On the Mechanism of the Conversion of Methanol to 2,2,3-Trimethylbutane (Triptane) over Zinc Iodide

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## Supporting Information

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NMR of triptane synthesized from $^{12}CH_3OH + {}^{13}CH_3{}^{13}CH_2OH$

A thick-walled glass tube was charged with 1.06 g ZnI_2, 0.21 g $^{12}CH_3OH$, and 0.064 g $^{13}CH_3{}^{13}CH_2OH$. The composition corresponds to a molar ratio of MeOH:EtOH = 4.7:1, and a total carbon isotope ratio of ^{13}C:^{12}C = 30:70.

The tube was sealed under vacuum and heated in an oven at 200 °C, without agitation, for 4 h, and the organic layer extracted for examination by ^{13}C NMR spectroscopy; a portion of the spectrum is shown in Figure S1. By comparison to the spectrum from an unlabeled reaction (see Figure 2, main text), it is clear that the signals for the internal carbons are considerably larger relative to those for the terminal methyls. Furthermore, each of the triptane signals consists of an apparent triplet — actually a singlet plus a doublet — showing that there is a significant probability (approximately 40%, from the relative intensities) that a ^{13}C nucleus in any position has an adjacent ^{13}C. The signals for C_b and C_c exhibit two additional outer peaks, corresponding to further overlap of a weak triplet signal arising from *two* adjacent ^{13}C nuclei, implying that some label must get into methyl groups as well.

Figure S1. Part of ^{13}C NMR spectra showing triptane signals for reaction of unlabeled MeOH with ^{13}CH$_3$^{13}CH$_2$OH.
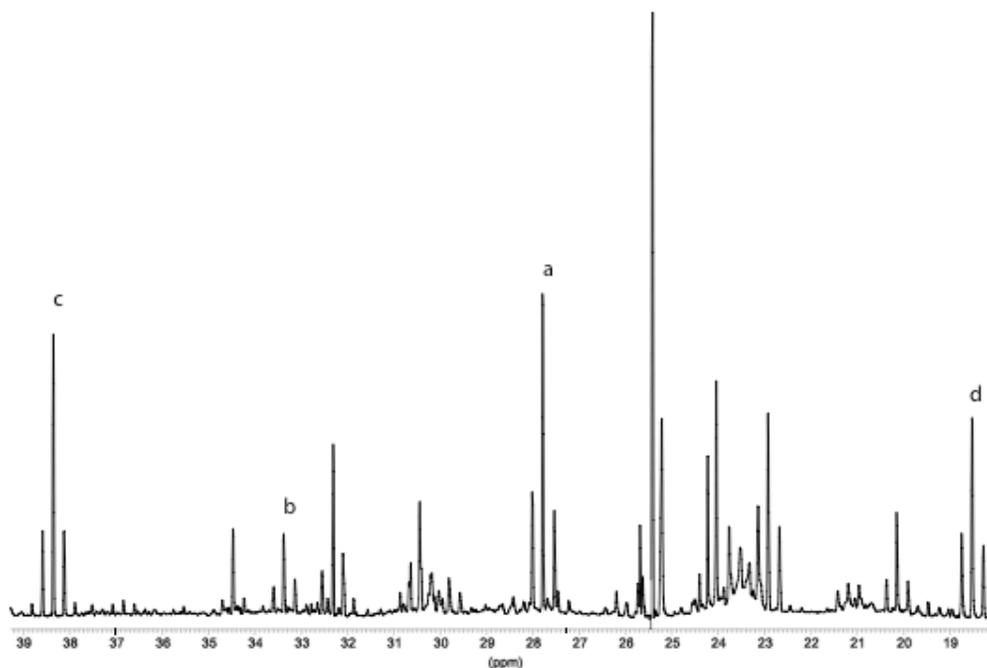
The intensities (as peak heights) of the various signals are shown in Table S1 — those for the weak outer peaks of the C_b and C_c signals are very approximate — along with the derived relative proportions of singlets and multiplets. The relative amount of ^{13}C at each position is calculated from the peak heights and sensitivity factors, determined from the corresponding relative peak heights in a spectrum of unlabeled triptane, acquired under the same spectrometer conditions. The reliability of the latter values is probably no better than ± 25-50%, so the difference between C_b and C_c is not significant; the fact that the terminal positions (methyls and methylene) of triptene readily exchange (see main text) requires that the two internal positions have equal label occupancy. Even so, the relative enrichment in the internal vs. terminal positions is quite clear.
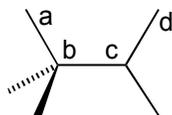
Table S1. NMR data for triptane from $^{12}CH_3OH + {}^{13}CH_3{}^{13}CH_2OH$

|	C_a	C_b	C_c	C_d
Chemical shift (ppm)	27.8	33.4	38.4	18.5
Approximate splitting pattern	1:3:1	1:10:30:10:1	1:8:27:8:1	1:3:1
Analysis of pattern	singlet: 59% doublet: 41%	singlet: 46% doublet: 39% triplet: 14%	singlet: 55% doublet: 36% triplet: 9%	singlet: 56% doublet: 44%
Total intensity (sum of peak heights)	103.5	26	91	68.5
Relative ^{13}C content	1.5	1.7	2.9	1 (defined)
Expected for statistical incorporation	1.5	0.5	0.5	1

We may analyze the splitting patterns with respect to the alternative proposed mechanisms. In both carbene- and carbocation-based routes, the reaction starts with ethanol-derived ethylene, which is cyclopropanated/ring-opened or methylated to give propene, and so on up to triptene, which is hydrogenated to triptane. As shown in the main text, the number of moles of triptane obtained can exceed the number of moles of promoter, so some of the triptane presumably arises from ethylene that comes from methanol. Assuming that label can get into the general pool by some route, we need to consider three modes of its incorporation into the product: in molecules that start with EtOH-derived ethylene; in molecules that do *not* start with EtOH-derived ethylene; and in the growth stage for both types. The last of these will primarily place label at terminal (methyl) positions, and the second will give statistical distribution among all positions, no

matter what the mechanism. However, the mechanism is crucial for the consequences of the first mode.

Analysis of NMR for carbene mechanism

Let us first examine, and dispose of, the carbene route. Cyclopropanation of ethylene would give a *symmetric* intermediate. As we continue along the route (shown in Scheme S1), when we reach the 2-methylbut-2-ene stage, we find that the amount of label in the terminal methyl positions is equal to or greater than the amount in the internal positions, depending on whether the C_4 olefin is but-2-ene or isobutene. From that point on to triptane the position of the labels is fixed. Since the other two modes of incorporating label will distribute it either statistically or (for carbons introduced at later growth stages) preferentially in methyl positions, this route is inconsistent with the observation that more label is found in the internal positions of triptane.

Scheme S1
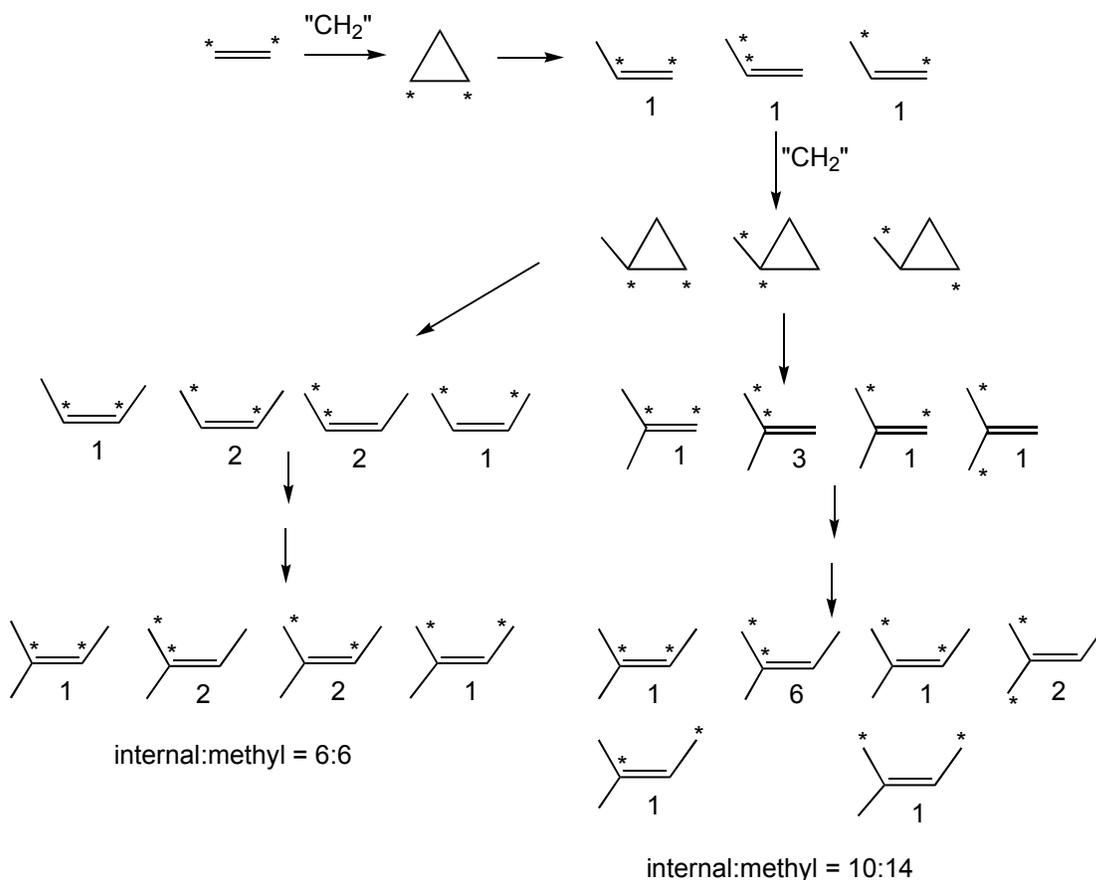
Analysis of NMR for carbocation mechanism

Now turn to our preferred, carbocation-based mechanism. Again, we first examine the

fate of label from incorporation mode 1 (from EtOH-derived ethylene). Even though

there is no symmetric intermediate, as in the prior case, the label will not all wind up in

internal positions because propene should be readily protonated/deprotonated under the

acidic reaction conditions, interconverting the two ends. Nor will the two ^{13}C nuclei

necessarily remain adjacent, as terminal positions of triptene were shown (main text) to

exchange rapidly as well. (Similar exchanges probably take place at other stages of

growth as well, but that does not affect the final outcome.) The expected labeling pattern

for triptane, neglecting for the moment any other mode of incorporation, is shown in

Scheme S2.

Scheme S2
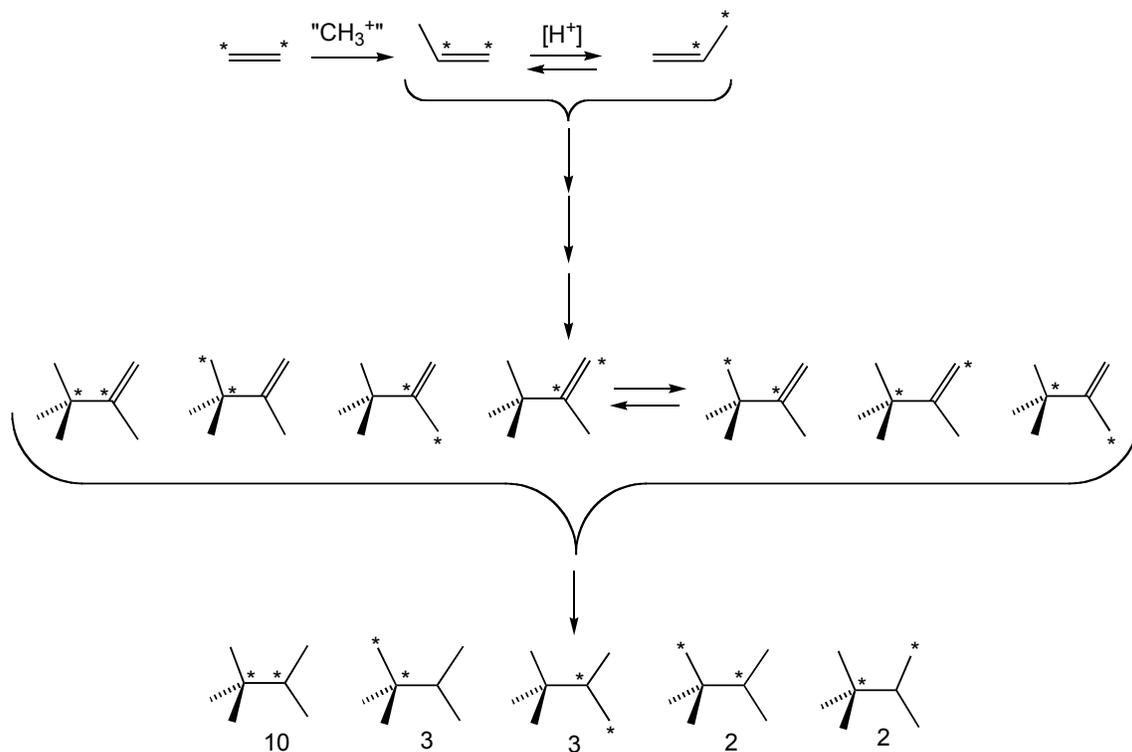
Straightforward statistical considerations predict the ratio of isotopomers shown, from

which one can calculate the relative occupancies of positions a:b:c:d = 1.5 : 3.75 : 3.75 :

1, in qualitative agreement with observations (Table S1); the predicted occupancy of

internal positions is somewhat too high, but perhaps not outside the range of precision of

(corrected) measurements. However, the splitting patterns come out completely wrong:

the internal signals should be mostly doublets (predicted singlet:doublet = 13:87 for b,

20:80 for c) which differ drastically from the observed values, which require no

correction factor and hence should be quite reliable. Furthermore, this inconsistency

cannot be "fixed" by including the other modes of label incorporation. There must be a mechanism for reducing the fraction of adjacent doubly-labeled isotopologs, which requires exchanging some label *out* of EtOH-derived molecules.

The additional process we propose to account for the label distribution is *reversible* methylation during growth: a carbocation formed by methylation of an olefin can lose proton to give the next higher olefin, *or* it can lose a methyl group to revert to the lower olefin. This will have the consequence of scrambling labeled methyl groups (formed as shown in Scheme S2) with the ordinary MeOH-derived methyl groups. Scheme S3 illustrates this process at the C_4 stage. (In principle it could occur at any stage of growth, with different rates relative to growth; the experiments on methylation of 2,3-dimethylbut-2-ene with labeled MeOH and on isotope shifts in labeled triptene (see main text) suggest that exchange is *not* fast at the C_6 to C_7 stage, although it should be noted those experiments were carried out at lower temperatures.)

Scheme S3
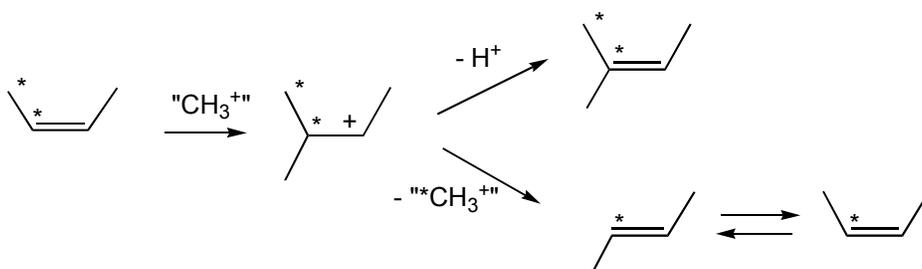
The experiment involving reaction of $^{13}CH_3OH$ and unlabeled *i*-PrOH (see main text) provides direct evidence that such a process does indeed operate. If so, isobutene derived from methylation of propene would retain the central ^{12}C but exchange any terminal ^{12}C

for ^{13}C. In the ^{13}C NMR spectrum of the gaseous products (condensed and redissolved) of that reaction, the signals for the olefinic carbons of isobutene are clearly distinguishable. That for the terminal carbon consists of a doublet ($^1J_{CC}$ ~ 71 Hz) of triplets ($^2J_{CC}$ ~ 3 Hz) along with a much weaker triplet in the middle, arising from the isotopologs $^{13}CH_2={}^{13}C({}^{13}CH_3)_2$ and $^{13}CH_2={}^{12}C({}^{13}CH_3)_2$ respectively; the relative total intensities are about 85:15. Thus in the latter isotopolog, which must have originated with (unlabeled) i-PrOH, the terminal methyls are essentially completely exchanged for ^{13}C. Because of facile proton exchange we would expect the methylene to be likewise completely labeled; in agreement, the signal for the central carbon is a doublet ($^1J_{CC}$ ~ 72 Hz) of triplets ($^1J_{CC}$ ~ 41 Hz).

Such a process will establish a quasi-equilibrated ("quasi" because we have no *a priori* way of knowing how fast the exchange process is compared to growth, although the above experiment suggests it is quite fast) pool of ^{12}C- and ^{13}C-methylating species, which will then participate in all subsequent steps — both methylation of intermediate olefins and synthesis of triptane directly from C_1 precursors. Hence the latter now must be included in the analysis as well.

We define x as the fraction of ^{13}C in the "methylating pool" that is established by these exchange processes (of course x may vary over time, but we only observe the final, time-averaged outcome); and y as the fraction of triptane molecules that originate from EtOH (as opposed to those arising entirely from MeOH). The initial propene population (before any methyl exchanges) will thus have the following isotopic composition:

y/2   y/2   1-y
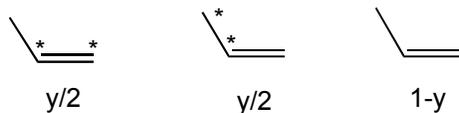
We could now allow these three isotopologs to grow to triptane, with the constraint that, at the end, all methyl groups will have probability x of being labeled. We further have to allow for the fact that an internal position of a triptane molecule formed only from C_1 precursors also has x probability of being labeled. We include statistical factors, and for the first approximation, neglect any isotopologs arising from incorporation of more than one ^{13}C from the methylating pool — i.e., we treat x^2 as negligibly small.

First, however, we must consider another question: do *any* di-labeled isotopologs survive (beyond those formed statistically, that is)? According to the postulated mechanism, the labeled methyl group in the middle isotopolog can exchange with the pool at all points along the growth process. But if the process occurs even at the C_3 stage, label will exchange out of the terminal (olefinic) position in the left-hand isotopomer, as shown in Scheme S4.

Scheme S4
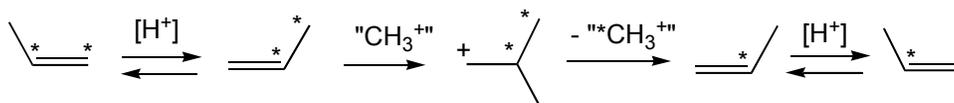
If that process is fast relative to growth, then the "founding population" will be, not the three isotopologs shown above, but just the following two:
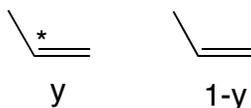
The $^{13}CH_3OH/i$-PrOH experiment (see above) suggests that there *is* a fast exchange process at the C_3 stage, as in Scheme S4, but it could also be explained by fast exchange at the C_4 stage if Scheme S3 is modified to include interconversion between but-2-ene and isobutene. Let us first try to complete the analysis assuming that exchange at this level does *not* take place, and triptane grows up from all three of the isotopologs above. In that case, the predicted triptane labeling distribution is shown in Scheme S5, and the consequent predicted NMR peak patterns in Table S2.
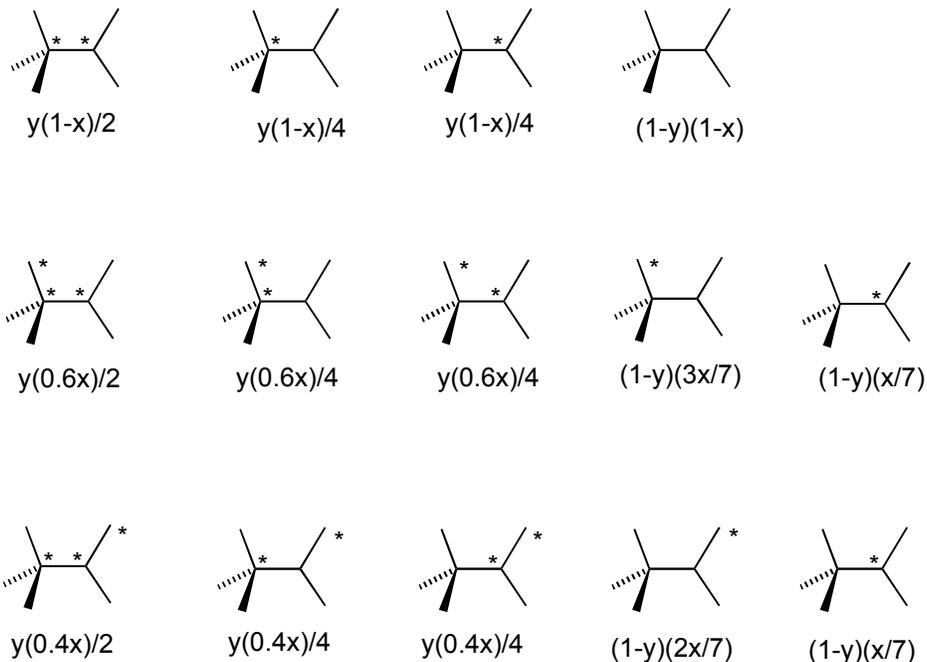
Scheme S5

y(1-x)/2   y(1-x)/4   y(1-x)/4   (1-y)(1-x)

y(0.6x)/2   y(0.6x)/4   y(0.6x)/4   (1-y)(3x/7)   (1-y)(x/7)

y(0.4x)/2   y(0.4x)/4   y(0.4x)/4   (1-y)(2x/7)   (1-y)(x/7)

Table S2. Predicted NMR peak intensities from distribution in Scheme S4

	C_a	C_b	C_c	C_d
Singlet	y(0.6x)/4 + (1-y)(3x/7)	y(1-x)/4 + y(0.4x)/4 + (1-y)(x/7)	y(1-x)/4 + y(0.6x)/4 + (1-y)(x/7)	y(0.4x)/4 + (1-y)(2x/7)
Doublet	y(0.6x)/2 + y(0.6x)/4	y(1-x)/2 + y(0.4x)/2 + y(0.6x)/4	y(1-x)/2 + y(0.6x)/2 + y(0.4x)/4	y(0.4x)/2 + y(0.4x)/4
Triplet	—	y(0.6x)/2	y(0.4x)/2	—

This model *cannot* satisfactorily account for the observed patterns. The easiest way to

see that is to note that the predicted singlet:doublet ratios for C_a and C_d are independent

of x. For C_a, singlet:doublet = 0.15y + 0.43(1-y) : 0.3y + 0.15y = 59:41, from which we

calculate y = 0.46; the analogous calculation for C_d gives y = 0.50. But if we try to use a

value for y around 0.5 to calculate x from similar equations for the singlet:doublet ratios

for C_b and C_c, we get negative values. We can fit the singlet:doublet ratios for the

internal carbons with much lower values of y; but then the methyl signals are predicted to

be almost entirely singlets. It is not possible to get the singlet:doublet ratios close to the

observed (~ 60:40) values for both internal and terminal positions simultaneously.

The alternative, then, must be the case: that only the central label in EtOH-derived

propene survives. Then the predicted final triptane speciation (again neglecting double

incorporation from the methylating pool for the time being; this is obviously not correct,

as it predicts no triplet signal for the internal carbons, but we will deal with that later) is

as shown in Scheme S6, and the intensity patterns in Table S3.
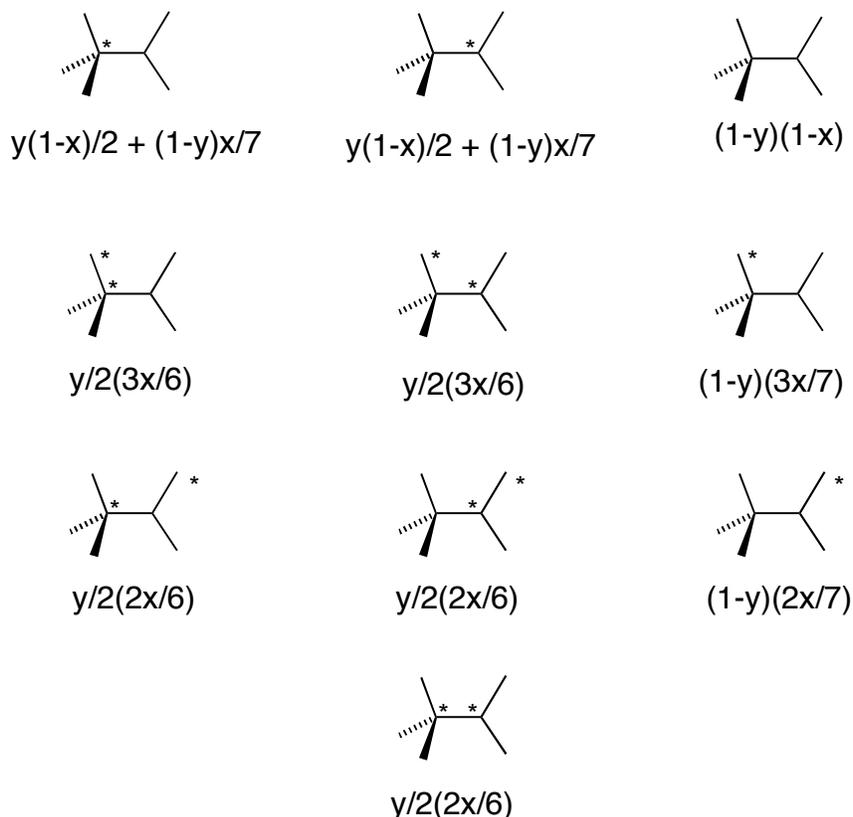
Scheme S6

y(1-x)/2 + (1-y)x/7   y(1-x)/2 + (1-y)x/7   (1-y)(1-x)

y/2(3x/6)   y/2(3x/6)   (1-y)(3x/7)

y/2(2x/6)   y/2(2x/6)   (1-y)(2x/7)

y/2(2x/6)

Table S3. Predicted NMR peak intensities from distribution in Scheme S6

	C_a	C_b	C_c	C_d
Singlet	xy/4 + (1-y)(3x/7)	y(1-x)/2 + (1-y)x/7 + xy/6	y(1-x)/2 + (1-y)x/7 + xy/4	xy/6 + (1-y)(2x/7)
Doublet	xy/4	5xy/12	xy/3	xy/6

In this case, if we solve for y using the terminal intensity ratios as before, and then use that value to solve for x using the internal ratios, a consistent solution *can* be found, with y ~ 0.8 and x ~ 0.6. We can now use those numbers to calculate the predicted intensities of *all* signals and compare to experimental results, as shown in Table S4. The agreement is quite good, certainly within the expected reliability of the data. Note that the intensities of the two internal peaks are predicted to be equal (as is obviously a requirement of the exchange steps in the mechanism); although the experimental (adjusted) values are not equal, the predicted value is very close to the average of the two.

Table S4. Comparison of experimental and predicted NMR data for approximate model

	C_a	C_b	C_c	C_d
Observed singlet:doublet	59:41	54:46	60:40	56:44
Predicted singlet:doublet	59:41	56:44	65:35	59:41
Observed relative intensity	1.5	1.7	2.9	1 (defined)
Predicted relative intensity	1.5	2.4	2.4	1

However, this successful modeling can amount only to a qualitative validation of the mechanism, because the approximation of incorporating only a single label from the pool per molecule — treating x^2 terms as negligible — is obviously incompatible with the large value of x obtained: there will be a large fraction of molecules with two or more such labels. (Those will account for the triplet components of the $C_{b,c}$ signals, of course.) The full statistical treatment cannot be solved analytically, as was the above approximation, but requires numerical fitting.

For simplicity let us assume that the mechanism described above is the *only* one for transferring label from EtOH into the general pool, and that the label introduced into internal positions from the general pool is small compared to that originating directly from EtOH. Since each EtOH-derived triptane molecule retains one labeled carbon and contributes the other to the pool, the probability of either internal position being labeled is y/2, and that for any one methyl position is y/(7(1-y) + 6y).

Calculated patterns for y = 0.6-1.0 are shown and compared to experimental results in Table S5. The best agreement for the C_a and C_c signals is obtained for y ≈ 0.7; for the C_b and C_c signals, y ≈ 0.9. Values outside this range give markedly poorer matches for all signals. The relative total intensity at each position is only slightly dependent on y in this model; the values are in reasonable agreement with observations, given the uncertainty of the latter as discussed earlier. Figure S2 shows the close match of observed and simulated splitting patterns for a value of y = 0.8, for the signals corresponding to C_c and C_d.

The fact that the y value calculated in the previous approximate model falls right in the middle of the range that gives acceptable fits for this more realistic one suggests that the value y will not depend strongly on the exact details chosen, and overall provides strong validation for the proposed mechanistic picture. It is likely that still better fits might be found by allowing x and y to vary independently, but the reliability/precision of the experimental data do not seem to warrant the (substantial) additional effort that would entail.

Table S5. Comparison of experimental and predicted NMR data for more realistic model.[a]

	C_a	C_b	C_c	C_d
Observed	59:41 1.5	46:39:14 1.7	55:36:9 2.9	56:44 1
Predicted y = 1.0	42:58 1.5	41:43:16 1.7	50:40:10 1.7	42:58 1
y = 0.9	47:53 1.5	47:41:12 1.8	55:37:8 1.8	48:52 1
y = 0.8	52:48 1.5	50:40:10 1.8	58:35:7 1.8	51:49 1
y = 0.7	57:43 1.5	55:37:8 1.9	63:32:5 1.9	59:41 1
y = 0.6	64:36 1.5	62:32:6 2.0	68:28:4 2.0	62:38 1

[a] For each entry the top line shows relative intensity of singlet:doublet:triplet; the second line the total relative intensity with that of C_d defined as 1.

Figure S2. Observed and simulated (y = 0.8) patterns for the C_c and C_d signals.