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Review

Grignard reagent formation

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Abstract

It is likely that reactions of magnesium metal with organic halides RX in ether solvents are typical metallic corrosions in which the stabilization of Mg^{2+}, substantially through its coordination by the solvent, drives its loss from the metal and consequently the reductions of RX and reaction intermediates such as $R^\bullet$ at the metal surface. Although alkyl halides form Grignard reagents through non-chain mechanisms in which intermediate radicals diffuse in solution, very small amounts of radical isomerization occur in Grignard reactions of certain vinyl and aryl halides, even when intermediate radicals $R^\bullet$ would isomerize very rapidly. This suggests a dominant non-radical mechanism for these vinyl and aryl halides or a mechanism in which intermediate radicals $R^\bullet$ have extremely short lifetimes. Since the former seems more likely, a dianion mechanism, through a transition state $[RX^{2-}]^\ddagger$, is proposed. Surface studies of polycrystalline Mg show that the “oxide” layer is mostly $Mg(OH)_2$ and that it is mechanically passivating. In the absence of promoters, Grignard reactions occur very slowly until enough RX has seeped to the magnesium surface and reacted there to undercut and cause the $Mg(OH)_2$ layer to flake off.

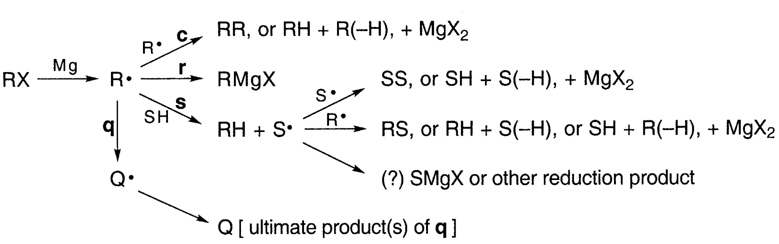
Keywords: Grignard reagents; Magnesium; Corrosion; Rreduction; Alkyl halide; Cyclopropyl halide; Vinyl halide; Aryl halide; Magnesium oxide; Magnesium hydroxide

1. Introduction

In a “Grignard reaction,” a Grignard reagent RMgX is formed in an appropriate solvent SH, usually diethyl ether (DEE) or tetrahydrofuran (THF), from magnesium metal Mg and an organic halide RX. By-products may include RR, RH, R(–H), RS, SS, S(–H), and MgX_2. During the past decade the mechanisms of Grignard reactions have been reviewed by Hamdouchi and Walborsky (HW) [1] and by Garst and Ungváry (GU) [2]. The early history of the subject is reviewed by Kharasch and Reinmuth (KR) [3].

HW and GU agree on the generally accepted proposition that “Grignard radicals” $R^\bullet$ are intermediates along a pathway **R** that is sometimes exclusive or major.

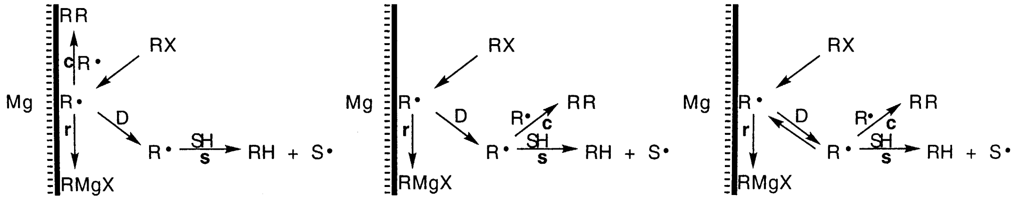
Pathway R



Along **R**, an intermediate radical $R^\bullet$ suffers reduction (**r**), coupling/disproportionation (**c**), attack on the ether solvent (**s**), or another first-order or pseudo-first-order reaction (**q**), such as isomerization or trapping, accounting for the formation of RMgX and by-products. Chain reactions are ruled out by radical trapping and other results (GU, 235).

Concerning details, HW and GU differ markedly. HW accept the hypothesis that almost all $R^\bullet$ remain adsorbed at the magnesium surface Mg_Z. GU reject it.

HW argue qualitatively for a mechanism like **AAD**. It is “**AAD**” because along the channels **rcs**, in that order, $R^\bullet$ remains adsorbed (“**A**”) at Mg_Z for **r** and **c** but diffuses in solution (“**D**”) for **s**.



AAD ADD DDD

Table 1
Isomerization in RMgX and the adequacy of **DDD**

Organic group	Extent of isomerization	Is **DDD** adequate?
Alkyl	100% (?)	Yes
Cyclopropyl	80–90%	As major pathway, at least
Vinyl	Down to 5%	Only if $R^\bullet$ is very short-lived
Aryl	Down to 1%	Only if $R^\bullet$ is very short-lived

Other possibilities include **ADD** and **DDD**. **DDD** is favored by GU.

From assumptions about the behaviors of radicals diffusing near a reactive surface, HW argue that certain data are not consistent with **DDD**. GU respond that these assumptions are not valid and that the data cited by HW are, in fact, consistent with **DDD**. For reactions of cyclopropyl bromide, the data are not only consistent with **DDD** but also inconsistent with **AAD** and **ADD** (GU, 216–218) [4].

If this were the whole story, the matter might be considered settled. However, results from isomerization studies complicate the picture.

Some intermediate radicals $R^\bullet$ can and do isomerize.

$$R^\bullet \xrightarrow{k_Q} Q^\bullet$$

At infinite dilution, where radical coupling is not important, the extents of isomerization are determined by the values of the isomerization rate constant k_Q and the lifetimes of $R^\bullet$ as limited by the reactions that compete with isomerization, **r** and **s**. Sometimes there is such a low extent of isomerization in RMgX that DDD can account for it only if $R^\bullet$ has an extremely short **r**-limited lifetime τ_R, 10^{-10} s or less (GU, 218–219). In contrast, kinetic analyses of other aspects of the product distributions for these or similar cases indicate a longer life-time, $\tau_R \approx 10^{-7}$ s.

Broadly, cases are categorized by the nature of the organic group R, Table 1.

Two major questions are raised.

(1) Do intermediate radicals $R^\bullet$ remain adsorbed at Mg_Z?
    For alkyl and cyclopropyl cases, it is now clear that $R^\bullet$ diffuses in solution near Mg_Z. Although there is no specific evidence for vinyl and aryl cases, there is no reason to believe that they differ in this way from alkyl and cyclopropyl.

(2) Why is there partial retention of configuration?
    This question has yet to be answered definitively. There must be a pathway **X** along which
    (a) some intermediate radicals $R^\bullet$ have such extremely short lifetimes that they retain their configuration or
    (b) $R^\bullet$ is not intermediate and R retains its configuration.

Pathway **X** is not yet defined.

These issues deal with the organic mechanism, which traces R from RX to RMgX. The inorganic mechanism traces Mg from the metal into RMgX. Although it has been little studied, analogy with other metallic corrosion reactions allows plausible speculation.

The induction period is another aspect of the mechanism. Typically, Grignard reactions don't start immediately on mixing reagents. Instead, initiation takes a noticeable time. Why? What happens during the induction period?

At least part of the answer may involve the "oxide" layer that coats Mg_Z as Mg is received, "out of the bottle," or after it is exposed to the atmosphere. The "oxide" layer consists primarily of $Mg(OH)_2$ (GU, 255) [5]. This layer gives magnesium a dull appearance, but in a Grignard reaction that is underway Mg_Z often gains a metallic luster.

This review is prompted by three considerations. First, HW and GU attempt to be comprehensive and very detailed. We are more selective—see HW and GU for more examples, details, and references. Second, new developments are considered. Third, recent results on the nature of the "oxide" layer and its interactions with various agents, some of which are typically used to "activate" Mg in Grignard reactions, are reviewed here for the first time.

JFG is the author of Section 2, "the Grignard reaction", and MPS is the primary author of Section 3, "the oxide layer and the induction period".

2. The Grignard reaction

2.1. Solvents

Grignard reagents can be prepared in a variety of aprotic solvents, including tertiary amines. Even so, one of two ethers, DEE and THF, is almost always used in practice. These have dielectric constants 4.3 and 7.4, respectively.

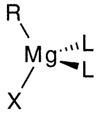
In dioxane, dielectric constant 2.2, reactions often fail to initiate. Further, MgX_2 is insoluble. Pouring a solution of RMgX into dioxane will precipitate MgX_2, leaving R_2Mg in solution.

1,2-Dimethoxyethane (DME, glyme), dielectric constant 7.2, is useful but sometimes there are solubility problems. In addition, the high water solubility of DME can hamper workup procedures when it is desired that the aqueous and organic layers separate cleanly.

For large-scale industrial process, the volatile and flammable ethers DEE and THF present safety hazards. "Butyl diglyme", $CH_3CH_2CH_2CH_2OCH_2CH_2OCH_2CH_2$-$OCH_2CH_2CH_2CH_3$, is an excellent solvent for Grignard reagent preparation and reactions [6]. Its flash point is 118 °C (DEE: −45 °C; THF: −14 °C) and its water solubility is very low. Its high boiling point 256 °C (DEE: 34 °C; THF: 66 °C) and flash point allow higher reaction temperatures than can be achieved with DEE or THF, and these can result in the initiation of Grignard reactions that are resistant in the latter solvents.

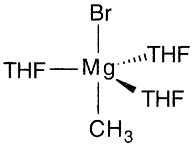
2.2. Coordination

For Grignard reagents, other organomagnesium compounds, and magnesium halides, a number of crystal structures have been determined [7,8]. Many Grignard reagents RMgX and diorganylmagnesium compounds R_2Mg crystallize with four-coordinate Mg at the center of a distorted tetrahedron:

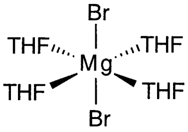


X = halogen
L = ether or other coordinating ligand

If the ligands can fit, Mg may be five-coordinated:



Magnesium bromide has been crystallized from THF in both 4-coordinate and 6-coordinate forms:



These structures emphasize the role of the coordinating solvent in stabilizing Grignard reagents and magnesium halides.

Solvent coordination to Mg^{2+} must also provide much of the thermodynamic driving force for reductions by Mg, including those of RX to form Grignard reagents in ether solvents. In Grignard reagent formation, Mg passes from a metallic state, where it is essentially unsolvated, into an essentially ionic state, Mg^{2+}, where it is strongly coordinated by ether solvent molecules as well as ligands R and X:

$$RX + Mg \overset{nL}{\rightarrow} RMgL_nX, \quad L = \text{coordinating solvent molecule}$$

In any particular case, many details of structure determine the position of the Schlenk equilibrium:

$$2RMgX \rightleftarrows R_2Mg + MgX_2$$

Similar details determine the positions of other equilibria, involving aggregation, complex ion formation, and solubilities of various species. Among these details are steric effects operating in the layers of coordination to Mg^{2+}. Although modern computational tools provide, in principle, means for understanding these and other effects on Grignard equilibria, no such understanding has been realized.

2.3. Corrosion, $^\bullet MgX$, and $RMg^\bullet$

A naive formulation of a radical mechanism for Grignard reactions invokes an intermediate $^\bullet MgX$:

$$RX + Mg \rightarrow R^\bullet + {}^\bullet MgX \rightarrow RMgX$$

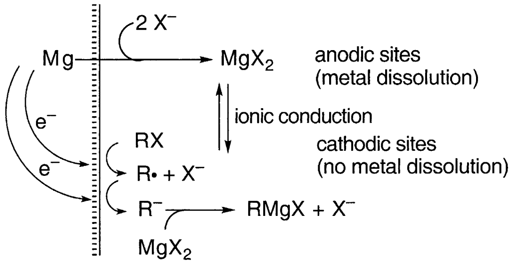
Despite the popularity of this scheme in the literature, there is no evidence supporting it. Indeed, the evidence is against it. CIDNP net effects arise from reactions of radicals with differing g values [9–12]. They would be expected if RMgX were formed from pairs $[R^\bullet\ {}^\bullet MgX]$, but in fact only multiplet effects, arising from pairs $[R^\bullet\ R^\bullet]$, are found [13].

There is no evidence of an intermediate $RMg^\bullet$, a possible product of a reaction of $R^\bullet$ with Mg:

$$R^\bullet + Mg \rightarrow RMg^\bullet$$

Typical invocations of $^\bullet MgX$ or $RMg^\bullet$ as intermediates do not explain how Mg leaves the metal lattice. The idea seems to be that it is simply plucked out by RX or $R^\bullet$. While this is possible, it does not conform to the usual mechanism of metallic corrosion.

Absent contraindicating evidence, it seems prudent to speculate that Grignard reactions follow mechanisms that are similar to other metallic corrosions:



Here, the reduction of RX and $R^\bullet$ are driven by the dissolution of Mg^{2+} from Mg at anodic sites. If no reductions occurred, Mg would be left with excess electrons, that is, it would be best represented as Mg^{-f}, where f is some small value. This kind of dissolution of metal ions is responsible for the familiar half-cell potentials of metals in contact with water.

In water, ionic conduction is facile and the anodic and cathodic sites of a corrosion process can be well separated, even on a macroscopic scale. When the liquid is much less polar, e.g., ethers, ionic conduction is slow and the anodic and cathodic sites must be close together, perhaps even on the molecular scale. Otherwise, the corrosion reaction would soon stop due to the development of unlike charge separation.

Typically, the corrosion of a metal follows geometric patterns determined by its lattice structure. Atoms lost to solution tend to be those surface atoms that are least bound to the lattice, corner atoms, for example. As this happens repeatedly, corrosion proceeds along crystal planes. This has been observed for Mg in Grignard reactions by both light [14] and atomic-force microscopy (GU, 253–255). In this way, Grignard reactions conform to other metallic corrosions.

Observations of patterned corrosion rule out nonselective plucking. However, selective plucking remains viable. Even so, there is no reason to suspect that Grignard reactions are not typical (nonplucking) metallic corrosions.

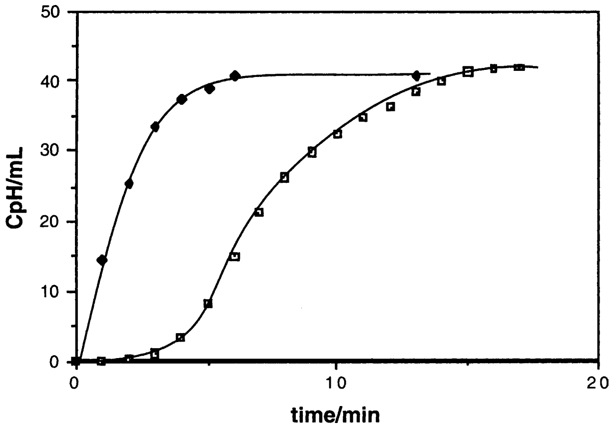


Fig. 1. Progress of reaction as a function of elapsed time, measured by volume of cyclopropane evolved, for the reaction of magnesium turnings with cyclopropyl bromide in DEE under an atmosphere of cyclopropane at 37 °C [15]. Open squares: $[MgBr_2]_0 = 0$. Closed diamonds: $[MgBr_2]_0 = 0.18\,M$. $[CpBr]_0 = 0.18\,M$.

2.4. Polar solutes

It has been long known that MgX_2 catalyzes Grignard reactions (KR, 8–11). Thus, the presence of $MgBr_2$ in DEE can eliminate the induction period that is otherwise observed in the Grignard reaction of cyclopropyl bromide, CpBr [15]. [*Note*: Here and throughout, "Cp" represents cyclopropyl, not cyclopentadienyl.] When $MgBr_2$ is absent initially, this reaction exhibits an "S"-shaped progress profile that is characteristic of autocatalysis (Fig. 1).

Since $MgBr_2$ accompanies other by-products, it may be the autocatalytic product. However, since other polar additives can also promote reaction (GU, 257–259), RMgBr could also contribute.

Agents such as I_2 and $BrCH_2CH_2Br$ are commonly used to promote Grignard reactions. It has been proposed that these agents activate Mg_Z by etching it in reactions with it. Specific tests of the etching hypothesis indicate that it is not a factor [15,16]. Including MgI_2 or $MgBr_2$ in the solvent initially has the same or better effect than including I_2 or $BrCH_2CH_2Br$, whether or not the Mg_Z used has been previously "etched".

Reluctant reactions have been initiated by "entrainment", that is, by including a reactive alkyl halide in the reaction mixture along with the reluctant halide whose Grignard reagent is sought (KR, 38–45) [17,18]. It now appears that entrainment is merely a method of introducing RMgX and MgX_2, polar solutes that promote the reaction of the reluctant halide (GU, 259).

The specific mode of action by which polar solutes promote Grignard reactions has not been identified.

2.5. Alkyl halides

2.5.1. Evidence of alkyl radical intermediates

The evidence of alkyl radical intermediates is overwhelming. It includes the facts that (a) by-products RR and RH + R(–H) are formed in characteristic radical coupling/disproportionation ratios; (b) characteristic radical isomerizations occur; (c) when radical traps are present, trapping products are formed at the expense of RMgX; and (d) RMgX and by-products exhibit CIDNP. Observations of solvent attack would also be evidence of radical intermediates, but little if any solvent attack is found in alkyl cases.

KR review the early history of hypotheses about intermediate radicals $R^{\bullet}$. It was speculated in the 1920s that Grignard reactions are radical reactions initiated by ${}^{\bullet}MgX$, formed from Mg and MgX_2. By 1954 pathway **R** was generally accepted, primarily because reactions of RMgX with RX had been found to be too slow, in most cases, to account for by-products RR and RH + R(–H), leaving radical coupling/disproportionation as the most plausible alternative.

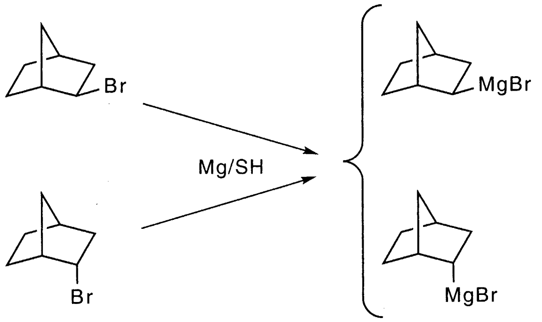
$$RMgX + RX \rightarrow RR + [RH + R(\text{–}H)] \quad \text{(usually insignificant)}$$

The ratios of RR to RH or R(–H) match those expected for reactions of primary, secondary, and tertiary radicals [19–21] and are very different from those that characterize SN2/E2 reactions. This is important because otherwise RR and RH + R(–H) could arise from the reaction with RX of an intermediate carbanion R^- or carbanionoid species, for which there is evidence [22–24]:

$$RX + Mg \rightarrow \text{“}R^-\text{”} + RX \rightarrow RR + [RH + R(\text{–}H)]$$

In principle, Grignard reactions of optically active alkyl halides could be investigated. A racemic product could reflect the racemization of $R^{\bullet}$. Racemic products *are* found in such studies (HW, 155–159), but this could be due to the racemization of RMgX, which has not been excluded.

