SELECTION RULES:

ALLOWED PROCESSES: You may consult your class notes, handouts, and problem sets; the 1986 exams; and any of the standard textbooks on orbital symmetry (those listed in Section 1, p. 3 of Books and Review Articles). You should also feel free to consult me when you run into difficulties; although I won't give away any answers, I will try to guide you to find the answer on your own.

FORBIDDEN PROCESSES: You may not search the primary literature or secondary review literature (except for the texts noted above) for answers to these questions, nor may you seek assistance from your classmates, from the faculty (other than "yr obdt srvt"), or anyone else.

There is no time limit (except for the deadline noted at the top of this page). Although the exam could be answered in a single setting, it's advisable to spread it out over several sessions. You ought to begin taking the exam fairly soon; it would be a terrible mistake to wait until near the deadline before starting. Once you have begun answering the exam, take care not to violate the ground rules listed above. [The literature references on which these questions are based will be distributed after the exams have been turned in, so that you won't be tempted to take "just a little peek."]

"Alas, the doors of fortune do not open inward so that by storming them one can force them open. They open outward, and so nothing can be done."
Søren Kierkegaard (In the earliest published reference to electrocyclic reactions)

"Like the college professor he was, Kittredge* grooped only for big words, and finding no apt ones he coined a lot of untranslatable new ones."
Kurt Vonnegut, Jr. (clearly a pseudonym for Woodward or Hoffmann)

"Any man who, upon looking at his bare feet, doesn't laugh has either no sense of symmetry or no sense of humor."
Rene Descartes (who used his toes rather than thumbs to demonstrate con and dis)

"I cannot give any scientist of any age better advice than this: The intensity of the conviction that a hypothesis is true has no bearing on whether it is true or not."
Peter Medawar (Nobel Laureate in Medicine and Physiology, 1960)

1. (25 points)

A. Consider the concerted transfer of two H's from eclipsed ethane to 1,3-butadiene, giving ethene and cis-2-butene.
Assume that the reactants approach in the geometry shown to the right.

1. Identify the various "reacting orbitals" of the reactants and products. Identify the symmetry element(s) which is(are) present throughout the reaction. Classify the reacting orbitals as symmetric or antisymmetric with respect to the symmetry element(s).

2. Construct the orbital correlation diagram; construct the electronic state correlation diagram for the ground states and first excited states of reactants and products.

3. Decide (with a brief justification) whether the concerted process is thermally or photochemically allowed.

B. The Diels-Alder reaction (e.g., of 1,3-butadiene plus ethene) is a symmetry-allowed \([\pi_4^s + \pi_2^s]\) process. Recently, it has been shown that reluctant diene/dienophile combinations can be accelerated by removing an electron from one of the partners using \(\text{Ar}_2\text{N}^+\). There are, in principle, two variations of this process: (a) in which the cation-radical of the diene reacts with the neutral dienophile and (b) in which
the cation-radical of the dienophile reacts with the neutral diene. The orbital correlation diagram for both processes will be identical to that shown in Handout IV, p. 5. Your task is to construct the electronic state correlation diagrams for reaction (a) and reaction (b), and to use these to help you decide which of these processes is likely to occur thermally in a supra-supra mode.

II. (55 points)

A. In lecture, two alternative mechanisms were suggested for the thermal conversion of bicyclo[4.2.0]oct-7-ene (1) into 1,2-cyclooctadiene (2). Griegue's mechanism (a) involves a diradical intermediate which flattens and closes to 2; Bloomfield postulates (mechanism (b)) a reversible conrotatory opening to an E,Z diene, 3, which undergoes a [1,5] sigmatropic shift of H to produce 2. The nature of the reaction 3 → 2 was recently investigated using a 50/50 mixture of 3-d and 3'-d.

1. What products are expected from 3-d and from 3'-d if they isomerize to 2-d by the Bloomfield process?

2. In fact, heating of the 50/50 mixture 3-d/3'-d at 77°C in CCl₄ gave 1-d (76%) and 2-d (24%) with deuterium distributed as shown to the right.

   a. What does this say about the proposed [1,5] H-shift for 3 → 2?

   b. What mechanism is possible for 3 → 2?

3. In lecture, your favorite orbital symmetry professor (this semester) asked you to think about experiments which could be used to differentiate between the Griegue (a) and Bloomfield (b) mechanisms for the conversion of 1 into 2 at 350°C. The deuterium experiment described above may well have negated one or more of your ideas about distinguishing (a) from (b). Can you now design an experiment which will allow you to distinguish? If so, now is the time to share it with me!

