Department of Chemistry
Cumulative Examinations
May 1, 2004

You may choose to answer any exam from any area covered in the examination booklet. Each exam may contain multiple parts. You may answer more than one exam but each exam is scored separately and is treated as an individual examination result. Thus, answering parts of two exams with a score of 50% would not yield a 100% grade for this cumulative exam. Instead you would receive 50% on each examination attempted.

This booklet contains five examinations.

1) Analytical Cumulative Examination, Pages 1-2
2) Biochemistry Cumulative Examination, Pages 3-4
3) Inorganic Cumulative Examination, Pages 5-6
4) Organic Cumulative Examination, Pages 7-9
5) Physical Cumulative Examination, Pages 10-13

On your examination booklet:

1) Print your student ID number.
2) Print this Exam Booklet number: _______
3) Print the question number you are answering.
4) Print the Exam Date.

Do not write your name anywhere on the examination booklet. Each exam will be scored anonymously. If you attempt more than one exam, you must use a separate examination booklet for each examination.

When you complete the examination, return the examination and your answer booklet to the proctor. Exam results will be posted on bulletin board #2B on the north side of the hall near BRWN 2124.
Analytical Chemist May 2004

One of the current challenges in Analytical Chemistry is the analysis of complex mixtures. In the past, analysts would typically focus on quantitatively determining the presence of a single chemical species. A new approach is to apply modern methods of statistical analysis and to try to quantitate all molecular species in parallel. This provides several interesting problems in treating the data.

As a starting point, consider the following NMR spectrum of human urine:

![NMR spectrum of human urine](image)

Figure 1. 500 MHz NMR spectrum of human urine.

In this spectrum there are likely a couple of thousand lines and several hundred metabolite compounds.

Please provide brief answers to the following questions. (no long paragraphs, please).

(a) Resolution and sensitivity are two very important issues in spectroscopy. Name two or three problems that you foresee in trying to analyze an NMR spectrum like this? NMR frequencies are often pH dependent. What if you had twenty such samples, do you think they would all be repeatable?

(b) An alternative approach is to do LC/MS of the mixture and identify each of the metabolites individually as they eluted from the chromatographic column. What are some advantages/disadvantages in this approach? How about if you had to analyze twenty such samples, would they be repeatable?

(c) A promising approach is the use of pattern recognition, or multivariate statistics. In this method, numerous samples are compared to see if there are repeatable patterns of variation between the samples. Let’s focus in on the calculation of the variance for a single peak in the spectrum. Write down the mathematical expression normally used for calculating the variance. How would you calculate a “relative” variance?, i.e., what would you reference it to? Now name
another type of variance that could be calculated that relates what is happening to the signals at two different frequencies.

(d) What is a simple solution to the problem that some samples may be more concentrated than others?

(e) The output from one often-used pattern recognition approach (principal component analysis, or PCA) is shown in Figure 2 below. In PCA, the amplitudes of the principal components indicate those frequencies that vary the most from sample to sample. Does either of the PCA "spectra" appear to be like a typically NMR spectrum? Explain.

![Figure 2](image)

**Figure 2.** Principal Component Analysis of a collection of NMR spectra. The amplitude of each line indicates how much variation there is between the NMR spectra at that frequency. The x-axis just labels the points along the frequency axis.

(f) In reality, we often have much more information available than just the data in the spectrum. For example, we know that the metabolites observed in the spectrum are molecules, each with its own NMR spectrum. What does this information tell you about how the various frequency peak amplitudes should change between different samples. How could you take advantage of this information to simplify your data analysis?

(g) How do you think that successful statistical analyses of such samples shown in Figure 1 could be used? Describe two applications.
1. Consider X-ray and NMR structures of one and the same protein molecule downloaded from the RCSB protein data bank. What are the measures of quality (accuracy, precision) of these structures? Please, explain where these measures come from. Describe different quantitative approaches to analyzing the quality of structures.

2. Kurian and co-workers (JMB vol. 336, p. 1047) investigated the structure of “clamp loader complex”. Their crystallographic study predicts that the complex exists in the “open” form (chains δ and δ are far apart). It has been speculated that in solution the complex adopts “closed” conformation. Give two general reasons for a possible difference between crystalline- and solution-state structures.

To test this hypothesis, Kurian investigated the topology of complex in solution using FRET (fluorescein donor, tetramethylrhodamine acceptor). The efficiency of FRET evaluated from a steady-state spectrum is given by \( E = 1 - \frac{I_{DA}}{I_D} \), where \( I_D \) is the intensity of the donor emission spectrum in the absence of acceptor and \( I_{DA} \) is the intensity of the donor emission spectrum in the presence of acceptor. Sketch the dependence of \( E \) on the distance between the donor and acceptor \( R \). Put numbers on the axes and explain the graph. What, approximately, is the range of distances \( R \) that can be determined with good accuracy from FRET data?

The \( E \) value measured by Kurian turned out to be 0.43. There are two possible interpretations of this result: a unique, well-defined structure or, alternatively, a mixture of “open” and “closed” species. Is there, in principle, a way to use FRET experiments to discriminate between these two possibilities?

3. Butler and Falke investigated thermal backbone motions in two-domain galactose/glucose binding protein (GBP) using a disulfide trapping technique (Biochemistry, vol. 35, p.10595). Devise the experimental scheme for disulfide trapping study aimed at investigation of internal protein dynamics. In your experiment, try to obtain maximum information about internal dynamics. Describe your experimental scheme using the style of Materials and Methods section. Predict some conclusions that you may be able to reach using this experiment.

4. GroES consists of 7 identical 10 kDa subunits arranged in a ring-like oligomeric particle. Semisotnov and co-workers (FEBS Letters vol. 471, p.211) investigated the solution structure of GroES using small-angle x-ray scattering. Sketch the distance distribution function derived from the SAXS data for the following cases: (i) narrow central hole (as in crystal form), (ii) wide central hole (as in solution), (iii) in the presence of 2M Gdn-HCl. Assuming that crystallographic coordinates of the monomeric unit are available, suggest the algorithm allowing to build a model of
GroES heptamer based on the SAXS data. How many variables should be included in the algorithm?

5. The graph below represents the data from differential scanning calorimetry study of barnase (Fersht and co-workers, Biochemistry 33, 3919).

Label both axes. Both curves in this plot are obtained for barnase – what is the difference in experimental conditions between the two curves? What is the quantity marked by a question mark in the plot? What is the physical origin of this quantity (please, elaborate)? This quantity appears to be the same between the two curves – why?

6. You are attempting NMR study of a certain tetrasaccharide molecule using $^1$H NMR at 600 MHz spectrometer. Your NOESY spectrum fails to show any contacts between the adjacent rings. Why? What is the recommended experiment, “experiment X”, in this situation? Describe the orientation of spin magnetization during the mixing time of NOESY and of “experiment X”. Is it possible to register a (through-space) contact between 1H and 19F using “experiment X”? Why?
Inorganic Chemistry Cumulative Exam

Purdue University

May 1, 2004

1. (20 points) (a) Two complexes of Ni$^{2+}$ are believed to be octahedral and tetrahedral. Each has three absorption bands, but complex A has $\varepsilon = 10$ and B has $\varepsilon = 150$. Which is most likely to be the tetrahedral complex? Explain.

(b) Measurement of what physical property would exclude the possibility of either complex being square planar?

2. (10 points) Common glass used for windows and bottles appears colorless, but when viewed through the edge it appears faintly green. Fe$^{3+}(d^5)$ causes the color. Why is it so faintly colored?

[Bonus] (15 points) An octahedral complex of Co$^{2+}$, with an amine and Cl$^-$ coordinated, gives two bands with $\varepsilon = 60-80$, one very weak peak with $\varepsilon = 2$ and a high energy band with $\varepsilon = 20,000$. What is the presumed nature of these transitions? Explain.

3. (15 points) Why are low-spin complexes usually not encountered for tetrahedral coordination?

4. (15 points) Negative ions might be expected to create stronger ligand fields than neutral molecules. Why is CO such a strong-field ligand?

5. (10 points) Identify the ground state term with the spin multiplicity for:

(a) Cu$^{2+}$ in an octahedral complex.
(b) Cu$^{2+}$ in a tetrahedral complex.
(c) Zn$^{2+}$ in a tetrahedral complex.

6. (15 points) (a) What is the free ion ground state term for Pt$^{2+}(d^8)$?
(b) What is the ground state term for $[\text{PtCl}_4]^{2-}(D_{4h})$?

(c) How many spin allowed d-d transitions are expected for $[\text{PtCl}_4]^{2-}(D_{4h})$?
7. (15 points) A Tanabe-Sugano energy level diagram for a d⁶ octahedral complex is given below. Arrows representing d-d transitions are drawn at appropriate values of $\Delta_0$ for CoF₆³⁺ and Co(H₂NCH₂CH₂NH₂)₃³⁺. (a) Which arrows apply to which complex? (b) Draw ground state electronic configurations for both compounds (Show only 3d-orbitals). (c) Why is there a discontinuity in the slopes of the lines at one particular value of $\Delta_0$?
1. (30 pts) The Bergman cyclization of 1 can give poly(1,4-naphthalene) (2) (Eq. 1).

(a) Write a plausible mechanism for Eq. 1.

(b) The polymer product of this reaction actually contains some other structural units, such as 3 and 4. Show how 3 and 4 might be formed from 1.

(c) Discuss and show how you might synthesize 2 that is free from the structural units 3 and 4 by using any well-established methods.

JACS 2003, 125, 14708.
2. (40 pts) Provide a plausible mechanism for each of the following reactions.

\[ \text{Eq. 2} \]

TBS = ^1\text{BuMe}_2\text{Si}, \text{Mes} = \text{mesityl}, \text{Cy} = \text{cyclohexyl}, \text{Ph} = \text{phenyl}.

\[ \text{JACS 2003, 125, 14901.} \]

\[ \text{Eq. 3} \]

\[ \text{JACS 2003, 125, 14694.} \]
3. (30 pts) Wacker oxidation of ethylene is thought to proceed via π-complexation and nucleophilic attack by water (Eq. 4).

\[
\begin{align*}
\text{PdCl}_2 & \rightarrow \text{CH}_2\text{OH}_2 \rightarrow \text{CH}_2\text{Pd} \rightarrow \text{CH}_2\text{PdH} + \text{HCl} \\
\beta\text{-elimination} & \rightarrow \text{CH}_2\text{OH} + \text{Pd} + \text{HCl} \rightarrow \text{CH}_3\text{CHO}
\end{align*}
\]

(i) (10 pts) Provide a mechanism for Eq. 5.

\[
\begin{align*}
\text{CH}_3 & \text{PdCl}_2, \text{H}_2\text{O} \rightarrow \text{CH}\text{CCH}_3
\end{align*}
\]

(ii) (20 pts) The following reaction is called the Pd-catalyzed Ferrier rearrangement. Show clearly and step by step how this rearrangement might proceed.

\[
\begin{align*}
\text{5 mol\% PdCl}_2 \text{, dioxane, H}_2\text{O} & \rightarrow \text{OH} \\
\end{align*}
\]

TL 1996, 37, 649.
The infrared spectrum below is a plot of transmission versus wavenumber (in cm⁻¹) for a room temperature, gas phase sample of deuterium chloride, DCI. Many of you have probably analyzed this spectrum (or its protonated version) in some detail in your undergraduate physical chemistry laboratory. In this cumulative exam, we will develop the vibration-rotation selection rules that produce the spectrum below. Having done so, we will see how things change when DCI molecules are imbedded in a matrix of para-H₂ held at 2-4 K.

In the gas phase, the DCI molecule is a free rotor (i.e., the spherical harmonics are its rotational eigenfunctions), and its vibrational motion can be approximated as a harmonic oscillator. Under typical circumstances, the interaction of a molecule with light is dominated by the interaction of the electric field E with the charge distribution in the molecule. In the electric dipole approximation, this leads to a perturbation term in the Hamiltonian:

\[ H^{(1)} = -\mu \cdot E \]

where \( \mu \) is the dipole moment operator and E is the electric field component of the electromagnetic radiation.

According to perturbation theory, the infrared light will induce a transition between two vibration-rotation states \( |ν'', J''⟩ \) and \( |ν', J'⟩ \) iff the perturbation matrix element connecting the two states is non-zero:

\[ <ν', J' \mid H^{(1)} \mid ν'', J''> ≠ 0 \]

If the light is assumed to be polarized in the z-direction (i.e., E points along the z-axis), and since \( \mu \) is a vector that points along the bond axis of the HCl molecule, rotating with it, then

\[ H^{(1)} = -\mu(R) E \cos \theta, \quad \text{where} \ R \ \text{is the internuclear distance and} \ \theta \ \text{is the spherical polar coordinate.} \]

Plugging into (1), the selection rules for vibration-rotation transitions in diatomics are determined by the circumstances under which the equation below is non-zero:

\[ <ν' \mid \mu(R) \mid ν''> <J' \mid \cos \theta \mid J''> ≠ 0 \]

where \( \theta \) is the angle between the electric field and the molecular axis and \( R \) is the bond length of the diatomic.
1. Analyzing the gas phase spectrum:
(a) Expand the dipole operator $\mu(R)$ in a Taylor series about $R=R_e$, the equilibrium bond length of the diatomic, and keep only the first two terms in the expansion.

(b) Use the recurrence relationships on the attached sheet to derive the selection rules for a diatomic:
   (i) $\Delta J = \pm 1$
   (ii) $\Delta v = \pm 1$
   (iii) $(d\mu/dR) = 0$

Use orthogonality of the eigenfunctions to simplify your work wherever possible!

(c) Along the way, you will probably also prove that $\Delta m=0$. Why is this selection rule not needed explicitly in assigning the vibration-rotation transitions in the above spectrum?

(d) Use the above selection rules to assign the $v''J'' \rightarrow v'J'$ transitions observed in the spectrum of DCI. Use the notation $P(J'')$ and $R(J'')$ to label the transitions, where $P$ is used to denote transitions for which $\Delta l=-1$ and $R$ is used for $\Delta l=+1$ transitions.
   (Note 1: For the purposes of this part of the problem, consider only the more intense transition in each closely-spaced doublet.)
   (Note 2: The spectrum is an absorption spectrum of room temperature HCl gas. Consider which vibrational state(s) have most of the population.)

(e) Within the assumptions of our rigid rotor – harmonic oscillator model, use the spectrum to determine
   (i) the harmonic vibrational frequency of DCI in wavenumbers, $\omega_e$. How does this frequency compare with the value in the gas phase (taken from the room temperature spectrum)?

   (ii) the rotational constant $B_e$ in wavenumbers.

(f) The intensity of a given vibration-rotation band is determined largely by the Boltzmann population of the lower $v'$, $J'$ level. At temperature $T$, the fractional population in level $J''$ is:

$$\frac{N_{J''}}{N_{tot}} = \left(\frac{h \omega_e}{kT}\right) \cdot (2J''+1) \cdot \exp \left(\frac{-h \omega_e \cdot J''(J''+1)}{kT}\right)$$

Recall that $(kT/h\omega) = 208 \text{ cm}^{-1}$ when $T=298 \text{ K}$. Use your derived value for the rotational constant to check that the intensity distribution is consistent with a room temperature Boltzmann population by computing the relative intensities of vibration-rotation transitions out of three $J''$ levels.

(g) The doublet structure of each ro-vibrational transition is due to the presence of $D^{35}\text{Cl}$ and $D^{37}\text{Cl}$ in the sample. Calculate the expected difference in wavenumbers of the fundamental transitions of the two isotopes. How does this compare with the experimental splitting?

2. Now we turn our attention to the spectrum of DCI in a para-H$_2$ matrix. These spectra were taken from D.T. Anderson, R.J. Hinde, S. Tam and M.E. Fajardo, J. Chem. Phys. 116, 594 (2002). Typically, matrix spectroscopy is carried out in a rare gas matrix composed of rare gas atoms like argon or neon. Here the matrix is made up of H$_2$ diatomics, which could in principle
have a preferred orientation relative to one another in the matrix. However, at a few degrees Kelvin, the para-H$_2$ matrix is composed entirely of $J=0$ H$_2$ molecules.

a) The spectrum on the bottom left of this page is the infrared spectrum in the region of the DCI vibrational fundamental for this sample. No other vibration-rotation transitions are observed outside the wavenumber range shown. Comment on the changes in the spectrum between the 298 K gas phase sample and the 2.8 K matrix sample. Which vibration-rotation transitions are observed and which are not? Why is this so? What does this mean about the HCl motion in the H$_2$ matrix compared to that in the gas phase?

b) How does the presence of an HCl molecule change the surroundings of an H$_2$ molecule? How might this effect the internal motion of the H$_2$ molecule?

c) The spectrum on the bottom right is taken in the region of the H$_2$ vibrational fundamental.