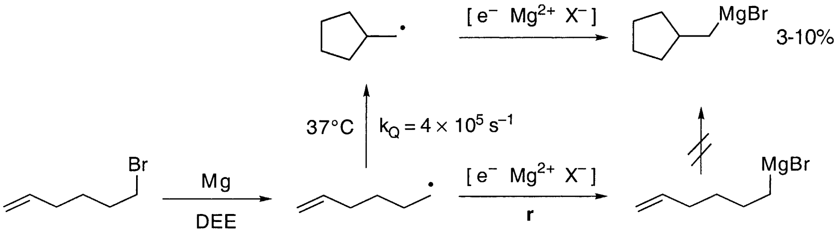
Although *exo-* and *endo*-norbornylmagnesium bromides adequately maintain their configurations, the two groups that have investigated the reactions of *exo-* and *endo*-norbornyl bromides obtained contradictory results. One obtained the same [25], the other different [26], product distributions from the isomeric reactants. This needs clarification.



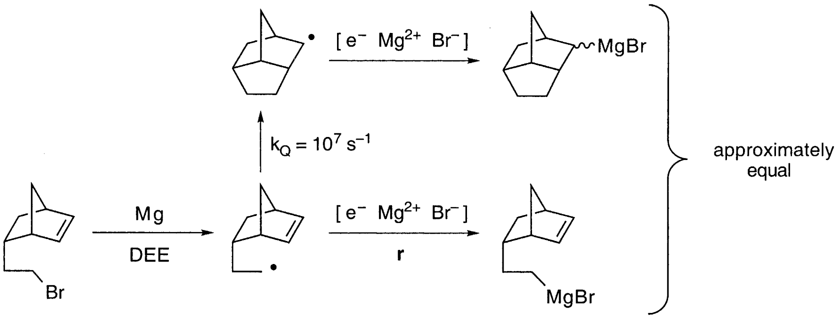
Intermediate primary alkyl radicals are trapped, inefficiently (~25%) by DCPH [27] and efficiently (up to 95%) by $TMPO^{\bullet}$ [20,28]. The high efficiency of trapping by $TMPO^{\bullet}$ suggests that **R** is the exclusive pathway.

CIDNP is found in RMgX. In the reaction of magnesium with ethyl iodide in di-*n*-butyl ether, conducted in an NMR tube, and E/A multiplet effect is seen in the NMR signal of the CH_2 of CH_3CH_2MgI [13]. This is the expected phase for CH_3CH_2MgI if is formed from radicals $CH_3CH_2^•$ that have escaped from random-spin pairs $[CH_3CH_2^•\ ^•CH_2CH_3]$, which result when independently diffusing radicals encounter one another [9–12].

Cyclizing radical probes such as 5-hexenyl indicate radical intermediates [29]. Grignard reactions of 5-hexenyl halides give (cyclopentylmethyl)magnesium halides in yields of 3–10%. (5-Hexenyl)magnesium halides cyclize too slowly to account for these observations.



A norbornenylethyl radical probe whose cyclization rate constant k_Q has a value of $\sim 10^7\ s^{-1}$ gives nearly equal yields of cyclized and uncyclized Grignard reagent [30]:



Since cyclization and **r** are in direct competition, this suggests that the **r**-limited lifetime τ_R of $R^•$ is $\sim 10^{-7}$ s [31].

2.5.2. *AAD*

In Grignard reactions, by-products of c often dominate over those of **s**. Thinking it unlikely that a methyl radical could leave Mg_Z, diffuse in solution, and undergo c without more s than is found, KR (63) suggest that intermediate radicals $R^•$ might remain adsorbed at Mg_Z with sufficient mobility there to encounter one another and undergo **c**. This is **AAD**.

However, KR (63) also comment, "Whether or not free radicals ever actually escape into the body of the solution in significant quantities is a question that can scarcely be answered with any assurance". They go on to suggest (KR, 64) that "less reactive radicals (i.e., those incapable of abstracting hydrogen atoms from the solvent) may be expected to accumulate in the system until their reactions with each other or with the Grignard reagent assume significant proportions". Included in this group, apparently, are alkyl radicals other than methyl. The corresponding mechanisms would be **ADD** and **DDD**.

One who accepts the KR position for methyl might ask, "Why should other alkyl radicals be different?" Finding no satisfactory reason, that person might favor AAD for Grignard reactions of all alkyl halides, assuming that the accumulation Grignard radicals "in the system," as described by KR, is actually at Mg_Z.

2.5.3. *DDD*

Lawrence and Whitesides noted that Grignard radicals derived from typical alkyl halides act much like the same kinds of radicals in solution [28]. In addition to being trappable, like "solution" radicals, they undergo characteristic radical isomerizations, give rise to CIDNP, and couple and disproportionate in characteristic ratios [19–21]. It is unlikely that adsorption would not affect these ratios. These facts strongly suggest diffusing Grignard radicals.

Intermolecular trapping suggests **DDD**. It is generally believed that trapping occurs mainly in solution, not at Mg_Z. Therefore, observations of both inefficient trapping by DCPH and highly efficient trapping by $TMPO^•$ point to diffusing intermediates $R^•$.

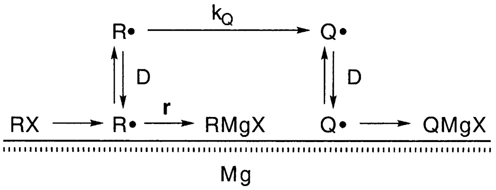
Although HW (203–205) accept the DCPH results, they criticize the $TMPO^•$ experiments on the grounds that the apparent trapping product could arise in reactions other than that of $R^•$ with $TMPO^•$. However, the authors of the $TMPO^•$ studies took great pains to find conditions under which other reactions were suppressed [20]. Further, since trapping by DCPH is expected to be less efficient because it is less reactive than $TMPO^•$, there is no apparent reason to suspect that the two sets of trapping results are not mutually consistent.

Where there is no significant **s**, as for Grignard reactions of alkyl halides, it is difficult to conceive of a test of **AAD**, which supports few definite predictions because the behaviors of adsorbed radicals are unspecified and unknown. Supplementary ad hoc hypotheses can bring it into agreement with many results that it does not actively predict (HW, GU) [32]. However, some of these ad hoc hypotheses are mutually contradictory.

In contrast, **DDD** has considerable predictive power. It can be tested through kinetic analyses of product distributions. The success of its predictions for reactions of alkyl halides leaves **DDD** as the preferred theory.

In the following, Mg_Z is treated as an infinite plane of uniform reactivity. Consequently, the only significant diffusion of $R^\bullet$ is in the direction x, perpendicular to Mg_Z.

For Grignard radicals $R^\bullet$ that can undergo first-order isomerizations to $Q^\bullet$, how does **DDD** predict that the extents of $Q^\bullet$ formation will vary with k_Q, other factors being kept constant?



A naive answer might assume that **r** could be represented as a first-order reaction, **r** rate $= \tau_R^{-1}[R^\bullet]$. Then QMgX/RMgX would be directly proportional to k_Q, which is incorrect:

$$\frac{\mathrm{QMgX}}{\mathrm{RMgX}} = k_Q \tau_R \quad \text{(incorrect)}$$

The flaw is that the t(time)-dependent survival probability $S(t)$ of a diffusing $R^\bullet$ undergoing **r** (only) is not an exponential decay:

$$S(t) = e^{-t/\tau_R} \quad \text{(incorrect for diffusing Grignard radicals } R^\bullet\text{)}$$

Instead, the mixing of diffusion in solution with reaction at the surface results in a complex law of decay,

$$S(t) = \exp(u)\,\mathrm{erfc}(u^{1/2}), \quad u = \frac{\kappa^2 t}{D} \quad (\mathrm{GU},\ 270)$$

where κ is the heterogeneous rate constant for **r** and $[R^\bullet]_0$ is the solution concentration of $R^\bullet$ at Mg_Z ($x = 0$):

$$\mathbf{r}\ \text{flux}\ (\mathrm{mol\,cm^{-2}\,s^{-1}}) = \kappa[R^\bullet]_0$$

Consequently, it is not trivial to obtain the expression relating q [QMgX/RMgX] to k_Q, even when **c** is neglected. (No **c** would occur at infinite dilution, so this is the "infinite-dilution" case.) The correct result is the "square-root law" (GU, 202) [31]:

$$q = \frac{\mathrm{QMgX}}{\mathrm{RMgX}} = (k_Q \tau_R)^{1/2} \quad \text{(square-root law)}$$

If τ_R is constant through a series of cases, then the yield ratio will be proportional to the square root of k_Q. Perhaps, it is relevant that diffusive spread follows a $t^{1/2}$ law and that the units of k_Q are inverse time.

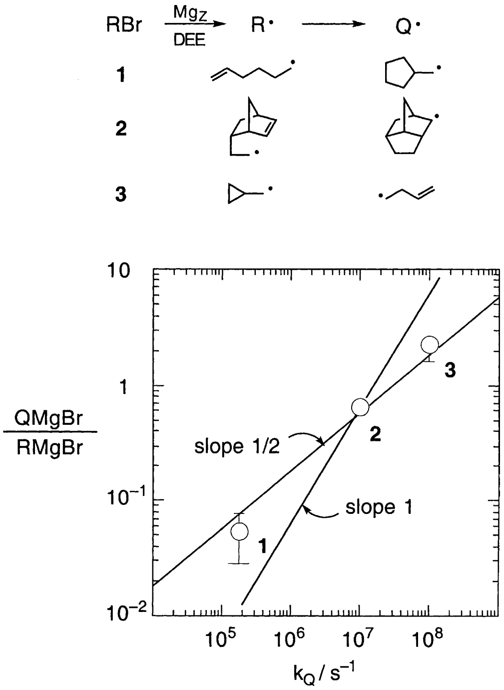


Fig. 2. Test of the square-root law, QMgX/RMgX $= (k_Q\tau_R)^{1/2}$, for Grignard reactions of primary alkyl bromides in DEE at ~40 °C. The axes are logarithmic and the lines are drawn with slopes 1/2 and 1 (based on values of the logarithms). Point 1 is shown here as plotted originally ($k_Q = 1.8 \times 10^5\ \mathrm{s^{-1}}$) [33]. A refined estimate of the value of k_Q for the 5-hexenyl radical is $4.4 \times 10^5\ \mathrm{s^{-1}}$ [34].

A log–log plot will have slope 1/2:

$$\log\left[\frac{\mathrm{QMgX}}{\mathrm{RMgX}}\right] = \frac{1}{2}\log k_Q + \frac{1}{2}\log \tau_R$$

This square-root law was first tested, Fig. 2, for three cases of isomerizing primary alkyl Grignard radicals with known values of k_Q (5-hexenyl: $1.8 \times 10^5\ \mathrm{s^{-1}}$ [33] (see also [34]); norbornenylethyl: $1 \times 10^7\ \mathrm{s^{-1}}$ [30]; cyclopropylcarbinyl: $1 \times 10^8\ \mathrm{s^{-1}}$ [33]).

The fit is satisfactory, much better than to a line of slope 1, which is predicted by the naive assumption of a first-order competition, QMgX/RMgX $= k_Q\tau_R$. A better fit for **1** is obtained when the occurrence of **c** is taken into account [35].

Whitesides collected and established a number of additional examples in which first-order or pseudo-first-order processes of Grignard radicals compete with their reduction to RMgX [25]. Fig. 3 shows that observed fractional yields A of RMgX agree reasonably with those predicted by the square-root law.

Although alkyl cases (solid ovals) fit well, cyclopropyl, vinyl, and aryl cases (open ovals) do not, suggesting that the latter have different values of κ or follow different mechanisms from the former.

Results of trapping experiments using DCPH and $\mathrm{TMPO}^\bullet$ can be plotted analogously, treating trapping as pseudo-first-order (Fig. 4).

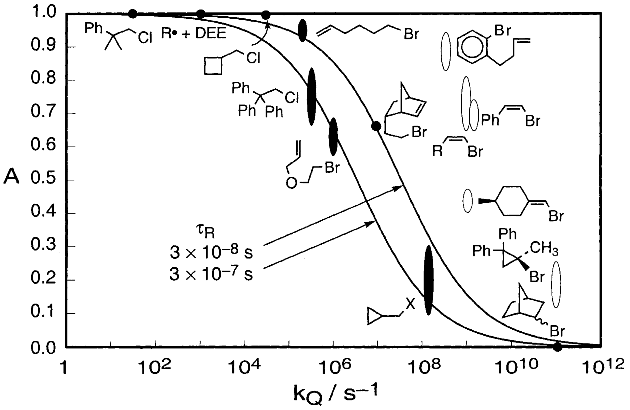


Fig. 3. Fractional yield A of RMgX as a function of the rate constant k_Q of a first-order or pseudo-first-order reaction of R$^\bullet$ that competes with its reduction to RMgX. The plotted curves represent the square-root law, $A = \mathrm{RMgX}/[\mathrm{RMgX} + \mathrm{Q}] = 1/[1 + (k_Q\tau_R)^{1/2}]$, where Q is the product of the reaction (isomerization, solvent attack) governed by k_Q. This plot is a modified version of one given by Root et al. [25].

Both sets of trapping data, DCPH and TMPO$^\bullet$ are consistent with the square-root-law correlation of Fig. 3, indicating that they are equally valid traps, despite the reservations, mentioned above, expressed by HW.

Exact solutions of the equations of diffusion-reaction have been obtained for **DDD** in an idealized case in which rate parameters (κ, k_S, k_C) for similar reactions have the same value [36]:

$$\mathrm{RX} \xrightarrow[\mathrm{Mg_Z}]{v} \mathrm{R}^\bullet, \quad v\,(\mathrm{mol\,cm^{-2}\,s^{-1}}) = \text{flux of formation of } \mathrm{R}^\bullet$$

$$\mathrm{R}^\bullet \overset{k_Q}{\rightarrow} \mathrm{Q}^\bullet$$

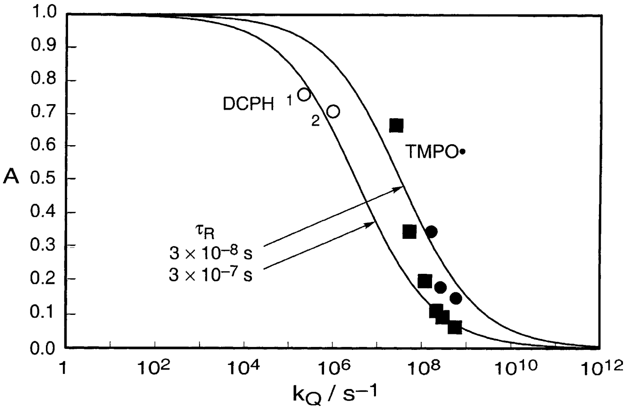


Fig. 4. Grignard-radical trapping by DCPH and TMPO$^\bullet$. k_Q is the pseudo-first-order rate constant for radical trapping, that is, $k_Q = k_T$ [trap]. The curves are identical with those of Fig. 3. Open circles: trap = DCPH. Closed symbols: trap = TMPO$^\bullet$: (1) *n*-octyl bromide/DCPH/THF/22 °C [27]; (2) 5-hexenyl bromide/DCPH/THF/22 °C [27]. Closed squares: cycloheptyl bromide/TMPO-/DEE/*t*-amyl alcohol (5.0 M)/LiBr (0.05 M)/20 °C [20]. Closed circles: cyclopentyl bromide/TMPO$^\bullet$/DEE/*t*-butyl alcohol (~0.8 M)/34 °C [28].

$$\mathrm{R}^\bullet, \mathrm{Q}^\bullet \xrightarrow[\mathrm{SH}]{k_S} \mathrm{RH}, \mathrm{QH} + \mathrm{S}^\bullet$$

$$\mathrm{R}^\bullet, \mathrm{Q}^\bullet, \mathrm{S}^\bullet \overset{\kappa}{\rightarrow} \mathrm{RMgX}, \mathrm{QMgX}, \mathrm{SMgX},$$

$$\kappa\,(\mathrm{cm\,s^{-1}}) = \text{heterogeneous rate constant for } \mathbf{r}$$

$$\mathrm{R}^\bullet, \mathrm{Q}^\bullet, \mathrm{S}^\bullet \overset{2k_C}{\rightarrow} \mathrm{RR}, \mathrm{RQ}, \mathrm{QQ}, \mathrm{RS}, \mathrm{QS}, \mathrm{SS}$$

(including disproportionation)

When both solvent attack and isomerization are significant, the complete product distribution is determined by the values of three composite, dimensionless parameters, V, Δ, and $G^2 - 1$:

$$V = \frac{4k_C v}{3k_S^{3/2} D^{1/2}}, \qquad \Delta = \frac{\kappa}{(Dk_S)^{1/2}}, \qquad G^2 - 1 = \frac{k_Q}{k_S}$$

When isomerization occurs but solvent attack is negligible, the product distribution is determined by two parameters, V_Q and Δ_Q:

$$V_Q = \frac{4k_C v}{3k_Q^{3/2} D^{1/2}}, \qquad \Delta_Q = \frac{\kappa}{(Dk_Q)^{1/2}}$$

When solvent attack occurs but isomerization is negligible, the product distribution is determined by V and Δ. When neither isomerization nor solvent attack occurs, the products consist only of RMgX and RR (including disproportionation products) and their distribution is determined by a single parameter F:

$$\frac{(\mathrm{RMgX})^3}{[1 - \mathrm{RMgX}]^2} = F, \quad F = \frac{3\kappa^3}{4k_C v D}, \qquad \mathrm{RR} = 1 - \mathrm{RMgX}$$

Fig. 5 (left) shows how the calculated product distribution compares with that observed for the Grignard reaction of 5-hexenyl bromide in DEE. These reactions give RMgBr [(5-hexenyl)magnesium bromide], QMgBr [(cyclopentylmethyl)magnesium bromide], RR (1,11-dodecadiene), RQ [(6-heptenyl)cyclopentane), and QQ (1,2-dicyclopentylethane) [37]. RR, RQ, and QQ include, in principle, disproportionation products, but these were not reported and are minor for primary alkyl radicals. Products of solvent attack were not detected.

The calculated values for DEE were obtained without adjusting any of the six rate parameters v, k_Q, k_S, κ, $2k_C$, and D. Each was assigned a measured or typical value: $v = 2 \times 10^{-5}\,\mathrm{mol\,cm^{-2}\,s^{-1}}$ (measured [35,38]); $k_Q = 4.4 \times 10^5\,\mathrm{s^{-1}}$ (measured [34]); $k_S = 4.4 \times 10^3\,\mathrm{s^{-1}}$ (measured as $\sim 10^3\,\mathrm{s^{-1}}$ [39]); $\kappa = 30\,\mathrm{cm\,s^{-1}}$ (measured [31]); $2k_C = 3 \times 10^9\,\mathrm{M^{-1}\,s^{-1}}$ (typical); $D = 3 \times 10^{-5}\,\mathrm{cm^2\,s^{-1}}$ (typical). These correspond to the following values of the relevant dimensionless parameters: $V = 25{,}000$; $V_Q = 25.0$; $\Delta = 82.6$; $\Delta_Q = 8.26$; $G^2 - 1 = 100$. All values are very near the line that represents a perfect fit.

The values of I_G, I_D, and H are especially noteworthy. I_G and I_D are the percentages of isomerized alkyl group

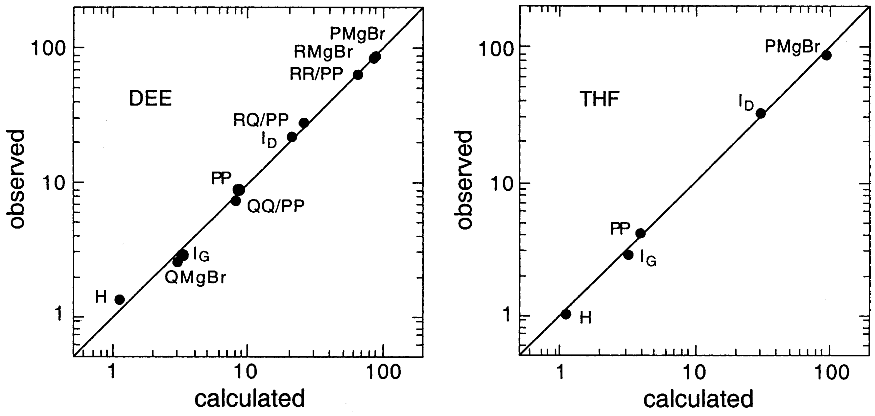


Fig. 5. Observed [37] vs. calculated [35] yields (%) and yield-based parameters for Grignard reactions of 5-hexenyl bromide (initially −2.1 M) in DEE (left) and THF (right) at ~40 °C. R = 5-hexenyl. Q = cyclopentylmethyl. P = R or Q. I_G = %Q in PMgBr. I_D = %Q in PP. $H = \mathrm{RQ}/[(\mathrm{RR})(\mathrm{QQ})]^{1/2}$. DEE: $V_Q = 25.0$, $\Delta_Q = 8.26$ (not adjusted for fit). THF: $V_Q = 15.0$, $\Delta_Q = 12.7$ (best fit).

Q (cyclopentylmethyl) in the Grignard reagent PMgBr (RMgBr + QMgBr) and PP (RR + RQ + QQ), respectively. I_G is about 3% while I_D is over 20% for reactions in both DEE and THF. If $R^\bullet$ and $Q^\bullet$ remained adsorbed at Mg_Z (**AAD**), this would require that PMgBr and PP be formed from different pools of $R^\bullet$ and $Q^\bullet$ at the surface Mg_Z. No explanation of why or how this might occur has been offered.

DDD provides a natural explanation—PMgBr is formed only at Mg_Z while PP is formed everywhere. For **DDD**, Fig. 6 gives calculated steady-state concentration profiles for $R^\bullet$ and $Q^\bullet$. The proportion of $Q^\bullet$ in $P^\bullet$ increases steadily with increasing distance from Mg_Z. Thus, PMgBr is formed in a plane, $x = 0$ (Mg_Z), where the proportion of $Q^\bullet$ is least (~3%), but PP is formed everywhere and much more $Q^\bullet$ is incorporated.

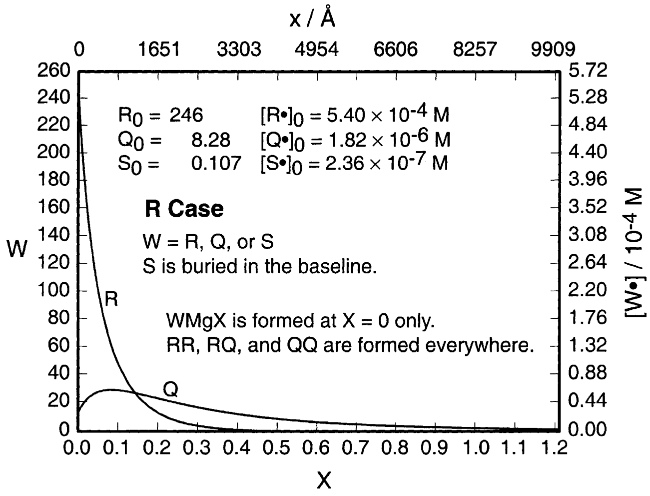


Fig. 6. Calculated steady-state concentration profiles for $R^\bullet$ (5-hexenyl) and $Q^\bullet$ (cyclopentylmethyl) in a Grignard reaction of 5-hexenyl bromide in DEE at 40 °C. R, Q, and S are scaled values of $[R^\bullet]$, $[Q^\bullet]$, and $[S^\bullet]$, respectively. See GU for details of scaling. The top and right axes are labeled with unscaled values.

H is the ratio of the yield RQ to the geometric mean of RR and QQ. Its value is expected to be 2 whenever PP incorporates $R^\bullet$ and $Q^\bullet$ in proportion to their populations:

$$H = \frac{\mathrm{RQ}}{[(\mathrm{RR})(\mathrm{QQ})]^{1/2}} = \frac{2k_C[R^\bullet][Q^\bullet]}{\{(k_C[R^\bullet]^2)(k_C[Q^\bullet]^2\}^{1/2}} = 2$$

The observed values are closer to 1 and agree reasonably with the calculated values. **AAD** predicts $H = 2$ unless adsorbed $R^\bullet$ and $Q^\bullet$ are not incorporated statistically into PP. No **AAD** explanation why $H \neq 2$ has been offered.

Again **DDD** provides a natural and simple explanation. Although $H = 2$ for PP formed in each plane parallel to Mg_Z, the observed PP is formed in all planes and the summing of yields over these planes changes the net value of H.

As an example of how summing can lower the value of H, consider possible distributions of RR, RQ, and QQ formed in two planes:

$$\mathrm{RR} = \tfrac{9}{16}, \quad \mathrm{RQ} = \tfrac{6}{16}, \quad \mathrm{QQ} = \tfrac{1}{16}, \quad H = 2$$

$$\mathrm{RR} = \tfrac{1}{16}, \quad \mathrm{RQ} = \tfrac{6}{16}, \quad \mathrm{QQ} = \tfrac{9}{16}, \quad H = 2$$

Now combine these in equal proportions:

$$H = \frac{12}{[(9+1)(1+9)]^{1/2}} = \frac{12}{10} = 1.2$$

The value of H for each plane is 2 but the combined value is 1.2.

For Grignard reactions of 5-hexenyl bromide in THF, di-*n*-butyl ether (DBE), and di-*n*-pentyl ether (DPE), rate parameters were adjusted for best fit, Figs. 5 (right) and 7.

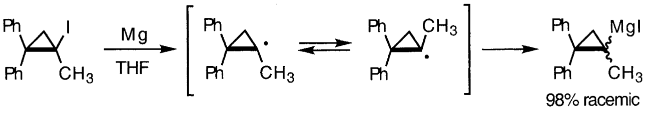
For Grignard reactions of alkyl halides, **DDD** predicts all of the known facts, including the discrepancy between I_G

and I_D and the unusual observed values of H. There is no valid support for **AAD** or **ADD**.

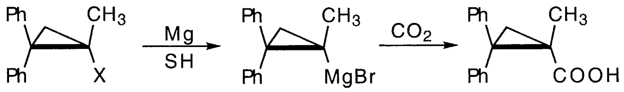
2.6. *Cyclopropyl halides*

2.6.1. *Evidence of cyclopropyl radical intermediates*

For cyclopropyl systems the evidence of intermediates $R^\bullet$ consists of racemization, coupling/disproportionation, and solvent attack. Optically active 1-methyl-2,2-diphenylcyclopropyl iodide gives a Grignard reagent that is 98% racemic, even though the Grignard reagent is optically stable under the reaction conditions [40]. The racemizing intermediate is probably $R^\bullet$:



Other l-methyl-2,2-diphenylcyclopropyl halides give more retention, but the large extents of racemization still point to cyclopropyl radical intermediates along the major pathway:



X	SH	T / °C	retention / %ee
Br	DEE	35	14-21
Br	THF	25-28	13
Cl	THF	65	25-26
Br	THF	65	15-19
I	THF	65	2

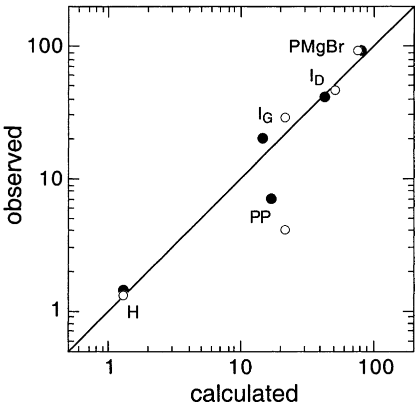
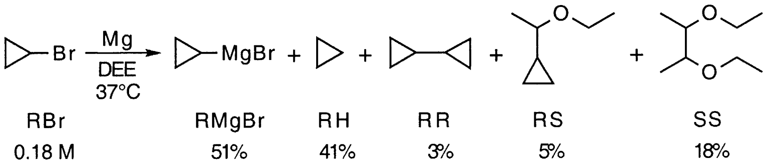


Fig. 7. Observed vs. calculated yields and yield-derived parameters for Grignard reactions of 5-hexenyl bromide (initially ~2.1 M) in DBE (solid circles) and DPE (open circles) at ~40 °C [35]. The fits for DBE ($V_Q = 2.15$, $\Delta_Q = 2.00$) and DPE ($V_Q = 1.21$, $\Delta_Q = 0.072$) are satisfactory.

The Grignard reaction of 1-methyl-2,2-diphenylcyclopropyl bromide in DEE gives products of **c** in yields totaling 16%, 4% RR and 12% R(–H) (HW, 160) [40]. This corresponds to a yield of RH from ($R^\bullet$ $R^\bullet$) disproportionation of 12%. Since the total yield of RH is 23%, an 11% yield of RH apparently results from **s** or $R^\bullet/S^\bullet$ disproportionation. The occurrence of **c** and **s** indicates $R^\bullet$ intermediates.

The Grignard reaction of cyclopropyl bromide in DEE gives clear evidence of **s** [19]:

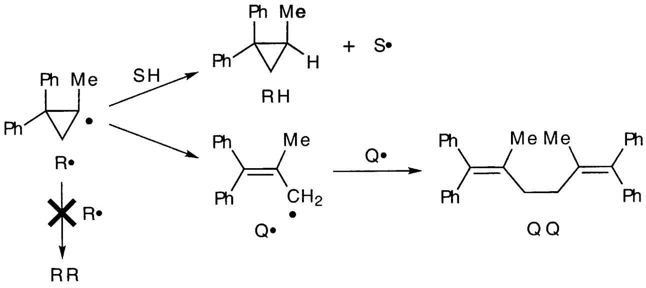


These products are expected for pathway **R**. It is difficult to conceive of a plausible alternative.

The presence of products of **s** from Grignard reactions of cyclopropyl halides and not from those of typical alkyl halides is a reflection of the greater reactivity of cyclopropyl in hydrogen-atom-transfer reactions. For a typical alkyl radical, the pseudo-first-order rate constant k_S for hydrogen-atom abstraction from an ether solvent is $\sim 10^3\,s^{-1}$, for cyclopropyl it is $\sim 10^6\,s^{-1}$ (GU, 214).

2.6.2. ***AAD***

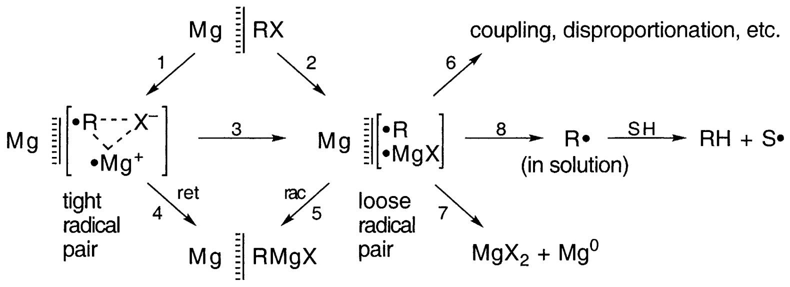
When it is generated in solution from a peroxide, the 1-methyl-2,2-diphenylcyclopropyl radical $R^\bullet$ attacks the solvent or ring opens to the allyl radical $Q^\bullet$, which then couples to QQ [41,42]. No RR is found:



In contrast, the Grignard reaction of 1-methyl-2,2-diphenylcyclopropyl bromide in DEE gives the isomerized Grignard reagent QMgBr in only 1% yield. RR and RH + R(–H) are formed (16%), but QQ is not detected, nor is RQ [40].

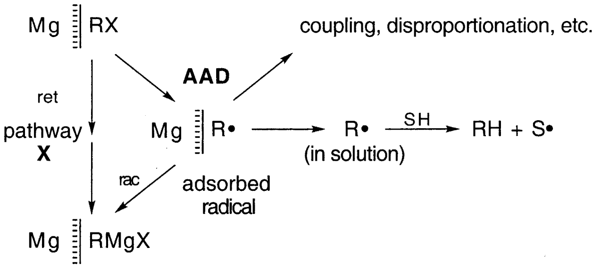
To explain the formation of RR and the absence of QQ in the Grignard reaction, Walborsky and Aronoff adopted KR's adsorption hypothesis (HW, 160–164) [40]. To account for the observed partial racemization and partial retention of configuration, they proposed two pathways, racemization through a "loose radical pair" [$R^\bullet$ $^\bullet MgX$] and retention through a "tight radical pair" [$RX^{\bullet -}$ $^\bullet Mg^+$], both of which remain at Mg$_Z$:

Kharasch-Reinmuth-Walborsky (KRW) Mechanism



Except schematically, neither the loose nor tight radical pair is defined. Since there is no evidence for these intermediates, the KRW mechanism is unnecessarily specific. Its essential features are preserved in a simpler mechanism in which an adsorbed $R^\bullet$ replaces the loose radical pair and a pathway **X** replaces the reaction through a tight radical pair. The simplified KRW mechanism is **AAD** augmented by pathway **X**:

Simplified KRW Mechanism



HW cite many parallel examples. There is no doubt that Grignard and "solution" radicals of the same kind often exhibit different patterns of reactivity. This is the original argument for **AAD**.

Another is based on radical trapping. For the Grignard reaction of cyclopropyl bromide in DEE, Garst and co-workers find (RMgBr) ≈ 50%, determined by titration [19]. According to Walborsky and Zimmerman [43], the same yield is 24%. In the presence of dicyclohexylphosphine-*P-d* (DCPD), which is expected to be an effective radical trap, only 4% (RD) is formed [43]. According to these authors, the extent of trapping is insignificant—few cyclopropyl Grignard radicals are trapped because few leave Mg_Z.

Although this has been cited as being among the strongest pieces of evidence for **AAD** [44], it is now clear that the reported results are incomplete and that the system is more complicated than assumed by Walborsky and Zimmerman. Additional results on these reactions are discussed below.

2.6.3. *DDD*

For Grignard reactions in which **s** is important, **DDD**, **ADD**, and **AAD** make distinct predictions of the effects of reducing the value of k_S. When the solvent is deuterated, k_S is reduced, perhaps by a factor near six, by a primary kinetic isotope effect. Since there is significant solvent attack in Grignard reactions of cyclopropyl halides, **AAD**, **ADD**, and **DDD** can be distinguished by determining the effects of solvent deuteration on product distributions.

In **AAD**, the competing fates of an adsorbed $R^\bullet$ are **r**, **c**, and desorption, which is invariably followed by **s**. Deuterating the solvent will have no effect on any of the competing processes that determine the product distribution. Therefore, it will have no effect on that distribution.

In **ADD**, **r** competes only with the desorption of $R^\bullet$. In solution, **c** and **s** compete. Deuterating the solvent will not affect **r** but will increase **c** at the expense of **s**. The yield RMgX will be unaffected but the yields of products of **c** will increase at the expense of those of **s**.

In **DDD**, **r**, **c**, and **s** are competitive with one another. Deuterating the solvent will increase **r** and **c** at the expense of **s**. The yields RMgX and RR will increase at the expense of those of products of **s**.

Experiments of Walborsky and Aronoff, who argued for **AAD**, provided the first disproof of that mechanism [40]. For other reasons, they investigated the effects of solvent perdeuteration on Grignard reactions of optically active 1-methyl-2,2-diphenylcyclopropyl bromide in DEE and THF, Table 2.

Even though the small observed changes are all in the direction predicted by **DDD**, the effects of perdeuterating DEE were judged to be insignificant and the results were considered to support **AAD**. Since RR was not determined, it could have increased and probably did (see below for corresponding results with cyclopropyl bromide). If so, the results could be consistent with **ADD**. They could even be consistent with **DDD** if the small, observed changes were, in fact, significant. Thus, the significance of the DEE results is not very clear.

For THF the results *are* clear. Solvent perdeuteration increases (RMgBr) at the expense of (RH + RD), as predicted by **DDD**. This rules out **AAD** and **ADD**, both of which predict that RMgBr will be unaffected.

With DEE results that could be interpreted as supporting **AAD**, Walborsky and Aronoff chose to ignore the implications of their THF results. Without commenting on the **DDD** nature of their explanation, they stated that a primary kinetic isotope effect on k_S diverts radicals $R^\bullet$ from **s** to **r** [40].

Table 2
Solvent isotope effects on Grignard reactions of optically active 1-methyl-2,2-diphenylcyclopropyl bromide

Solvent	t (°C)	RMgBr (%)	RMgBr optical purity (%)	Hydrocarbon (RH + RD) (%)	Hydrocarbon optical purity (%)	RD in RH + RD (%)
DEE	35	26	20.4	22.9	3.7	0
DEE-d_{10}	35	25	18.2	20.2	4.6	6.7
THF	65	70	18.5	6.0	6.2	0
THF	65	79	16.2	4.8	4.2	0
THF-d_8	65	90	13	1.0	9.0	28.5

Garst et al. determined the products of Grignard reactions of cyclopropyl bromide in undeuterated and perdeuterated DEE and THF [4], The results are summarized in Table 3.

In all of the four cases examined, the yields of **s** products are affected by solvent deuteration. This rules out **AAD**.

For DEE without added $MgBr_2$, there is a marginal increase in RMgBr and a large increase in RR at the expense of **s** products. This is most consistent with **ADD** but could also be consistent with **DDD** if the increase in RMgBr is genuine.

For DEE/$MgBr_2$ there are substantial increases in RMgBr and RR at the expense of **s** products, as expected for **DDD** but not **ADD** nor **AAD**. For THF and THF/$MgCl_2$, RR could not be determined, but RMgBr increases substantially at the expense of **s** products.

Only **DDD** passes the test. **AAD** and **ADD** are ruled out.

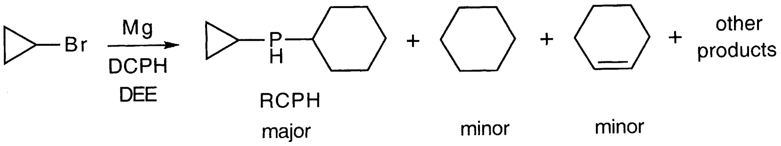
As noted above, Walborsky and Zimmermann find only 4% (RD) from the Grignard reaction of cyclopropyl bromide in DEE in the presence of DCPD [43]. They conclude that this is “strong experimental evidence that not very many radicals leave the surface of the magnesium”. However, the experimental section of reference [43] reveals a fact that is not discussed: RMgBr is reduced from 24 to 6% by the presence of DCPD! Since RMgBr is stable in the presence of DCPD [43], this is inconsistent with a lack of trapping.

Table 3
Solvent isotope effects on yields of product of reactions of cyclopropyl bromide

Solvent	$[MgX_2]_0$	$RBr_{0.40\,M} \xrightarrow[SH(D),37^{\circ}C]{Mg}$			
		RMgBr[a]	+ RR[a]	+ SS[a]	+ RS[a]
DEE	0	52	3	7	3
DEE-d_{10}	0	54	14	1.2	3
DEE	2.6 M $MgBr_2$	71	2	5	2
DEE-d_{10}	2.6 M $MgBr_2$	84	4	0.04	0.3
THF	0	58	–	16	10
THF-d_8	0	70	–	0.3	3
THF	0.50 M $MgCl_2$	68	–	4	6
THF-d_8	0.50 M $MgCl_2$	80	–	0.07	6

[a] Yield (%).

DCPD somehow interferes with RMgBr formation without forming much RD. Further investigation with DCPH reveals that cyclopropylcyclohexylphosphine (RCPH), cyclohexane, and cyclohexene are formed [45], indicating that cyclohexyl as well as cyclopropyl radicals are intermediates:



Thus, it appears that the chemistry of cyclopropyl radical trapping by DCPH(D) is unusual. It is not simple abstraction of $H^{\bullet}$ from P–H.

Garst and Ungváry find that DCPH is an effective radical trap in Grignard reactions of cyclopropyl bromide in DEE, Table 4 [46].

As expected, **s** products disappear and (RMgBr) steadily decreases as $[DCPH]_0$ increases. In addition, RCPH steadily increases. As this occurs, the sum RMgBr + RCPH varies only slightly, 40–35–30%. Clearly, RCPH is a major product of $R^{\bullet}$ trapping. RH appears to be a minor product.

Contrary to the interpretation offered by Walborsky and Zimmermann, DCPH is an effective trap for cyclopropyl Grignard radicals.

According to the square-root law, $k_Q\tau_R = \{[1 - \mathrm{RMgBr}]/\mathrm{RMgBr}\}^2$. Applying this to the entries of Table 4 gives the results in Table 5.

In the last column is given calculated values of $k_T\tau_R$ where k_T is the second-order rate constant for the trapping of cyclopropyl radicals by DCPH, $k_Q = k_T$ [DCPH]. In principle, the value of $k_T\tau_R$ should be constant. These estimates are obtained by dividing $k_Q\tau_R$ by $[DCPH]_0$, that is, by approximating [DCPH] as constant at its initial value. This is, of course, not true, but it is a better approximation when there is a larger excess of $[DCPH]_0$ over $[RBr]_0$. Even so,

Table 4
DCPH trapping in Grignard reactions of cyclopropyl bromide in DEE

$[DCPH]_0$ (M)	RMgBr (%)	RS (%)	SS (%)	RCPH (%)
0.00	40	2.1	3.0	0
0.20	23	–	–	12
0.60	11	0.0	0.0	19

$[RBr]_0 = 0.20$ M, $[MgBr_2]_0 = 0.12$ M, RMgBr was determined by carbonation, methylation of the resulting acid with diazomethane, and GC. RCPH is cyclopropylcyclohexylphosphine.

Table 5
Kinetics of trapping of cyclopropyl Grignard radicals by DCPH in DEE

$[\mathrm{DCPH}]_0$ (M)	RMgBr (%)	$k_Q\tau_R$	$k_T\tau_R$ (M^{-1})
0.20	23	11	56
0.60	11	65	109

Concentration and yield data from Table 4. $k_Q\tau_R = \{[1 - \mathrm{RMgBr}]/\mathrm{RMgBr}\}^2$ (from the square-root law). $k_Q = k_T[\mathrm{DCPH}]$, $k_T\tau_R = k_Q\tau_R/[\mathrm{DCPH}]_0$.

the calculated values of $k_T\tau_R$ differ only by a factor of two. If 109 is the better estimate of $k_T\tau_R$ and if $\tau_R = 1 \times 10^{-7}$ s, then $k_T = 1 \times 10^9\,M^{-1}\,s^{-1}$. If $\tau_R = 3 \times 10^{-8}$ s then $k_T = 4 \times 10^9\,M^{-1}\,s^{-1}$. These values, approaching the diffusion control limit, are plausible, about three orders of magnitude larger than k_T for a primary alkyl radical and DCPH.

Kinetic analyses of product distributions provide further tests of **DDD** for Grignard reactions of cyelopropyl bromides, Fig. 8.

The fits are satisfactory to excellent.

Thus, **AAD** is disproved and **DDD** is confirmed by results for Grignard reactions of cyclopropyl halides. **AAD** fails a direct test (solvent deuteration). **DDD** passes this test, the test of trapping by DCPH(D), and tests involving kinetic analyses of the reactions.

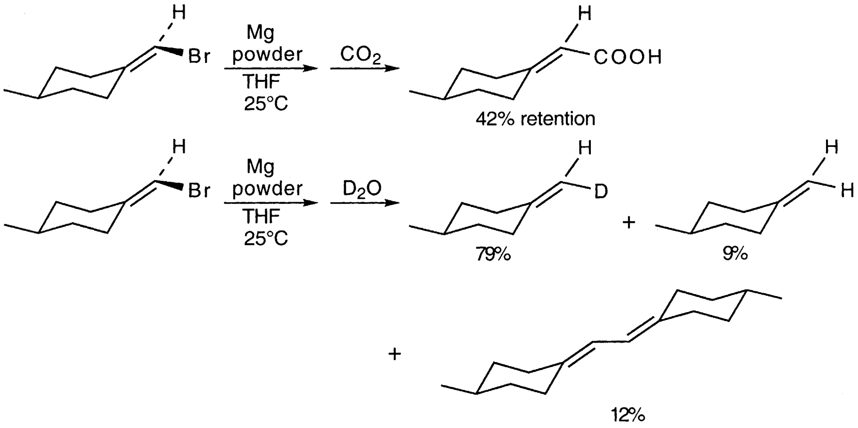
Even so, simple **DDD** cannot be the whole mechanistic story. It does not account for observations of partial retention of configuration. From kinetic analyses of product distributions the derived values of τ_R for cyclopropyl Grignard radicals are similar to those for typical alkyl radicals, near 10^{-7} s. The relaxation rate constant for inversion and racemization of a cyclopropyl radical is of the order 10^{-11} s. With these values, the square-root law predicts ~1% retention of configuration in RMgX. Up to 26% is observed.

Although the major pathway appears to be **R**, these considerations point to a minor pathway **X**.

2.7. Vinyl halides

2.7.1. Evidence of vinyl radical intermediates

An optically-active vinyl bromide, 4-methylcyclohexylidenebromomethane, gives RMgBr with racemization (58%) and products of **c** and **s**, indicating vinyl radical intermediates [47]:



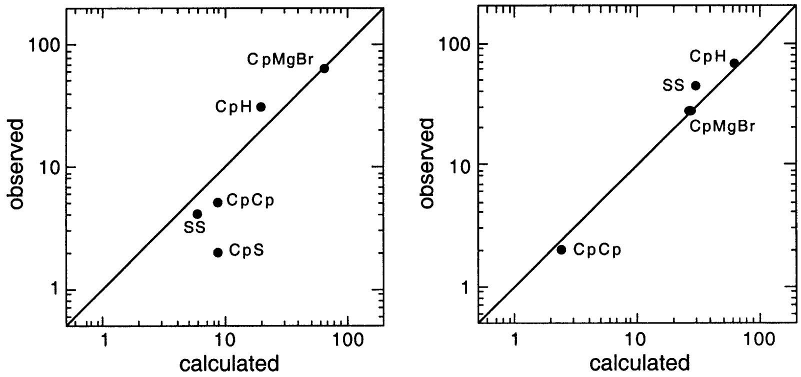


Fig. 8. (Left) Observed vs. calculated ($V = 2.58$, $\Delta = 2.71$) yields for Grignard reactions of cyclopropyl bromide, CpBr, in DEE containing $MgBr_2$ at 37 °C. Calculated values of CpCp, SS, and CpS include radical disproportionation products and are consequently too large. The calculated value of CpH is for solvent attack only (does not include disproportionation) and is consequently too small. Appropriate corrections would move the points for CpCp, SS, CpS, and CpH toward the line representing a perfect fit. (Right) Observed vs. calculated ($V = 0.075$, $\Delta = 0.413$) yields for Grignard reactions of tetramethylcyclopropyl bromide, CpBr, initially ~0.17 M in DEE containing 2.6 M $MgBr_2$ at 37 °C [15].

2.7.2. *ADD*

The reactions of 4-methylcyclohexylidenebromomethane are analogous to those of 1-methyl-2,2-diphenylcyclopropyl bromide (HW, 157–158, 161) [47]. Accordingly, Walborsky and co-workers favor **AAD**.

2.7.3. *DDD*

Since Grignard reactions of 4-methylcyclohexylidenebromomethane and 1-methyl-2,2-diphenylcyclopropyl bromide give parallel results, and since **DDD** is the major mechanism of the latter reactions, it is likely a significant mechanism for the former reactions as well. The formation of products of **c** and **s** in substantial yields suggests that the **r**-limited lifetimes τ_R of vinyl radicals are similar to those of cyclopropyl and alkyl radicals, $\sim 10^{-7}$ s.

The inversion rate constants k_Q of vinyl and cyclopropyl radicals are similar, it is believed, $\sim 10^{11}\,\mathrm{s}^{-1}$ [48]. For $k_Q = 1 \times 10^{11}\,\mathrm{s}^{-1}$ and $\tau_R = 1 \times 10^{-7}$ s, the square-root law predicts 1% retention, far less than the observed 42%.

Much more retention of configuration is reported for Grignard reactions *cis*- and *trans*-β-bromostyrenes in THF [49]:

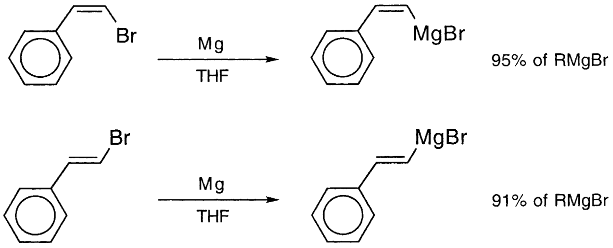


Table 6
Cyclization in Grignard reactions of *o*-(3-butenyl)phenyl bromide and iodide

Solvent	X	$[\mathrm{MgX}'_2]_0$ (M)	RMgX (%)	QMgX (%)	*q*
DEE	Br	0	82	16	0.20
DEE	Br	2.6	82	3.7	0.045
DEE	I	0	56	25	0.45
DEE	I	2.6	90	8.3	0.092
THF	Br	0	101	0.35	0.0035
THF	Br	0.50	101	0.1	0.001
THF	I	0	98	1.5	0.015
THF	I	0.50	96	1.0	0.010

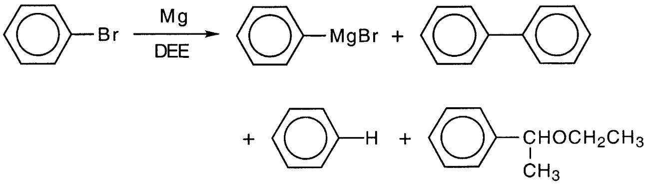
Reactions at 37 °C. DEE: $\mathrm{MgX}'_2=\mathrm{MgBr}_2$, THF: $\mathrm{MgX}'_2=\mathrm{MgCl}_2$, $q = [\mathrm{QMgX} + \mathbf{s}]/\mathrm{RMgX}$. Since $\mathbf{s} = 0$, $q = \mathrm{QMgX}/\mathrm{RMgX}$.

The results for vinyl systems seem to require a pathway **X**. Further, the large amounts of retention in the styryl cases suggest that **X** is the major pathway.

2.8. *Aryl halides*

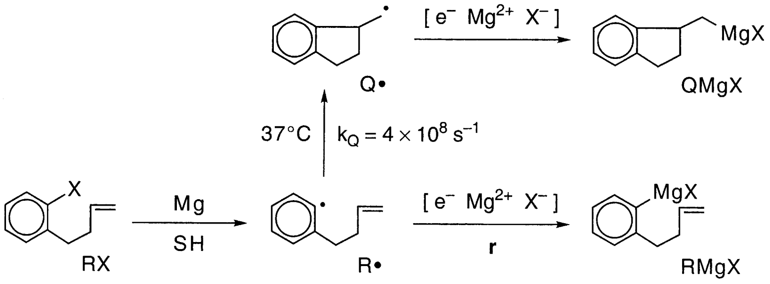
2.8.1. *Evidence of aryl radical intermediates*

Grignard reactions of phenyl bromide in DEE give by-products of **c** and **s** [50–52], clearly indicating phenyl radical intermediates:



However, yields of phenylmagnesium halides can be very high, usually ≥90% for phenyl bromide in DEE and close to 100% in THF. Accordingly, by-product yields are often very small. Radical intermediates are indicated but not necessarily for the major part of the reaction.

Despite the high reactivity of the *o*-(3-butenyl)phenyl radical in cyclization, $k_Q = 4 \times 10^8\,\mathrm{s}^{-1}$ at 37 °C [53,54], Grignard reactions of *o*-(3-butenyl)phenyl halides give low yields of cyclic products, especially in THF, Table 6 [52].



Again, the indication is that aryl radicals are intermediates for some part of the reaction but that part could be minor, especially in THF.

2.8.2. *AAD*

According to KR (63), "In the cases of such highly reactive free radicals as the phenyl, or even the methyl, the notion that they could survive long enough in the presence of any of the usual Grignard solvents to undergo ... [**c**] to an appreciable extent is absurd". Thus, the presence of RR among the products of reactions of phenyl halides indicates **AAD**.

Although they give little attention to aryl halides, HW (181) imagine that **AAD** applies to their Grignard reactions.

2.8.3. ***DDD***

Since cyclopropyl and phenyl radicals have similar reactivities in other instances [52], analogy with cyclopropyl halides suggests **DDD** for Grignard reactions of aryl halides. For alkyl, cyclopropyl, and vinyl radicals, the value of τ_R appears to be $\sim 10^{-7}$ s, so it is plausibly assumed that a similar value applies to aryl radicals.

With $\tau_R \approx 10^{-7}$ s, **DDD** fails badly. For *o*-(3-butenyl) phenyl iodide in DEE with no added $MgBr_2$, the observed value of q is 0.45 (Table 6), but a value of 3.6 is calculated from the square-root law with $\tau_R = 3 \times 10^{-8}$ s [52]. For *o*-(3-butenyl)phenyl bromide in THF containing $MgCl_2$, the calculated value of q is 3.87 while the observed value is 0.001.

Such discrepancies suggest a pathway **X**. In THF, at least, it may be the major pathway.

2.9. *Fallacies of arguments against **DDD***

In supporting **AAD** by arguing against **DDD**, KR and HW neglect the differences between:

1. behaviors of radical–radical and surface–radical pairs,
2. lifetimes of "solution" and Grignard radicals,
3. steady-state concentrations of "solution" and Grignard radicals, and
4. values of k_S for DEE and DEE-d_{10} (kinetic isotope effect).

2.9.1. *Radical–radical vs. surface–radical pairs*

The properties of surface–radical pairs ZB differ markedly from those of radical–radical pairs AB (GU, 195–202, 267–271). Inert AB disappear rapidly by escape, that is, by separating and gaining diffusion trajectories that never bring the original partners into contact again. In contrast, ZB never escape–inert ZB last forever.

This reflects a fundamental difference between one- and three-dimensional diffusion. A ZB is a one-dimensional case because the only significant direction is x, perpendicular to the surface Z. A diffusing inert particle B will always come into contact with Z in the future, no matter how far it may stray. An AB is a three-dimensional case because all three component directions (x, y, z) of relative diffusion are significant. If a diffusing inert particle B is not near A, then there is a low probability that it will ever come into contact with A in the future (GU, 198–202).

$[Mg_Z\ R^\bullet]$ is a ZB—diffusive separation does *not* lead to escape. $[R^\bullet\ R^\bullet]$ is AB—diffusive separation *does* lead to escape. For spherical molecules that were once in contact, the probability that escape has occurred is $s/(R+s)$, where R is the contact radius and s is the separation (distance between surfaces) of the spheres.

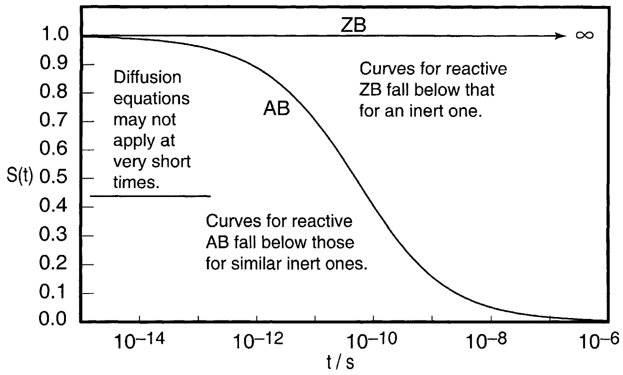


Fig. 9. Survival probability *S*(*t*) as a function of time *t* for standard inert AB and ZB (GU, 270, Eq. (7A.22)).

For a typical inert AB and ZB, Fig. 9 gives the survival probability S(t) as a function of time t for pairs that are in contact when $t = 0$. By 10^{-10} s more than 50% of AB escape and become independently diffusing radicals and by 10^{-9} s, about 85% (Fig. 9).

Reactive AB disappear by reaction as well as escape and consequently have shorter lifetimes than inert AB. For the representative case shown in Fig. 10, 50% of pairs initially in contact disappear by 10^{-11} s, 60% of these by escape, 40% by pair reaction. Reactive ZB disappear *only* by reaction. The case illustrated is that of a typical alkyl Grignard radical in $[Mg_Z\ R^\bullet]$. It takes more than 10^{-8} s for 50% of pairs initially in contact to disappear and about 10^{-6} s for 90%. [*Erratum*: The AB curve of the analogous figure in GU (201, Fig. 7.11) is erroneously shifted to shorter times.]

If a radical pair $[R^\bullet\ R^\bullet]$ has not suffered pair reaction within about 10^{-10} s, then it has probably suffered escape by diffusing to a separation of several contact radii. Escaped radicals diffuse independently in solution. If the original radicals pairs were generated homogeneously in solution, then escaped radicals behave like those generated singly and homogeneously. They have long lifetimes and never reach very high concentrations. This allows them to undergo (pseudo-)first-order reactions such as solvent attack and isomerization and, if they are sufficiently reactive, makes it unlikely that they will couple and disproportionate with one another.

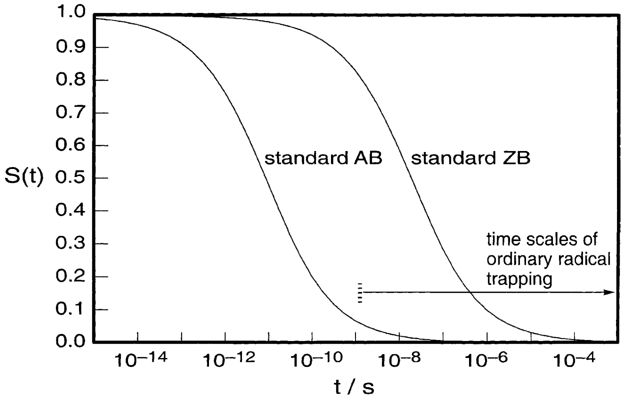


Fig. 10. Survival probability *S*(*t*) as a function of time *t* for standard reactive AB and ZB (GU, 270, Eq. (7A.22)). (See text for notice of an error in GU.)

These are the behaviors of the “solution” radicals of KR and HW, who assume that Grignard radicals that leave Mg_Z will behave similarly. Thus, KR (63) think it “absurd” to imagine that phenyl or methyl Grignard radicals could live long enough in solution to undergo **c**, and HW (160–161), following Walborsky and Aronoff [40], think that 1-methyl-2,2-diphenylcyclopropyl Grignard radicals would necessarily undergo **s** or **q** (ring opening) if they left Mg_Z and diffused in solution.

Neither idea is correct. There is no escape from [Mg_Z $R^\bullet$] and radicals diffusing near Mg_Z do not behave like “solution” radicals. In their reasoning, KR and HW neglect [(2) and (3)] the much shorter lifetimes and higher concentrations (near Mg_Z) of Grignard radicals.

2.9.2. Lifetimes of “solution” vs. Grignard radicals

Simple calculations give conservative estimates of limits on lifetimes and steady-state concentrations of alkyl “solution” radicals (GU, 248). Measurements and calculations mentioned earlier provide similar information for Grignard radicals.

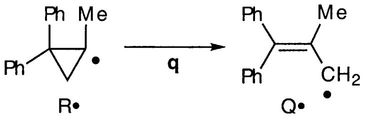
Lifetimes τ and steady-state concentrations [$R^\bullet$] of alkyl “solution” and Grignard radicals

	τ (s)	[$R^\bullet$] (M)
“Solution”	$>10^{-4}$	$<10^{-6}$
Grignard	$\sim 3 \times 10^{-8}$	10^{-5} to 10^{-3}

The lifetimes of alkyl Grignard radicals are limited by **r** to values that are at least three orders of magnitude less than 10^{-4} s, the lower limit of lifetimes of “solution” radicals. Consequently, “solution” radicals will undergo reactions with (pseudo-)first-order rate constants up to $10^4\,s^{-1}$ that will be unavailable to Grignard radicals of the same kind. Reactions with rate constants near $10^5\,s^{-1}$ will dominate for “solution” radicals but will be minor, though significant (square-root law), for Grignard radicals of the same kind.

This explains why solvent attack ($k_S \approx 10^3\,s^{-1}$) is not significant in Grignard reactions of alkyl halides. It also explains why the cyclization of 5-hexenyl ($k_Q = 4\times10^5\,s^{-1}$) is essentially complete for “solution” radicals but occurs only to the extent of 3–10% for Grignard radicals. To explain these and similar differences, it is not necessary to hypothesize that Grignard radicals remain adsorbed at Mg_Z.

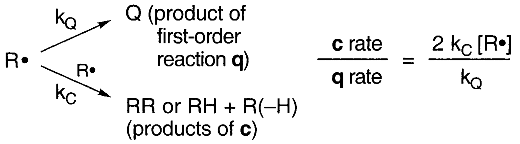
1-Methyl-2,2-diphenylcyclopropyl “solution” radicals $R^\bullet$ attack the solvent or isomerize extensively (HW, 151–152):



Quoting Walborsky and Aronoff [40], HW (162) cite the insignificance of both **s** and **q** in the Grignard reaction of 1-methyl-2,2-diphenylcyclopropyl bromide in DEE as evidence of **AAD**. However, **DDD** accounts for these facts as consequences of the short **r**-limited lifetime of $R^\bullet$. In addition, there appears to be more **s** than Walborsky and Aronoff thought—see Section 2.9.4.

2.9.3. Steady-state concentrations of “solution” vs. Grignard radicals

The tendency of Grignard radicals to couple and disproportionate more than “solution” radicals reflects the higher concentrations, by factors of $10–10^3$ or more, of Grignard radicals. For Grignard reactions of alkyl halides at high concentrations, ~1 M or more, the pseudo-steady-state concentrations of radicals approach 10^{-3} M at Mg_Z and exceed 10^{-5} M for several thousand angstroms into the solution (Fig. 6). Due to this, the ratio of rates, **c**/**q**, will be a factor of $10–10^3$, or more, greater for Grignard than “solution” radicals:



$$\frac{\mathbf{c}\text{ rate}}{\mathbf{q}\text{ rate}} = \frac{2\,k_C\,[R^\bullet]}{k_Q}$$

In a Grignard reaction **c** will occur to the near exclusion of **q** when k_Q is $10^4\,s^{-1}$ or less. This is reckoned by taking the effective [$R^\bullet$] in the region near Mg_Z, where **c** occurs, to be 10^{-4} M (Fig. 6), so that **c** rate/**q** rate $= (3\times10^9\,M^{-1}\,s^{-1}) \times (10^{-4}\,M)/10^4\,s^{-1} = 30$.

The high value of [$R^\bullet$] near Mg_Z explains how **c** can be significant in Grignard reactions while **s** is not, even though “solution” radicals of the same kind, at 10^{-7} M, undergo more **s** than **c**:

Grignard radicals :

$$\frac{\mathbf{c}\,\text{rate}}{\mathbf{s}\,\text{rate}} = \frac{(3 \times 10^9\,M^{-1}\,s^{-1}) \times (10^{-4}\,M)}{10^3\,s^{-1}} = 300$$

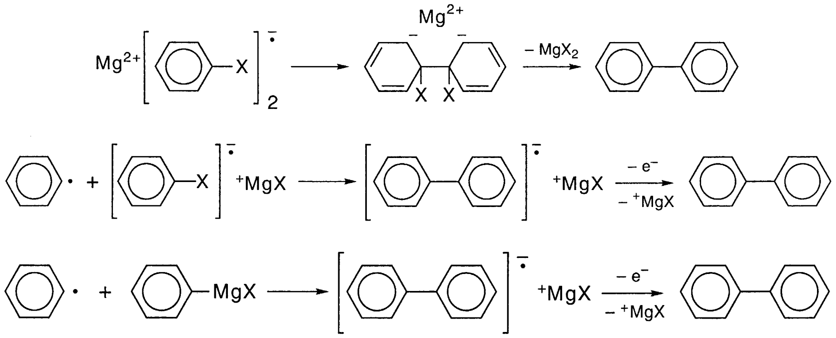
“solution“ radicals :

$$\frac{\mathbf{c}\,\text{rate}}{\mathbf{s}\,\text{rate}} = \frac{(3 \times 10^9\,M^{-1}\,s^{-1}) \times (10^{-7}\,M)}{10^3\,s^{-1}} = 0.3$$

It also explains how **c** can compete with **r** in Grignard reactions. Applying the square-root law, we obtain $\mathbf{c}/\mathbf{r} = [(3\times10^5\,s^{-1})\,(3\times10^{-8}\,s)]^{1/2}$ and $\mathbf{c} = 9\%$. Depending on the initial concentration of RBr in DEE, and on the hydrodynamics of the experimental method, the observed **c** ranges over 0–40% (GU, 209). For reactions in which RBr is initially ~2.1 M and there is no hydrodynamic control, the observed **c** is ~10%, in excellent agreement with the approximate calculation just given and with proper **DDD** calculations (Fig. 5).

Citing Walborsky and Aronoff [40], HW (162) argue that the formation of RR in the Grignard reaction of 1-methyl-2,2-diphenylcyclopropyl bromide (RBr) in DEE implies that intermediate radicals $R^\bullet$ are not “free in solution”. “Solution” radicals $R^\bullet$ do not couple—instead they isomerize to $Q^\bullet$, which couples to give QQ. The short lifetime and high concentration of $R^\bullet$ near Mg_Z account for the products of the Grignard reaction for $R^\bullet$ that *are* “free in solution”.

In arguing that phenyl Grignard radicals could not survive long enough to couple, KR (63) ignore the high concentrations near Mg_Z that these radicals could reach. That said, this does not necessarily mean that the small amounts of biphenyl formed in Grignard reactions of phenyl halides are products of phenyl radical coupling. Biphenyl could result, for example, from the coupling of phenyl–halide anion–radicals or the reaction of a phenyl radical with a phenyl–halide anion–radical or phenylmagnesium halide:



2.9.4. Values of k_S for DEE vs. DEE-d_{10} (kinetic isotope effect)

For the cyclopropyl radical in DEE, it is estimated from a measurement on a close relative that $k_S = 2 \times 10^6\ s^{-1}$ [55]. Since this is $\sim 10^3$ times the corresponding value for alkyl radicals, it is reasonable to expect more solvent attack by cyclopropyl Grignard radicals.

Consistent with this expectation, Garst et al. find nearly 25% **s** products for Grignard reactions of cyclopropyl bromide in DEE that does not contain $MgBr_2$ initially. This decreases to about 6% when $MgBr_2$ *is* present [15,19] (GU, 214–217). For 2,2,3,3-tetramethylcyclopropyl bromide nearly 70% **s** is found, even in the presence of $MgBr_2$ [15].

Following Walborsky and Aronoff [40], HW (162) report the yield of RD as 1.4% from the Grignard reaction of 1-methyl-2,2-diphenylcyclopropyl bromide in DEE-d_{10}. Ignoring the possibility of a primary kinetic isotope effect on k_S, they take the yield of RD in DEE-d_{10} as a measure of the extent of **s** for reactions in DEE-d_0. Concluding that **s** is negligible, they claim that “the lack of solvent cleavage” indicates that intermediate radicals $R^\bullet$ are “surface-bound”.

In related reactions, a significant isotope effect on k_S affects product distributions in the ways expected for **DDD** (Tables 2 and 3). By neglecting it, Walborsky and Aronoff misjudge the extent of **s** in the Grignard reaction of 1-methyl-2,2-diphenylcyclopropyl bromide in DEE [40]. Their own data suggest that there is ∼11% **s**. This is the difference between the reported yields of RH (23%) and R(–H) (12%).

There is no genuine lack of solvent cleavage. The data for **s** in Grignard reactions of cyclopropyl halides are consistent with **DDD** and offer no support for **AAD**.

2.10. Pathway *X*

2.10.1. Insensitivity of τ_R to structural variations in $R^\bullet$

For primary alkyl Grignard radicals along **DDD**, $\tau_R \approx 1 \times 10^{-7}$ s. For cyclopropyl and vinyl Grignard radicals, the yields of products of **s** and **c** imply a similar value of τ_R, despite the fact that in other reactions cyelopropyl and vinyl are much more reactive than alkyl radicals.

Why should the value of τ_R be insensitive to variations in the structure of $R^\bullet$? The possibility that **r** is encounter controlled can be ruled out. For $\tau_R = 1 \times 10^{-7}$ s and $D = 3 \times 10^{-5}\ cm^2\ s^{-1}$, the probability is only 0.03 that an $R^\bullet$ at Mg_Z will suffer **r** before diffusing to a separation of 5 Å.

Perhaps the **r** rate is governed by other events in the complex corrosion. The processes that maintain Mg_Z in a steady-state condition during the reaction include the dissolution of Mg as Mg^{2+} (presumably), the accompanying solvent and ionic aggregate reorganizations, and the reduction of RX, as well as that of $R^\bullet$. Perhaps $R^\bullet$ is reduced at the rate that is required to keep all the processes synchronized.

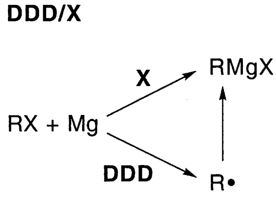
2.10.2. Exclusive *DDD*

If **DDD** were the exclusive pathway then values of lifetimes τ_R would be given by the square-root law and observed values of k_Q and q_{obs} [$QMgX_{obs}/RMgX_{obs}$] (Table 7).

The values of τ_R derived from isomerizations of certain cyclopropyl, vinyl, and aryl Grignard radicals are much shorter than 10^{-7} s. Several are short enough, 10^{-15} to 10^{-12} s, to make the applicability of diffusion equations, and the square-root law, dubious. Some are short enough, 10^{-15} to 10^{-13} s, to be of doubtful physical significance. These results do not support the assumption of an exclusive pathway **DDD** for cyclopropyl, vinyl, and aryl halides.

2.10.3. $D7/X0$

Pure **DDD** is not adequate. Perhaps another pathway, **X**, competes with it:



Along pathway **X**, there is no intermediate R• or, if there is, it has such a short lifetime that only the fastest probes could reveal it.

Table 7
DDD values of the **r**-limited lifetimes τ_R of Grignard radicals $R^\bullet$ in DEE or THF

RX	Solvent	MgX_2 (M)	k_Q (s^{-1})	q_{obs}[a]	τ_R (s)
Primary alkyl, cyclopropyl, and simple vinyl bromides	DEE or THF	–	–	–	$\sim 10^{-7}$[b]
1-Methyl-2,2-diphenyl-cyclopropyl bromide	DEE	–	$\sim 1 \times 10^{11}$	6.1	4×10^{-10}
1-Methyl-2,2-diphenyl-cyclopropyl chloride	THF	–	$\sim 1 \times 10^{11}$	2.8	8×10^{-11}
4-Methylcyclohexyli-denebromomethane	THF	–	$\sim 1 \times 10^{11}$	1.4	2×10^{-11}
cis-β-Bromostyrene	THF	–	$\sim 1 \times 10^{10}$[c]	0.053	3×10^{-13}
o-(3-Butenyl)phenyl bromide	DEE	2.6	4×10^{8}	0.045	5×10^{-12}
o-(3-Butenyl)phenyl bromide	THF	0	4×10^{8}	0.0035	3×10^{-14}
o-(3-Butenyl)phenyl bromide	THF	0.50	4×10^{8}	0.001	3×10^{-15}

[a] $QMgX_{obs}/RMgX_{obs}$.
[b] Based on 5-hexenyl cyclizations, **s**, and **c**.
[c] For the styryl radical, $k_Q = 1 \times 10^{10}\,s^{-1}$ is used because there are indications that β-conjugation may slow inversion slightly [45]. If instead $k_Q = 1 \times 10^{11}\,s^{-1}$, then $\tau_R = 3 \times 10^{-14}$ s.

Let **D7** be **DDD** with $\tau_R = 1 \times 10^{-7}$ s. Let **X0** be a pathway **X** along which there is no radical intermediate or isomerization. The combination is the **D7/X0** mechanism.

If **D7/X0** is assumed, the data of Table 7 provide sufficient information to partition Grignard reactions into **D7** and **X0**. Since all of the values of k_Q are significantly greater than $10^7\,s^{-1}$, isomerization along **D7** is nearly complete and the yield of unisomerized Grignard reagent RMgX (versus that of completely isomerized, i.e., equilibrated, Grignard reagent QMgX) is a good measure of the fraction of the reaction through pathway **X0**.

Even so, a slightly better calculation is available. Using known values of the isomerization rate constants k_Q, the square-root law provides calculated values of q_7 for products formed along **D7**:

$$q_7 = \frac{(QMgX)_7}{(RMgX)_7}$$

From the definitions of q_{obs} [$QMgX_{obs}/RMgX_{obs}$)] and q_7 and a mass-balance relationship, $QMgX_7 + RMgX_7 + RMgX_X = 1$, the following expression for the fraction of the reaction that proceeds through pathway **X0** can be derived:

$$\mathbf{X0} = \frac{q_7 - q_{obs}}{q_7(1 + q_{obs})} \quad (\mathbf{X0} = \text{fraction through pathway } \mathbf{X0})$$

Table 8 gives the resulting partitions of reactions into pathways **D7** and **X0**.

The results provide a quantitative expression of the trend that increasing conjugation in RX correlates with an increasing fraction of pathway **X**.

2.10.4. *D7/XR*

In another scenario the radical $R^\bullet$ is an intermediate along pathway **X**, denoted **XR**. Let $R^\bullet$ be very short-lived because it is a member of a geminate pair. In **D7**/**XR**, there are two subsets of intermediate radicals $R^\bullet$, the **D7** set ($\tau_R = 1 \times 10^{-7}$ s) and the **XR** set ($\tau_R \ll 1 \times 10^{-7}$ s).

If Mg_Z were "freckled" with active sites F, if $R^\bullet$ were formed from RX at an F, and if that F were to remain active after the formation of $R^\bullet$ then $R^\bullet$ and F would form a geminate pair [F $R^\bullet$] in three dimensions. The behavior of this pair would resemble that of a radical pair in solution. It would have a very short life-time, even if that lifetime were limited largely by escape (Fig. 9). If a geminate reaction **r** did not occur, then $R^\bullet$ would escape and enter the pool of **D7** radicals diffusing near Mg_Z. Geminate reaction **r** (**XR**)

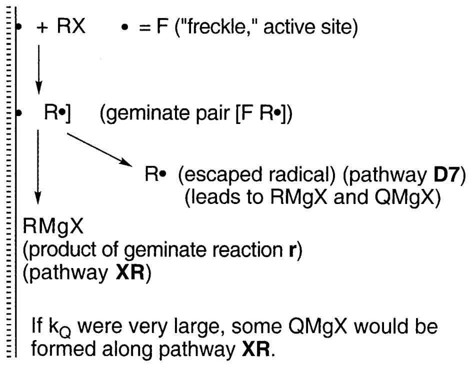
Table 8
Fractions of pathways **D7** and **X0**[a]

RX	Solvent	MgX_2 (M)	q_7[b]	q_{obs}[c]	**D7**[d]	**X0**[d]
Primary alkyl bromides	DEE or THF	–	–	–	(1.00)[e]	(0.00)[e]
1-Methyl-2,2-diphenyl-cyclopropyl bromide	DEE	–	100	6.1	0.87	0.13
1-Methyl-2,2-diphenyl-cyclopropyl chloride	THF	–	100	2.8	0.74	0.26
4-Methylcyclohexyli-denebromomethane	THF	–	100	1.4	0.59	0.41
cis-β-Bromostyrene	THF	–	31.6[f]	0.053	0.05[f]	0.95[f]
o-(3-Butenyl)phenyl bromide	DEE	2.6	6.3	0.045	0.05	0.95
o-(3-Butenyl)phenyl bromide	THF	0	6.3	0.0035	0.004	0.996
o-(3-Butenyl)phenyl bromide	THF	0.50	6.3	0.001	0.001	0.999

[a] Calculated from the square-root law, assuming that $\tau_R = 10^7$ s. See text for details.
[b] $QMgX_7/RMgX_7$, calculated from the square-root law using the value of k_Q given in Table 7.
[c] $QMgX_{obs}/RMgX_{obs}$ from Table 7.
[d] Fractions of pathways **D7** and **X0**.
[e] For simple alkyl halides there is no evidence of a pathway **X**.
[f] For the styryl radical, $k_Q = 1 \times 10^{10}\,s^{-1}$ is used because there are indications that β-conjugation may slow inversion slightly [45]. The calculated fractions of pathways **D7** and **X0** are nearly the same for $k_Q = 1 \times 10^{11}\,s^{-1}$.

would lead to RMgX unless k_Q were very large, in which case some QMgX would be formed:

D7/XR



In the **D7/XR** case, radical probes whose isomerization rate constants are much greater than $10^7\,s^{-1}$ would equilibrate along **D7** and could partially equilibrate along **XR**. In principle, this allows **D7/XR** to be distinguished experimentally from **D7/X0**. For **D7/X0** there is only time scale for isomerization τ_R ($\tau_R = 1 \times 10^{-7}$ s). If k_Q were large enough for nearly complete equilibration, further increases would give little additional isomerization. For **D7/XR** further increases in k_Q will give significantly more isomerization. Attempts to test this scenario are described below.

2.10.5. Freckled and uniformly reactive Mg_Z

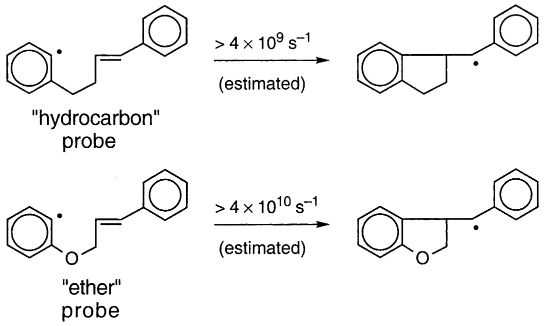
In principle an objection can be raised. If reductions occurred at freckles, then Mg_Z would not be uniformly reactive, as assumed in the treatment of **DDD** kinetics described above. Since the **DDD** treatment is successful, it might be argued that Mg_Z cannot be freckled and **XR** cannot be pathway **X**.

Actually, a successful treatment requires only that the system behave *as if* Mg_Z were uniformly reactive. When $R^\bullet$ is at Mg_Z there is α probability a that it will react to form RMgX instead of separating. If the surface were uniformly reactive, the same value of α would apply to all Mg_Z–$R^\bullet$ encounters. If instead the surface were freckled, the value of α would vary from encounter to encounter but the kinetics of the system could behave as if Mg_Z were uniformly reactive with an *average* value of α. This would be the case for sufficiently long-lived radicals and a sufficiently high density of freckles. If **XR** is to be ruled out, it must be on other grounds.

2.10.6. Evidence for XR

Very low yields of products of radical cyclization led Garst et al. to suggest that for Grignard reactions of aryl halides the dominant pathway is **X0**: "there is no aryl radical intermediate along the dominant reaction channel" [52]. However, their data do not rule out **XR**, which might be revealed by faster radical probes.

Using probes that are assumed to cyclize faster than *o*-(3-butenyl)phenyl, Bodineau et al. have attempted to probe for intermediate radicals $R^\bullet$ with very short lifetimes [56]:



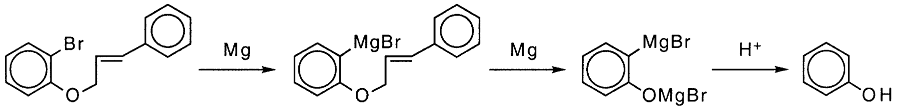
The faster probes *do* result in increased isomerization. For the reaction at room temperature of Mg* (atomic clusters) in THF with the aryl bromide corresponding to the "hydrocarbon" radical, the observed value of q is 0.15. This contrasts with $q = 0$ for the similar experiment with *o*-(3-butenyl)phenyl bromide [57] and $q = 0.0035$ (average of two experiments) reported by Garst et al. for the same reaction using ordinary Mg [52]. More cyclization yet is found from the Grignard reaction of the bromide of the even faster "ether" probe, for which $q = 1.6$. Using the estimated minimum values of k_Q for the "hydrocarbon" and "ether" probes, the square-root law and observed values of q give $\tau_R = 6 \times 10^{-12}$ s for the "hydrocarbon" probe and $\tau_R = 6 \times 10^{-11}$ s for the "ether" probe, values that are much less than 10^{-7} s.

These data suggest that **XR** dominates. The data for *o*-(3-butenyl)phenyl bromide rule out **D7** and the increase in extent of isomerization with faster probes seems to rule out **X0**. However, there are uncertainties with this interpretation.

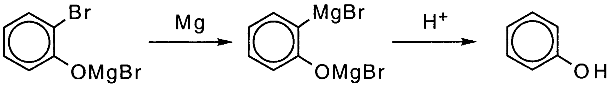
2.10.7. Possible complications with very fast probes

Ruling out **X0** in favor of **XR** on the basis of results from the fast "hydrocarbon" and "ether" probes may not be justified. Possible complications cloud the picture.

After workup, phenol is among the products of Grignard reactions of the "ether" substrate. Assuming that it results from reductive cleavage of C–O in RMgBr, Bodineau et al. count phenol as RMgBr [56]:

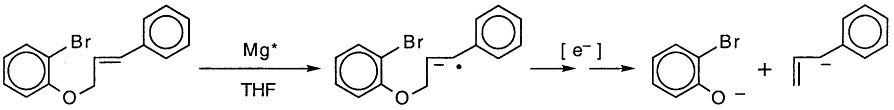


There is another plausible route to phenol. One of the by-products is *o*-bromophenol, indicating that reduction occurs with initial cleavage of a C–O bond instead of the C–Br bond. The authors do not comment on the possibility that *o*-bromophenoxide might be reduced by Mg to phenoxide, in which case it would be erroneous to count phenol as RMgBr:



Another possible complication with the "ether" probe concerns the role of the oxygen. Ethers coordinate to Mg^{2+}. Coordination involving the substrate could influence the course of the Grignard reaction.

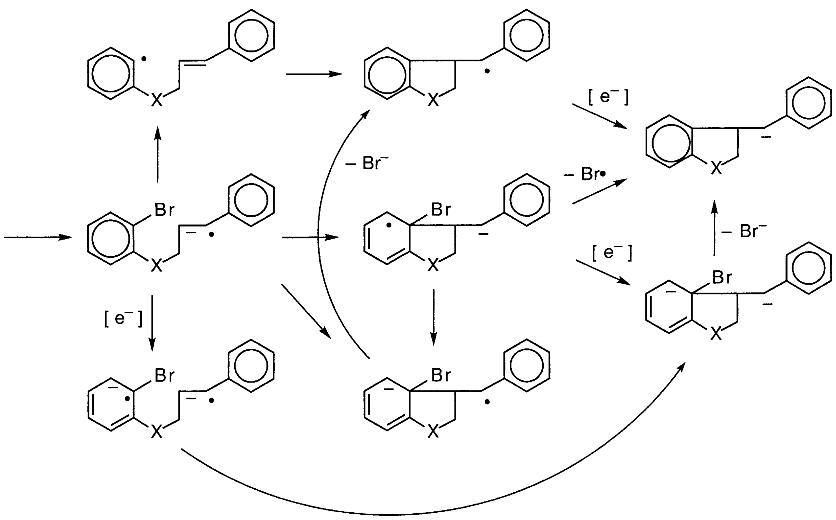
For both the "hydrocarbon" and "ether" substrates, there is yet another complication. The aryl bromide moiety is not the only plausible site of reduction. The second is the styryl group. Indeed, reduction there of the "ether" substrate provides a plausible pathway to *o*-bromophenol, and this could be the origin of that product:



This is made especially likely by the fact that debromo analog of the "ether" substrate undergoes this reaction [56].

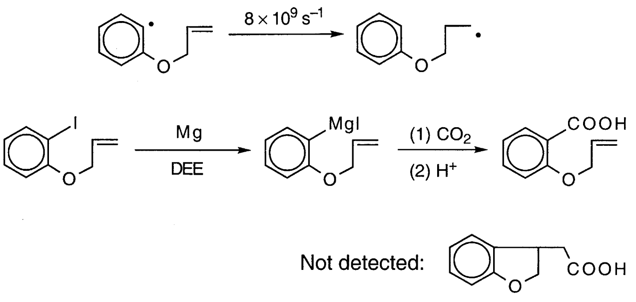
The reduction of the styryl group is a plausible first step of the Grignard reactions of both the "hydrocarbon" and "ether" substrates. One can envision subsequent pathways to cyclic products, including QMgX, which is represented as an anion in the scheme below:

X = CH_2 or O



These considerations cast doubt on the validity of the "hydrocarbon" and "ether" substrates as probes of mechanisms of Grignard reagent formation and other reductions. Isomerizations in the corresponding Grignard reactions could be artifacts arising through other processes.

A report from Walter [58], who studied the Grignard reaction of *o*-allyoxyiodobenzene in DEE, casts additional doubt. Despite the large value of k_Q for this probe, no isomerized Grignard reagent was detected:

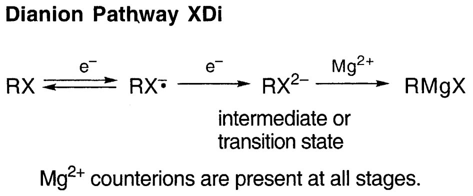


Strangely, Walter found less isomerization for the faster probe, *o*-allyoxyiodobenzene, than Garst et al. found for *o*-(3-butenyl)phenyl iodide [52]. Further, despite the facts that (1) the *o*-allyoxyphenyl radical has a value of k_Q that is similar to that for the "hydrocarbon" probe and (2) Garst et al. found more isomerization for iodides than bromides and more in DEE than THF, there is more isomerization for "hydrocarbon" bromide/THF than for *o*-(3-butenyl)phenyl iodide/DEE.

Until ambiguities are resolved, the evidence for **XR** provided by the "hydrocarbon" and "ether" probes should be regarded with caution.

2.10.8. Dianion pathway *XDi*

If **XR** applied, why would the extent of **X** correlate with increasing conjugation (Table 8)? This is better explained by a "dianion" pathway **XDi**. In the conversion of RX to RMgX, two electrons are delivered (formally) from Mg to RX. Along **XDi** the second electron is delivered while R and X are still together. If the "extra" electrons occupy π orbitals in the dianion intermediate or transition state, then increasing conjugation will stabilize it:



2.10.9. *Solvent and salt effects*

With a higher dielectric constant, THF (7.4) is a considerably more polar solvent than DEE (4.3). For Grignard reactions of *o*-(3-butenyl)phenyl bromide and iodide, isomerization decreases in going from DEE to THF (Table 6). Similarly, isomerization decreases when the polarity of the medium is increased by adding salts ($MgBr_2$ in DEE, $MgCl_2$ in THF). The apparent extent of pathway **X** increases with increasing polarity of the medium (Table 8). Is this consistent with **XDi**?

In gas-phase ion pairs, smaller and more highly charged anions interact more strongly with metal ions, that is, they have higher "cation affinities" [59]. Anions of higher cation affinity also have stronger ion–dipole interactions, including hydrogen bonding.

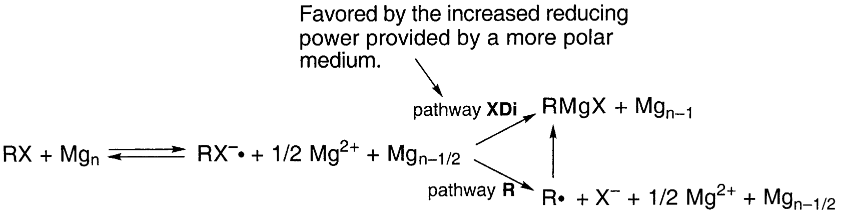
In polar protic solvents, where ions are free, anions of higher cation affinity are favored by more polar solvents, by which they are more strongly solvated. In less polar aprotic solvents, where ions are in ion pairs or higher aggregates, anions of higher cation affinity are favored by less polar solvents, where there is less competition between interionic Coulombic attractions and ion solvation. This is the essence of the principle of inversion of solvent effects (PISE) [59].

For **XDi**, the transition-state anion will have a higher cation affinity than the monoanionic transition state that leads to $R^\bullet$. A naive application of the PISE indicates that a more polar ether should favor pathway **R**. This is opposite what is observed.

Actually, the PISE applies only when the metal ions are spectators, that is, when they are neither formed nor destroyed as anions change from reactants to products. In Grignard reactions and other metallic corrosions, metal ions are formed in the reaction itself.

The loss of Mg^{2+} and its stabilization in the medium by solvation and ionic aggregation drives reductions by Mg. The more polar ether THF provides better cation solvation and consequently more reducing power than DEE. Similarly, ethers containing salts provide more reducing power than salt-free ethers.

More reducing power can increase the rate of formation of the **XDi** transition state $[RX^{2-}]^\ddagger$ from $RX^{\bullet-}$ without increasing the rate at which $RX^{\bullet-}$ disappears by fragmentation. Consequently, more polar media can favor **XDi**:



Despite intensive study of electrochemical reductions of aryl halides in solvents of high polarity [60,61], dianion reductions have not been detected. In the electrochemical reductions there is no stabilization of the dianion transition state by extensive ionic aggregation, the countercations are spectators, and they are not metal cations. Perhaps these differences could allow a dianion pathway to be favored in Grignard reactions but not in electrochemical reductions of the same aryl halides (GU, 224–225).

2.10.10. *Radical lifetime and extent of diffusion*

For a pathway **XR**, consider the implications of very short lifetimes of radicals $R^\bullet$. How far would they diffuse from Mg_Z?

The excursion probability χ is a useful measure (GU, 202) $-\chi$ is the probability that an $R^\bullet$ that is inert in every reaction except **r** will reach a separation *s* from Mg_Z (before suffering **r** and being converted to RMgX):

$$\chi = \frac{(D\tau_R)^{1/2}}{[(D\tau_R)^{1/2} + s]}$$

Let $s_{1/2}$ be the excursion distance for which $\chi = 1/2$. Then $s_{1/2}$ is given by the following relationship:

$$s_{1/2} = (D\tau_R)^{1/2}$$

Table 9 gives $s_{1/2}$ for various values of τ_R.

For *o*-(3-butenyl)phenyl bromide in THF and THF/$MgCl_2$, the square-root-law values of τ_R are near 10^{-14} s (Table 7), corresponding to $s_{1/2} = 0.055$ Å. On this time scale, there is almost no diffusion and the significant motions of molecules are pseudo-oscillatory, within the "cage" defined by Mg_Z and solvent molecules. Indeed, all of the values of τ_R in Table 7 are $\sim 10^{-10}$ s or less, and so are the values for the "hydrocarbon" and "ether" probes, corresponding to $s_{1/2}$ $\sim$5 Å or less.

If diffusion is not significant, then perhaps the square-root law does not apply. Instead, a simple first-order law, $q = k_Q\tau_R$, might be appropriate. Recalculation of τ_R on this basis gives longer lifetimes, in the range 10^{-12} to 10^{-10} s, the shortest being 2×10^{-12} s [*o*-(3-butenyl)phenyl

Table 9
Excursion limits $s_{1/2}$

τ_R (s)	$s_{1/2}$ (Å)
10^{-7}	173.0
10^{-8}	55.0
10^{-9}	17.0
10^{-10}	5.5
10^{-11}	1.7
10^{-12}	0.55
10^{-13}	0.17
10^{-14}	0.055
10^{-15}	0.017

Values of $s_{1/2}$ are calculated for a typical value of D, 3×10^{11} Å^2 s^{-1}.

bromide/THF/MgCl$_2$]. For each of the "hydrocarbon" and "ether" probes, the corresponding value is 4×10^{-11} s, corresponding to $s_{1/2} = 3.5$ Å. Even on this basis one must conclude that if an aryl R$^\bullet$ is an intermediate it never gets very far from Mg$_Z$ during its lifetime (Table 9).

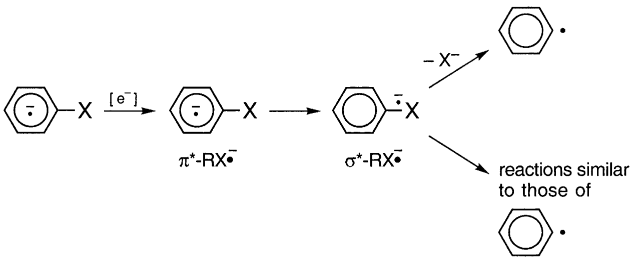
Along pathway **XR**, R$^\bullet$ and X$^-$ are created as solvent-caged, contact, geminate pairs. How much separation of R$^\bullet$ and X$^-$ occurs on such short time scales as those derived from observed extents of isomerization?

For $D = 6 \times 10^{11}$ Å^2 s^{-1} (two diffusing species, twice that for a single diffusing species) and the smallest value of τ_R (2×10^{-12} s) derived from the first-order law, $(6D\tau_R)^{1/2} = 2.7$ Å, implying that there little separation of R$^\bullet$ from X$^-$ during the lifetime of R$^\bullet$. If the square-root law applied, values of τ_R would be even smaller and there would be less separation. A small separation is also implied by Fig. 9, from which it is seen that 70–90% of inert AB pairs, created with A and B in contact, survive at times 10^{-12} to 10^{-11} s—many of these will remain in, or will have returned to, contact.

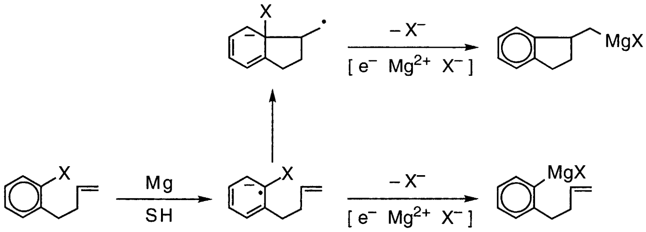
The assumption of pathway **XR** implies that much of the observed isomerization must occur while R$^\bullet$ and X$^-$ are contact partners in a solvent cage. Would such an R$^\bullet$ be an unencumbered radical? Would its isomerization rate constant be the same as that for a "free" radical in solution?

2.10.11. *Anton-radicals RX$^{\bullet -}$*

The literature suggests that an R$^\bullet$ adjacent to an X$^-$ in solution would probably not act as an unencumbered radical and that its isomerization rate constant would probably be less than that for a "free" radical in solution. Symons has provided evidence that adjacent carbon-centered radicals and halide ions bond, at least weakly. By ESR, in a low-temperature matrix, he observed the σ* anion–radical of phenyl iodide [62–65]. He hypothesized that σ*-RX$^{\bullet -}$ is what fragments, not π*-RX$^{\bullet -}$, and that σ*-RX$^{\bullet -}$ can undergo reactions similar to those of R$^\bullet$:



If, for aryl Grignard reactions, the species that isomerizes and is reduced is an adjacent pair [R$^\bullet$X$^-$], as lifetimes suggest if pathway **XR** is assumed, then that species is a version of RX$^{\bullet -}$. If there is significant σ bonding between R$^\bullet$ and X$^-$, then the adjacent pair is really σ*-RX$^{\bullet -}$ and lifetime calculations based on cyclization rates for unencumbered radicals R$^\bullet$ are invalid. It is also possible that π*-RX$^{\bullet -}$ is the species that cyclizes and is reduced, in which case lifetime calculations would also be invalid:

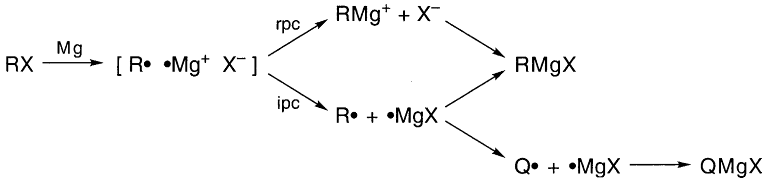


For reductions of [R$^\bullet$ X$^-$], σ*-RX$^{\bullet -}$, and π*-RX$^{\bullet -}$, the transition state has the composition [RX]$^{2-}$, plus counterions and solvent. Therefore all of these are "dianion" pathways **XDi**. Along **XDi**, any isomerization that may occur is not due to a reaction of unencumbered R$^\bullet$.

Similarly, Walborsky's proposed reduction of RX through a "tight radical pair" [RX$^{\bullet -}$ $^\bullet$MgX$^+$] is a dianion pathway **XDi** [40]. Although this proposal did not draw immediate criticism in 1973, a similar proposition in another context did later. In 1991, based on anomalies in S$_{RN}$ and related reactions that might be explained by their hypothesis, the Denneys suggested that aryl-halide anion–radicals RX$^{\bullet -}$ might be the reactants in some of the reactions that had been assigned to aryl radicals R$^\bullet$ [66]. Bunnett seriously questioned this but did not refute the proposal rigorously, leaving the matter unresolved [67]. The relevance here is that the Denney's and Symons' proposals are ideological analogs of dianion reduction pathways in Grignard reagent formation.

2.10.12. *Triad mechanism*

Berg et al. have proposed a mechanism in which a geminate "triad," [R$^\bullet$ $^\bullet$Mg$^+$ X$^-$], suffers ion pair collapse (ipc) or radical pair collapse (rpc) [68]:



Rpc and ipc are presumed to be too fast to allow $Q^\bullet$ formation in the triad and once rpc has occurred there is no further opportunity. Thus, RMgX is formed through rpc and ipc while QMgX is formed only through ipc.

The triad mechanism introduces a layer of complexity for which there is no evidence. In addition, $^\bullet Mg^+$ and $^\bullet MgX$ are unlikely intermediates, as noted previously.

2.10.13. Conclusions

(1) **DDD** cannot be the exclusive pathway for aryl halides because some of the implied lifetimes τ_R of $R^\bullet$ are unrealistically short. There must be a pathway **X**.
(2) If aryl halides react partly through **D7**, **DDD** with $\tau_R = 1 \times 10^{-7}$ s, and partly through a pathway **X0**, along which there is no isomerization, then the extent of **X0** is sometimes very nearly 100% (Table 8).
(3) A pathway **XR**, along which $R^\bullet$ is an intermediate with an extremely short lifetime, is an alternative to **X0**.
(4) Attempts to detect **XR** using very fast probes have provided inconsistent results that are subject to other interpretations.
(5) If a pathway **XR** applied, then the lifetimes of intermediate radicals $R^\bullet$ would be so short that many would remain at Mg_Z in geminate pairs $[R^\bullet\ X^-]$ until they were reduced to RMgX. Since radicals $R^\bullet$ interact with partial bonding to adjacent halide ions, $[R^\bullet\ X^-]$ is really a version of the anion–radical $RX^{\bullet-}$. Because reductions of $RX^{\bullet-}$ proceed through dianion transition states $[RX^{2-}]^\ddagger$ a pathway through $[R^\bullet\ X^-]$ is a dianion pathway **XDi**.
(6) If there is a transition state that resembles π^*-RX^{2-}, a pathway **XDi** could explain why the extent of pathway **X** increases with increasing conjugation (Table 8).
(7) **XDi** should be favored by the increased reducing power provided by the more polar ether THF and the presence of salts ($MgBr_2$, $MgCl_2$), as is observed.
(8) The balance of available evidence favors **XDi** as the pathway that competes with **R**. If so, then **XDi** is negligible for alkyl halides and **R** is negligible for aryl halides in THF. In other cases pathways **R** and **XDi** are both significant.

3. The “oxide” layer and the induction period

As received, or after exposure to the atmosphere, the surface Mg_Z is coated with an “oxide” layer that gives it a dull finish. During a Grignard reaction it often gains a metallic luster, suggesting that the “oxide” layer has been removed.

A passivating “oxide” layer could be responsible for the induction period, which would consist of the early stages of reaction during which it was being lost. When Mg_Z was fully exposed the reaction could proceed freely. This is the “surface-cleaning” hypothesis.

1,2-Dibromoethane is often used as a promoter. Although the effective action could be surface cleaning, it is not obvious that this must be so. In conventional laboratory experiments the initial presence or absence of $MgBr_2$ can be critical. Thus, in the absence of $MgBr_2$ there is a pronounced induction period in the Grignard reaction of cyclopropyl bromide in DEE, while in its presence there is none (Fig. 1) [15].

Since $BrCH_2CH_2Br$ reacts with Mg to give $MgBr_2$, perhaps it is an effective promoter simply because it generates this soluble salt. In promoting the Grignard reaction of 2,2,3,3-tetramethylcyclopropyl bromide, $MgBr_2$ is effective whether or not Mg_Z has been “etched” by reaction with $BrCH_2CH_2Br$ prior to the introduction of RBr. “Etching” is not effective when $MgBr_2$ is absent (GU, 257–259) [15].

These facts suggests the “autocatalysis” hypothesis. Polar solutes such as $MgBr_2$, and probably RMgBr as well, enhance the rates of Grignard reactions. Since they are absent initially but are formed as a reaction proceeds, Grignard reactions are autocatalytic. They are very slow initially but they accelerate as autocatalytic species build up during the induction period.

Whether or not surface cleaning is responsible for the induction period, the change in the luster of Mg_Z during a Grignard reaction suggests that it *does* occur. Understanding these reactions requires understanding the “oxide” layer.

In the studies of Abreu [5,69–71], a selected crystal plane of a clean, single crystal of Mg was exposed in an ultra-high-vacuum (UHV) apparatus. Potentially reactive gases were leaked in and the various surfaces were characterized by spectroscopic and diffraction methods. Treatments with liquids were made possible by transferring samples between the high-vacuum chamber and an antechamber where ordinary laboratory operations could be performed. This approach maximizes information gain. However, Grignard reactions are ordinarily carried using polycrystalline Mg (turnings, chips, rods, powder, etc.), making it essential that polycrystalline Mg be studied. Abreu studied single- and polycrystalline Mg; surface reactions with O_2, CO_2, H_2O, and 6% aqueous HNO_3; and interactions of MgO- and $Mg(OH)_2$-coated Mg_Z with $MgBr_2$ and $BrCH_2CH_2Br$ [5,69–71].

Nitric acid treatments were suggested by earlier work. “To remove the oxide film and to decrease the density of defects generated in producing the surface”, Hill et al. “polished” Mg_Z by treating it with 6% aqueous HNO_3 [14]. Although this treatment may reduce defects, it turns out that it does not remove the oxide film. Instead, it leaves an even thicker film. This proved to be valuable in our studies, but the method is not effective for activating magnesium.

It was expected that the “oxide” layer might contain MgO, $Mg(OH)_2$, $MgCO_3$, $Mg(HCO_3)_2$, or some mixture of these, but its actual composition was unknown. X-ray photoelectron spectroscopy (XPS) can distinguish between the oxygen atoms of O^{2-} and ^-OH and between the carbon atoms of ${CO_3}^{2-}$ and ${HCO_3}^-$. XPS showed that the “oxide” layer on polycrystalline Mg_Z, whether it is “out of the bottle” or etched with dilute aqueous HNO_3, is really $Mg(OH)_2$ containing a little $Mg(HCO_3)_2$ in its outer layers (GU, 255) [5,70]. MgO and $MgCO_3$ were not detected, although MgO could be generated by baking Mg_Z–$Mg(OH)_2$. After baking, exposure to the atmosphere for several days restored the surface to its original state, primarily $Mg(OH)_2$.

To determine whether or not $MgBr_2$ or $BrCH_2CH_2Br$ bears a direct role in the removal of oxide or hydroxide from Mg_Z, their interactions with oxided or hydroxided Mg_Z were studied. Two leading hypotheses were considered. (1) $MgBr_2$ promotes surface cleaning by hastening the dissolution of the "oxide" layer. (2) The reaction of $BrCH_2CH_2Br$ with Mg_Z occurs underneath the "oxide" crust and is made possible by the seepage through defects or channels in the oxide film.

A partial resolution of this question can be attained by a comparative study of the reactivities of three types of Mg-oxide/hydroxide surfaces: (i) a well-defined Mg(0 0 0 1)–MgO(1 0 0) single-crystal surface, (ii) an air-exposed polycrystalline Mg surface, and (iii) an aqueous-acid-etched polycrystalline Mg surface. A well-ordered Mg(0 0 0 1)–MgO(1 0 0) surface contains minimal defects, and it has been shown to be unreactive towards CO_2 [70], an acid–base reaction that proceeds fairly rapidly when the oxide is disordered [72,73]. In comparison, the polycrystalline samples are covered with a layer consisting mostly of $Mg(OH)_2$ [5,69,71]. Such films are disordered and an abundance of channel-defects exists. They have been found to be rather reactive [5,69–73]. The hydroxide overlayer on the aqueous-acid-etched Mg is more than twice as thick as that on the untreated (non-etched) surface. This is a relevant difference since, even if channel-defects remain plentiful, the increased thickness may enforce a more tortuous path towards the metal substrate; retarded reaction rates would thus be a consequence if such a mechanism were rate-limiting.

The Mg(0 0 0 1)–MgO(1 0 0) surface was prepared in a UHV chamber by exposure of Mg(0 0 0 1) to a low dosage of high-purity O_2 [70]. The long-range order of the surface oxide is evident from the low-energy electron diffraction (LEED) pattern shown in Fig. 11; included in this Figure is the real-space structure of the MgO adlayer. Based upon Auger electron spectroscopy (AES) measurements, the thickness of the MgO film was estimated to be 18 Å [70]. Reactions between this surface and the promoters were carried out in an ante-chamber under an inert-gas (Ar) atmosphere.

UHV sample-preparation protocols were not required for the polycrystalline materials. Hence, although the reactions were also carried out in an Ar environment, transfer of the samples from the reaction vessel to the X-ray photoelectron spectrometer for surface characterization briefly exposed them to atmospheric O_2 and H_2O. From XPS measurements, the thickness of the $Mg(OH)_2$ film for the untreated sample was estimated to be 16 Å; for the sample etched with 6% HNO_3, the overlayer thickness was greater than 36 Å [5].

Fig. 12 shows AES spectra for the Mg(0 0 0 1)–MgO(1 0 0) surface prior to (Fig. 12(a)) and after 3 min immersions in ethereal $MgBr_2$ (Fig. 12(b)) and $BrCH_2CH_2Br$ (Fig. 12(c)) solutions.

For the unreacted MgO(1 0 0), only two signals, one for Mg and another for O, were observed.

After exposure to $MgBr_2$, two new peaks emerged; one at 100 eV, is characteristic of Br, and the other at 270 eV is attributable to C. The presence of Br is most likely due to solid $MgBr_2$ not removed even after multiple rinses with pure DEE. The presence of C, on the other hand, may have been a result of a reaction between *residual* $BrCH_2CH_2Br$ with *metallic* Mg. $BrCH_2CH_2Br$ is a starting material in the preparation of ethereal $MgBr_2$.

The AES spectrum for the $BrCH_2CH_2Br$-exposed Mg(0 0 0 1)–MgO(1 0 0), Fig. 12(c), indicates the absence of surface Br. However, a slight diminution of the O peak can be noted, concomitant with a slight increase in both the C and Mg peak intensities.

The data in Fig. 12(b) and (c) convey the impression that $BrCH_2CH_2Br$ is only slightly reactive, while

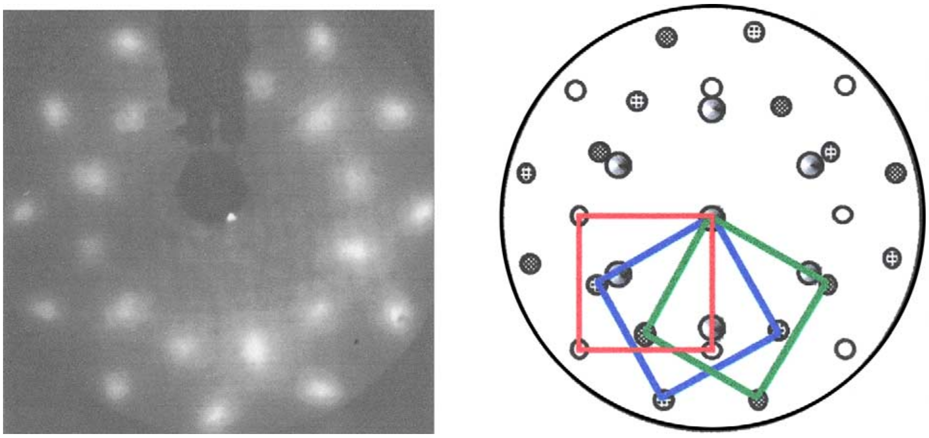


Fig. 11. LEED pattern for clean and ordered Mg(0 0 0 1) after 10 l O_2 exposure. $E_p = 52.0$ eV. Schematic LEED pattern of the Mg(0 0 0 1) surface with Mg(1 0 0) unit cell shown in three equivalent domains.

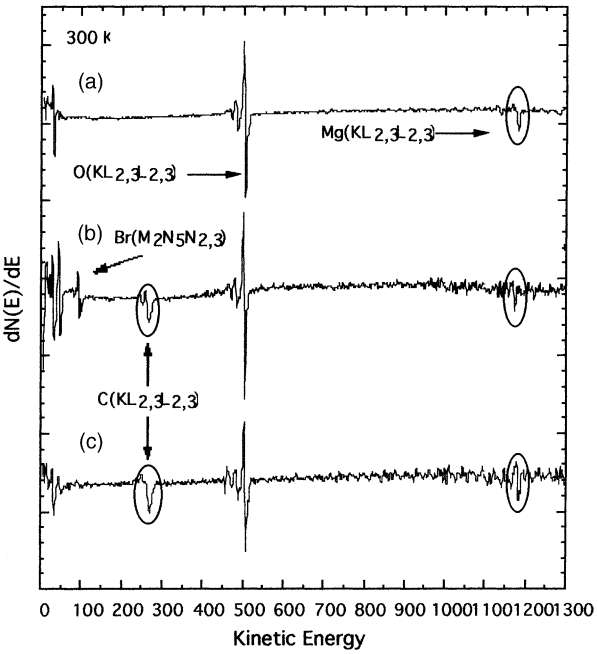


Fig. 12. Auger electron spectra for clean and ordered Mg(0 0 0 1): (a) after exposure to 10 L O_2 at 300 K, (b) surface in (a) after immersion into 2.6 M $MgBr_2$ in DEE at 300 K for 3 min, (c) surface in (a) after immersion into 0.5 M $Br_2H_2CH_2Br$ in DEE at 300 K for 3 min. AES conditions: incident beam energy = 2 keV, beam current = 1 μA.

$MgBr_2$ is completely inert, towards the well-ordered Mg(0 0 0 1)–MgO(1 0 0) surface. However, it cannot be established whether the Mg–$BrCH_2CH_2Br$ reaction is preceded by the dissolution of the oxide or if the $BrCH_2CH_2Br$ simply burrows through the film via the (sparse) channel-defects.

The “burrowing” scenario is suggested by both the implausibility of MgO dissolution and the fact that the O signal remains large. Support for this view is provided by experiments in which the exposure time was increased from 3 to 30 min. The results, in terms of AES spectra, are shown in Fig. 13; these are unmistakably identical to those in Fig. 12. The implication is that the reaction is sluggish because the promoters need to tunnel through the channel-defects which, in the well-ordered MgO(1 0 0) adlayer, are meager.

Critical insights into the role of channel-defects may be gleaned from a comparative study of the reactivities of the polycrystalline Mg with ethereal $BrCH_2CH_2Br$. Fig. 14 shows the XPS spectra for the untreated Mg turnings before and after immersion in $BrCH_2CH_2Br$ at various exposure times. As noted previously, the “oxide” layer here is primarily $Mg(OH)_2$.

The most significant trend is that, as the reaction proceeds, the O 1s signal (531 eV) is attenuated, whereas the Br 3d signal (70 eV) is increased. In order to ascertain if the attenuation of the O 1s peak is due to actual hydoxide removal or to simple formation of an insoluble $MgBr_2$ precipitate, the Mg 2p and the O 1s peaks were scrutinized in finer

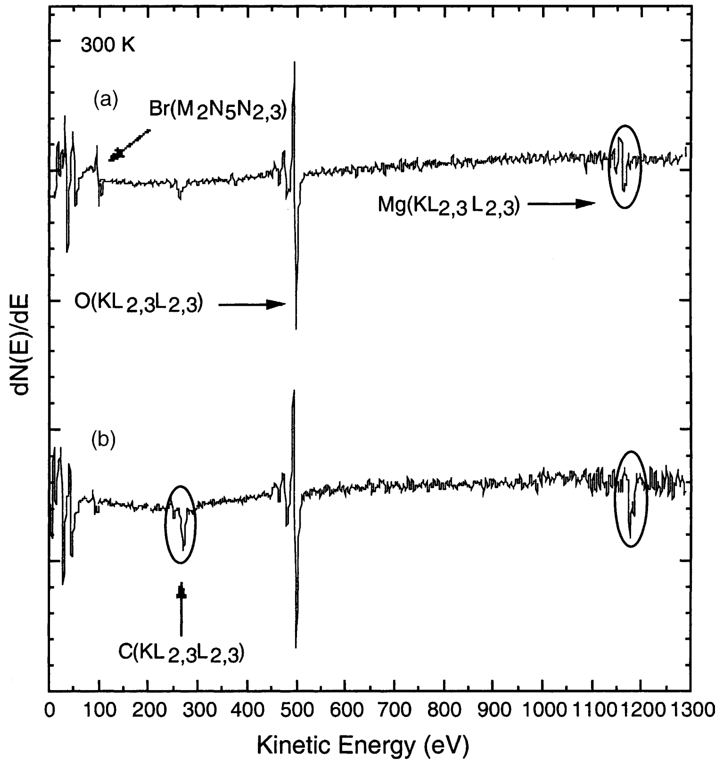


Fig. 13. Auger electron spectra for an ordered MgO(1 0 0) ultra-thin film: (a) after immersion into 2.6 M $MgBr_2$ in DEE at 300 K for 30 min, (b) after immersion into 0.5 M $BrCH_2CH_2Br$ in DEE at 300 K for 30 min. AES conditions: incident beam energy = 2 keV, beam current = 1 μA.

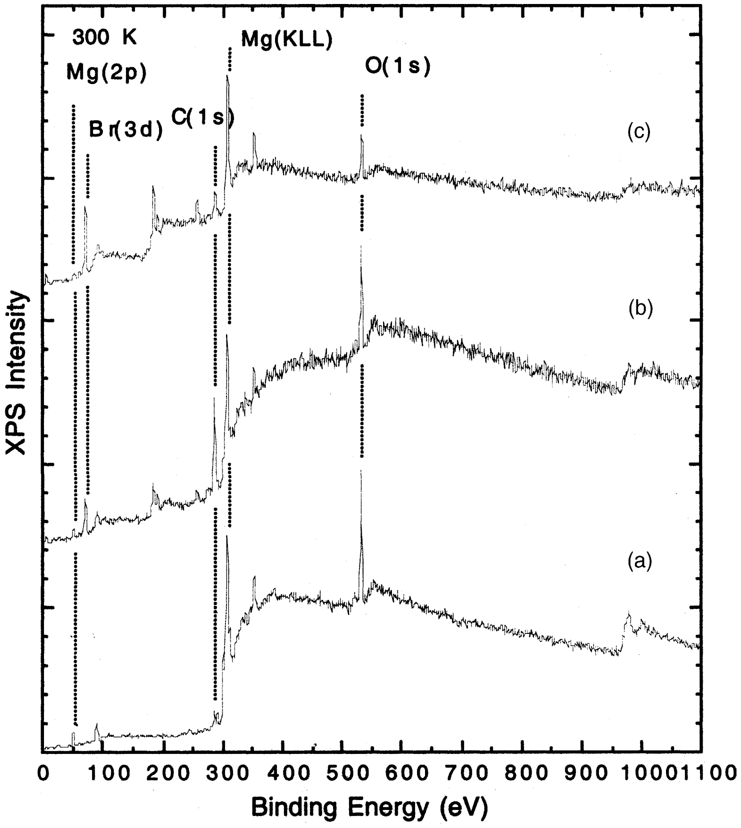


Fig. 14. X-ray photoelectron spectra of Mg turnings: (a) as received, (b) after immersion into 0.5 M $BrCH_2CH_2Br$ in DEE at 300 K for 10 min, (c) after immersion into 0.5 M $BrCH_2CH_2Br$ in DEE at 300 K for 60 min.

detail. Fig. 15 shows the O 1s peak intensity as a function of reaction time.

It is clear that, as the reaction time was increased from to 10 to 60 min, the amount of surface oxygen decreased. Removal of the original hydroxide crust upon exposure to $BrCH_2CH_2Br$ is thus demonstrated. The fact that the O surface coverage becomes constant at longer reaction times is most probably related to the *regeneration* of a hydroxide film when the post-reacted sample came in contact with atmospheric O_2 and H_2O upon transport to the XPS analysis chamber.

Fig. 16 gives the Mg 2p XPS spectra as a function of exposure time.

For the unreacted surface, the shoulder at the lower binding energy (E_B) is the *hydroxide-attenuated* peak for *metallic* Mg; the main peak at 50.5 eV is due to hydroxylated Mg [5,69,71]. As the reaction time was increased, two principal changes were observed: (i) the shoulder at lower E_B value disappeared, and (ii) the peak at 50.5 eV was shifted to higher E_B at 52 eV. Comparison with spectra for reference compounds indicated that the peak at 52 eV is due to the presence of bulk-like $MgBr_2$. These results provide evidence that a reaction has occurred between $BrCH_2CH_2Br$ and Mg in spite of the existence of a (disordered) $Mg(OH)_2$ film. Still, the mechanism for the removal of the overlayer, whether by promoter-induced chemical dissolution or by physical stripping brought about by the *underlayer* reactions, is not resolved.

A more definitive view of the interfacial processes can be obtained when the above results are combined with those for the acid-etched Mg turnings. Fig. 17 shows O 1s XPS spectra for the acid-etched samples after immersion in $BrCH_2CH_2Br$ for 10, 30 and 90 min.

In stark contrast to the data shown in Fig. 15, no changes in the peak intensities were noted. This can only signify that no reaction had transpired. Evidently, while channel-defects still abound in the hydroxide overlayer, the latter has become too thick. The paths to be taken by $BrCH_2CH_2Br$ through the film have thus become overly tortuous and only served to severely retard the reaction.

The conclusion that can drawn from the above results is that the $Mg(OH)_2$ mechanically passivates Mg_Z. The interfacial mechanism for $BrCH_2CH_2Br$ access to Mg_Z is by seepage through channel-defects. The hydroxide crust flakes off as it is stripped from the metal substrate by underlayer reactions.

There is evidence that Grignard reactions can result in the release of a small amount of metallic Mg from Mg_Z. Thus, in reactions of adamantyl bromide, Mg_Z becomes coated with a black deposit that probably consists mostly of biadamantyl but which appears to contain metallic Mg at a distance from Mg_Z [74]. The authors inter-

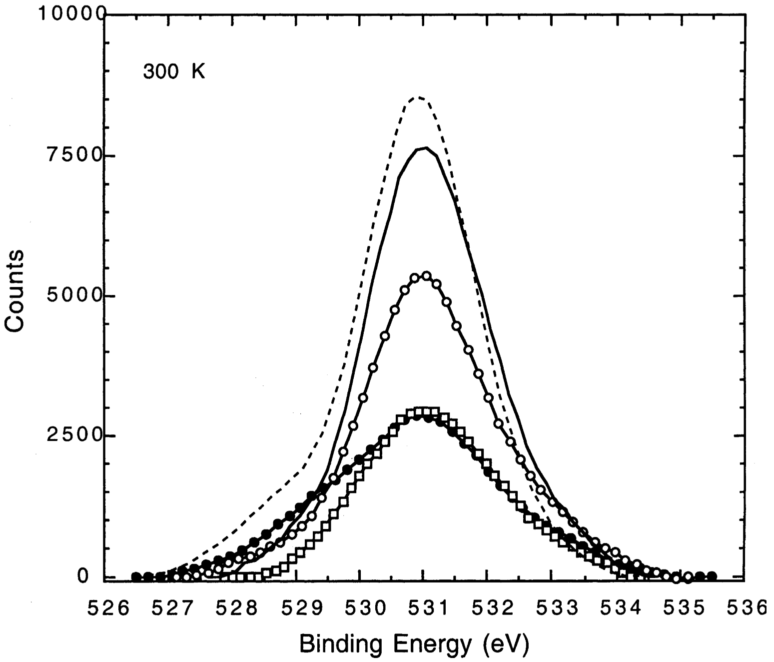


Fig. 15. Oxygen 1s X-ray photoelectron spectra for Mg turnings as-received (—), after immersion into 0.5 M $BrCH_2CH_2Br$ in DEE for 10 min (- - -), 30 min (○), 60 min (□) and 90 min (●).

preted the distant Mg as the disproportionation product of $^{\bullet}$MgBr.

$$2^{\bullet}\text{MgBr} \rightarrow \text{Mg} + \text{MgBr}_2$$
$$\text{(in solution, depositing Mg away from Mg}_\text{Z}\text{)}$$

It is more plausible that the distant Mg results from corrosive undercutting of the $Mg(OH)_2$. Undercutting is not likely to cleanly separate Mg_Z from $Mg(OH)_2$. The material that flakes off probably consists of small pieces Mg–$Mg(OH)_2$, in which some metallic Mg remains attached to the residue of the $Mg(OH)_2$ layer (GU, 256, Fig. 7.37). Stirring or convection would carry these pieces away from the bulk reactant Mg_Z, as found [74]. If the pieces were fine enough, they could also give the biadamantyl deposit its black color.

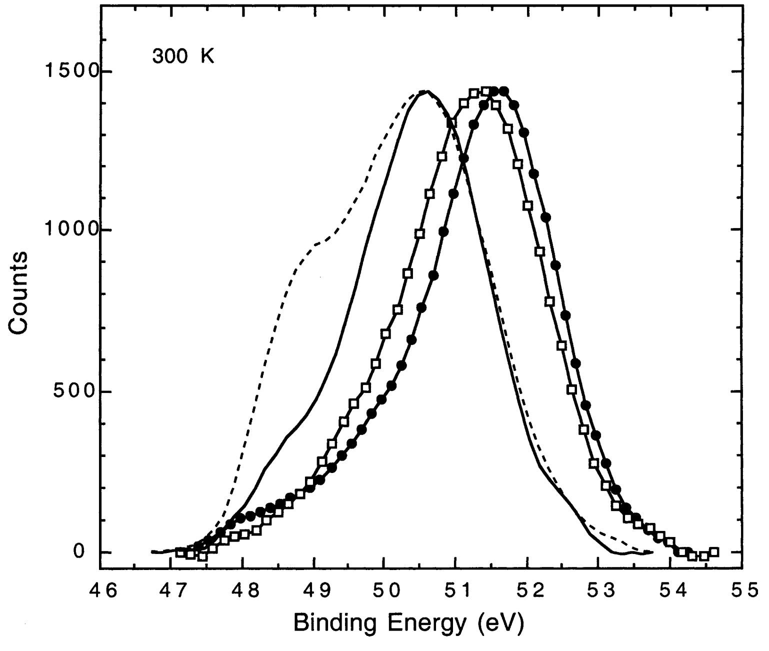


Fig. 16. Magnesium 2p X-ray photoelectron spectra for Mg turnings as-received (- - -), after immersion into 0.5 M $BrCH_2CH_2Br$ in DEE for 10 min (—), 60 min (□), and 90 min (●).

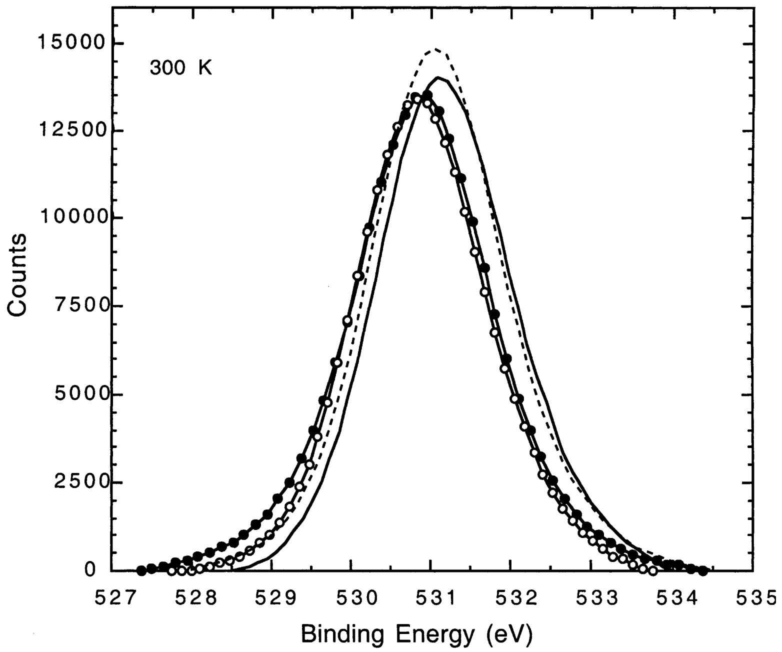


Fig. 17. Oxygen 1s X-ray photoelectron spectra for Mg turnings etched in 6% HNO_3 (- - -), etched Mg turnings after immersion into 0.5 M $BrCH_2CH_2Br$ in DEE for 10 min (—), 30 min (○), and 90 min (●).

$BrCH_2CH_2Br$ is both a Grignard-reaction promoter and a model substrate. Presumably, the reason that a Grignard reagent, $BrMgCH_2CH_2MgBr$, is not the final product is that an intermediate such as $BrCH_2CH_2MgBr$ decomposes to $CH_2{=}CH_2$ and $MgBr_2$.

Just as for $BrCH_2CH_2Br$, in pure DEE the overlayer of $Mg(OH)_2$ will mechanically impede the access of any RX to Mg_Z. This is sufficient to account for induction periods that are observed when no MgX_2 is present initially.

The fact that the initial presence of $MgBr_2$ in DEE eliminates the induction period, Fig. 1, still requires explanation. Three plausible actions reflect the higher polarity of $MgBr_2$-DEE than pure DEE. (1) By wetting and penetrating the disordered $Mg(OH)_2$ layer, perhaps enlarging its defect-channels, $MgBr_2$-DEE could enhance the diffusion of RX to Mg_Z. (2) By dissolving the $Mg(OH)_2$ layer, $MgBr_2$-DEE could clean Mg_Z. (3) By enhancing the reducing power of Mg_Z, $MgBr_2$-DEE could promote electron transfer to RX. These possibilities are not mutually exclusive.

4. Conclusions

For an alkyl halide, Grignard reagent formation in the reaction of Mg with RX proceeds through an intermediate radical $R^\bullet$ that diffuses in solution near the surface Mg_Z (pathway **R/DDD**). The lifetime τ_R of $R^\bullet$, as limited by its reduction at Mg_Z to RMgX, is near 10^{-7} s.

For a cyclopropyl or vinyl halide, pathway **R/DDD**, with a similar value of τ_R, describes part of the reaction. The other part is a pathway **X** along which there is no intermediate $R^\bullet$ or, if there is, it has an extremely short lifetime. For a vinyl halide with extended conjugation, pathway **X** can dominate.

The similarity of the values of τ_R for alkyl, cyclopropyl, and vinyl radicals may be a consequence of the necessity that all steps of the complex metallic corrosion process remain synchronized. In addition to electron transfer to $R^\bullet$, these steps include loss of Mg^{2+} from Mg_Z to solution, concomitant reorganization of the solvent and halide ions that may be present to accommodate Mg^{2+}, electron transfer to RX, and possibly conduction of ions between the anodic and cathodic sites on Mg_Z.

For an aryl halide in THF, pathway **X** dominates to the near exclusion of **R**. In DEE, there is more reaction along pathway **R** but its extent remains minor. The presence of a magnesium halide, $MgBr_2$ in DEE or $MgCl_2$ in THF, increases the importance of pathway **X**.

The correlation between the extents of conjugation and of pathway **X** suggests that it is a dianion pathway **XDi**, that is, a pathway along which the second electron is delivered to RX while its components, R and X, are still together. The transition state for **XDi** has the composition $[RX^{2-}]^\ddagger$ plus counterions and solvent.

The "oxide" layer than gives polycrystalline Mg its dull appearance consists primarily of $Mg(OH)_2$ and is about 16 Å thick. It contains a small amount of $HCO_3{}^-$ in its outer layers. No detectable amount of O^{2-} or $CO_3{}^{2-}$ is present.

The hydroxide layer is mechanically passivating. For an RX in pure DEE, the initial reaction is slow because RX must reach Mg_Z through defect-channels in the overlayer. Once RX, or a promoter such as $BrCH_2CH_2Br$, reaches Mg_Z, Grignard reactions there undercut the $Mg(OH)_2$ layer, which then flakes off, leaving Mg_Z exposed. This occurs during the induction period, after which the reaction proceeds rapidly.

In DEE, the initial presence of $MgBr_2$ can eliminate the induction period. This may be through one or more of the actions of $MgBr_2$-DEE in wetting, penetrating, and swelling the $Mg(OH)_2$ overlayer; dissolving it; and enhancing the reducing power of Mg_Z by stabilizing Mg^{2+} in solution.

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