B. One of orbital symmetry's greatest early triumphs was in explaining why "Dewar benzene" (bicyclo[2.2.0]hexa-2,5-diene) which is thermodynamically very unstable relative to benzene (ΔH ≈ -60 kcal/mol) is remarkably stable kinetically (ΔH⁰ ≈ 25 kcal/mol). Consider, now, the case of bridged "Dewar benzene" 4 and its possible transformation into bridged benzene 5.

1. In striking contrast to the parent case, the reaction 4 → 5 is estimated to have ΔH = 0 kcal/mol. What is it about 5 which tends to negate the advantages of aromaticity and relief of four-membered ring strain which the parent enjoys?
2. Pyrolysis of 4 at 200°C gives a mixture of dimeric compounds 8 and 9. When the pyrolysis is run at a lower temperature, compounds 6 and 7 can be isolated; upon heating, 6 and 7 are transformed into 8 and 9, respectively.

\[ \text{4} \rightarrow [\text{6} + \text{7}] \rightarrow \text{8} + \text{9} \]

a. It is proposed that 4 does open to 5, but that 5 is unstable and undergoes a Diels-Alder dimerization in two different ways to give compounds A and B; intramolecular Diels-Alder reaction then transforms A into 6 and B into 7. Suggest structures for A and B.

b. Show how 6 can be transformed into 8 and how 7 can be transformed into 9 by symmetry-allowed reactions.

C. Photolysis of racemic 10a (one enantiomer of which is shown) produces a 4:1 mixture of 11a and 12a; photolysis of racemic 10b gives a 1:1 mixture of 11b and 12b.

1. Is the formation of 11 plus 12 an allowed process? Explain briefly.

2. Using models and clear drawings, suggest an explanation for the unequal formation of 11a and 12a from 10a vs. the equal formation of 11b and 12b from 10b.

D. Some thermal rearrangements are "invisible" and can only be revealed by the use of an isotopic label. For example, compound 13-d at 100°C is in equilibrium with 13'-d. A mechanism involving electrocyclic openings and closings has been proposed for this transformation. Try to find it.

III. (65 points)

A. 1. Propose a reasonable mechanism for the following transformation (E = ester COOCH₃, Bn = benzyl CH₂Ph).

2. On the basis of your mechanism, draw (with a brief rationalization) the product(s) which will arise from heating the stereoisomer shown to the right.

B. The benzene oxide/oxepin equilibrium is a well-known thermally allowed k = 6 process. A substituent on the ring frequently shifts the equilibrium to the side of the bicyclic compound. For example, 1 is so favored at equilibrium that monocyclic oxepin 2 is not detected in the NMR spectrum. Nevertheless, evidence that 1 is in equilibrium with 2 is provided by the following ¹H NMR data:
1. At room temperature, the CH2 protons of 1 appear as a sharp singlet at 6.497. When a solution of 1 in dimethyl ether is cooled, this signal broadens and gradually separates until at -135°C it is a clean four-line AB pattern. (This transformation from singlet to AB-pattern is reversible.) Provide an explanation for this dependence of the spectrum on temperature. [Be careful—think about what can make apparently equivalent methylene protons non-equivalent.]

2. In contrast to 1's behavior, compound 3 shows an ABX3 pattern for its CH2 protons at room temperature; this persists up to 100°C (above this temperature the compound decomposes, so further heating is not possible). Explain why the methylene protons of 3 remain distinct, even at 100°C, whereas the methylene protons of 1 coalesced at room temperature and below.

G. Two mechanisms have been proposed for the thermal equilibration of endo and exo methyl compounds 4 and 5. In mechanism (a), there is formation of a dipolar or diradical species whereas mechanism (b) involves a dipolar six-membered ring intermediate.

1. In Woodward-Hoffmann terminology, what sort of reaction is the ring-opening in mechanism (b)? Is it symmetry-allowed or forbidden? Explain briefly.

2. In an attempt to decide between mechanisms (a) and (b), optically active non-methylated compound 6 was prepared; upon heating to 70°C, 6 was found to racemize at almost exactly the same rate that 4 → 5. By which of the two mechanisms can 6 racemize? Explain.

3. At no time is any 7 (or its enantiomer) found in the thermolysis of 6. Explain clearly why a dipolar intermediate like that in mechanism (b) is not expected to cyclize to 7.