(i) In the absence of HCl in the matrix, there is no absorption in this region. Why does para-H$_2$ show no intensity in its vibrational fundamental in pure H$_2$?

(ii) In the upper trace, the pH$_2$ matrix is doped with 102 ppm DCI at 2.4 K. The sharp transition at 4149.4 cm$^{-1}$ is labeled by the authors as the Q(0) transition of H$_2$. Suggest a reason why the presence of HCl might turn on some intensity in some of the H$_2$ molecules.

(iii) What is the wavenumber difference between the sharp transition at 4149.4 cm$^{-1}$ and the broadened transition above it? Compare this with the rotational constants for H$_2$ ($B_c=60$ cm$^{-1}$) and HCl (10.6 cm$^{-1}$). Do the same for the transitions that appear in the bottom trace, in which DCI was doped into the matrix.

What do these traces suggest as the transitions responsible for these absorptions? Can you think of any reason why these transitions might appear in the spectrum? (Note: This is a research-level question, but give it a shot!).

\[\text{DCI/pH}_2 = 102 \text{ ppm}\]

\[\text{HCl/pH}_2 = 88 \text{ ppm}\]
Formula sheet for the P-Chem course

The Taylor Series expansion of $f(x)$ about the point $x=x_0$ is:

$$f(x) = f(x_0) + \left( \frac{df}{dx} \right) (x-x_0) + \frac{1}{2} \left( \frac{d^2 f}{dx^2} \right) (x-x_0)^2 + ...$$

Recall that for a harmonic oscillator – rigid rotor, the vibration-rotation energy levels are:

$$E_{v,J} = (v+\frac{1}{2}) \omega_e + B_e J(J+1)$$

Where $\omega_e$ is the harmonic vibrational frequency in wavenumbers (with units cm$^{-1}$) and is related to the force constant $k$ and reduced mass $\mu$ for the oscillator by

$$\omega_e = \sqrt{\frac{k}{\mu}} \quad \text{where} \quad \mu = \frac{m_1 \cdot m_2}{m_1 + m_2} \quad \text{and} \quad \hbar = 3 \times 10^{10} \text{ cm/sec.}$$

$B_e$ is the rotational constant in wavenumbers (with units cm$^{-1}$).

$$B_e (\text{cm}^{-1}) = \left( \frac{\hbar}{8 \pi^2 I c} \right) \quad \text{where} \quad I = \mu R_e^2$$

Harmonic oscillator wave functions:

$$\psi_v(R-R_e) = N_v \exp(-\xi^2/2) H_v(\xi),$$

where $N_v$ is a normalization constant,

the $H_v(\xi)$ are the Hermite polynomials

where $\xi = \alpha^{1/2}(R-R_e)$ with $\alpha = \frac{2 \pi \nu m}{\hbar}$.

The $H_v(\xi)$ determine the symmetry (even or odd character) of the vibrational wave functions:

$v=0,2,4,\ldots \quad \psi_v(R-R_e) = \text{even}$

$v=1,3,5,\ldots \quad \psi_v(R-R_e) = \text{odd}$

Rigid rotor wave functions (spherical harmonics):

$$Y_{jm}(\theta,\phi) = N_{jm} P_j^{m|}(\cos \theta) e^{im\phi}$$

Where $N_{jm}$ is a normalization constant

$P_j^{m|}(\cos \theta)$ are the Legendre polynomials in $\cos \theta$.

The rigid rotor wave function for $J=0$ is:

$$Y_{00}(\theta,\phi) = (1/4\pi)^{1/2}$$

Recurrence relations:

Hermite polynomials:

$$2\xi H_v(\xi) = H_{v+1}(\xi) + 2vH_{v-1}(\xi)$$

Legendre polynomials:

$$(2J+1)(\cos \theta) P_j^{m|} = (J+m) P_{j-1}^{m|} + (J-m+1) P_{j+1}^{m|}$$
Periodic Classification of the Elements

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(Numbers in parentheses are the mass numbers of the most stable isotopes.)