its addition, the auxiliary is easily removed by treatment of the products with *N*-hydroxylamine hydrochloride; a process which allows for re-isolation and reuse of the auxiliary. The method we document should find use in medicinal chemistry to provide access to a new class of useful building blocks for the asymmetric synthesis of pharmacologically important compounds.



1 2 (1)

R: aliphatic, aromatic diastereoselectivity: 92:8 to 98:2

There are scant, scattered reports that document diastereoselective additions to chiral nitrones. These typically involve additions of Grignard or organolithium compounds

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