4. At much higher temperatures (above 400°C), 4 rearranges to compounds 8 and 9. Suggest mechanisms for these two transformations.

D. 1. Explain clearly why compounds of type 10 are reluctant to solvolyze when n is small (say 3 or 4); use clear drawings in your answer.

2. Explain why this reluctance increases in compounds of type 11 even though they are tertiary.

3. Nevertheless, compounds of types 10 and 11 do undergo Sn1 reaction if the bridging chain is long enough and/or if X is a good enough leaving group.

a. Generation of diazonium ion 12 in CH3OH gives a 65% yield of six products in the proportions shown. Suggest a mechanism for the formation of these compounds.
b. Generation of diazonium ion 13 in CH₃OH at room temperature gives an 80% yield of two bicyclic alkenes, whereas the isomeric compound 14 gives only one bicyclic alkene plus a tricyclic ether. Write mechanisms for both reactions and explain why 14 does not give a second bicyclic alkene.

IV. (55 points)

A. 1,3-Butadiene and cyclopropene undergo rapid Diels-Alder reaction at 0°C. In order to determine if cyclopropene adds preferentially via an endo or exo transition state (or neither), the reaction was repeated with stereospecifically deuterium-labeled compounds 1 and 2.

1. The adduct from 1 plus cyclopropene gave a sharp singlet in the ²H-NMR spectrum (NOTE: not ¹H NMR) at δ2.25; the adduct from 2 gave a sharp singlet at δ2.36. While these resonances are too close to allow a definitive structural assignment, this experiment does reveal an important feature of the reaction. What is it?

2. To establish the stereochemistry of the adducts above, the adduct from 1 plus cyclopropene was epoxidized with MCPBA, giving a mixture of cis and trans products whose ¹H-NMR spectra were compared with those for the unlabeled cis and trans epoxides (see the chemical shifts in δ units to the right). In fact, the cis epoxide from 1's adduct gave a ¹H-NMR spectrum having a 1 : 2 intensity ratio of signals at δ2.4 : δ2.2; the trans epoxide showed a 2 : 1 intensity ratio of signals at δ2.2 : δ1.9. What does this indicate about the structures of the Diels-Alder adducts from 1 and 2? Explain.

3. Is the stereochemistry of the Diels-Alder reaction of 1,3-butadiene with cyclopropene endo, exo, or neither? Explain, using clear drawings.

B. Suggest mechanisms for the formation of both products in the following reaction.
C. All of the following compounds undergo a rapid retro Diels-Alder reaction at 80°C.

1. Provide a rationalization for the relative rates of the first three compounds.

2. Explain why retro Diels-Alder reaction of the fourth compound is so very much faster than that of the others.

D. The very unstable cyclic allene 3 can be generated at low temperature (-30°C) and trapped at this temperature. For example, styrene gives a 54% yield of an equal mixture of 4 and 5; also produced is polystyrene plus other products which are characteristic of radical intermediates. When this equal mixture of 4 and 5 is heated to 150°C, it is transformed into a 20 : 1 : 1 mixture of 4 : 5 : 6.

1. Suggest a mechanism for the formation of equal amounts of 4 and 5 the cyclic allene is trapped at low temperature. Given that the thermodynamic mixture would be very rich in 4, what does the 1 : 1 mixture signify about the mechanism?

2. Suggest a mechanism for the transformation which occurs when the 50/50 mixture of 4 and 5 is heated to 150°C.

E. 1. Most 1,3-dipolar additions are stereospecific (and, therefore, presumably concerted). Ylide 7, for example, reacts with E or Z NC-CH=CH-CN to give, cleanly, E or Z adducts with > 99.9% retention of configuration. In contrast: reaction of 7 with E-8 gives clean formation of E-9 plus, as major product, the strained ketene imine 10; reaction with Z-8, however, produces a mixture of E- and Z-9 along with 10. Control experiments show that reactants E- and Z-8 do not interconvert under the reaction conditions, nor do products E- and Z-9. Suggest a mechanism to account for all of these results; be clear in indicating which reaction steps are reversible and which are not.

2. Compound 10 at higher temperature is unstable and rearranges exclusively to E-9; the rate is strongly dependent on solvent polarity (reaction in CH₃CN is 840 times faster than in cyclohexane). Suggest a mechanism for this process.
LITERATURE CITATIONS FOR QUESTIONS ON EXAM I

I. For the most recent experimental results and for references to earlier theoretical work on the H₂ transfer and on the cation-radical Diels-Alder reaction, see:

