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## EXAM III - Oct. 31, 2019

You may work until 10:50 to complete this exam. Please show all work in the space provided or on the attached scratch page. Remember to report your final answers with the correct number of significant figures, as appropriate. A Periodic Table, a table of thermodynamic data, and a sheet of helpful constants, conversion factors and equations are provided for your use. GOOD LUCK!!

1. (11 pts) Dr. Hanna and I are working with our research students to design and evaluate compounds to prevent a protein-aggregation process involved in Alzheimer's disease. Two compounds made by a Winthrop chemistry student are shown below. Note that (1) they differ only in the presence of $\mathrm{O}-\mathrm{CH}_{3}$ versus $\mathrm{O}-\mathrm{H}$ groups and (2) that lone pairs are not shown.


I


II
a. Choose either one of the structures above and show how this compound engages in hydrogen bonding with water molecules. Be sure to clearly show the atoms involved in these interactions.
b. One of the two compounds shown dissolves in water much more readily than the other. Which one do you think is more soluble in water and how can this be explained on the basis of intermolecular forces?
2. (36 pts) The U.S. produces approximately 2.6 billion gallons of methanol $\left(\mathrm{CH}_{3} \mathrm{OH}\right)$ each year. It is used in fuels, as a solvent for perfumes and dyes, and in the preparation of a wide range of other chemicals - formaldehyde, plastics, paints, explosives, etc. A common preparation method involves reacting carbon monoxide and hydrogen gas as shown below:

$$
\mathrm{CO}(g)+2 \mathrm{H}_{2}(g) \rightarrow \mathrm{CH}_{3} \mathrm{OH}(g)
$$

The following questions are related to this reaction (or these substances). Note that your answer to each part is independent of the others.

Problem 2, continued: $\quad \mathrm{CO}(\mathbf{g})+2 \mathrm{H}_{2}(\mathrm{~g}) \rightarrow \mathrm{CH}_{3} \mathrm{OH}(\mathrm{g})$
a. (8 pts) Which of the two reactants do you expect to have the higher molar entropy at 25 ${ }^{\circ} \mathrm{C}$ ? Briefly explain your choice, being sure to specifically discuss intermolecular forces and at least one other factor influencing molecular entropy.
b. (4 pts) Suppose that you react 1 mole of CO with 2 moles of $\mathrm{H}_{2}$. Which reactant has the greater partial pressure? How do you know?
c. (4 pts) If all three gases are present in a mixture at $25^{\circ} \mathrm{C}$, which molecules are moving at the fastest average speed? How do you know?
d. (10 pts) Using the thermodynamic data provided (p.5), please calculate $\Delta H^{\circ}$ for this reaction in kJ per mole of $\mathrm{CH}_{3} \mathrm{OH}$ formed. Is the reaction endothermic or exothermic?
e. (10 pts) Suppose that an engineer in a chemical plant performs this reaction in a 1500.0liter stainless steel vat at $25.0^{\circ} \mathrm{C}$ and determines the pressure of methanol to be 25.4 atm . How many moles of $\mathrm{CH}_{3} \mathrm{OH}$ were formed?
3. (24 pts) The questions below relate to the following reaction:

$$
\mathrm{P}_{4} \mathrm{O}_{10}(\mathrm{~s})+6 \mathrm{PCl}_{5}(\mathrm{~g}) \rightarrow 10 \mathrm{Cl}_{3} \mathrm{PO}(\mathrm{~g}) \quad \Delta \mathrm{H}_{\mathrm{rxn}}=? ? ?
$$

a. Please use the thermodynamic data below to determine $\Delta H_{\mathrm{rxn}}$ for this process.

$$
\begin{array}{cc}
\mathrm{P}_{4}(\mathrm{~s})+6 \mathrm{Cl}_{2}(g) \rightarrow 4 \mathrm{PCl}_{3}(g) & \Delta \mathrm{H}=-1225.6 \mathrm{~kJ} \\
\mathrm{P}_{4}(\mathrm{~s})+5 \mathrm{O}_{2}(g) \rightarrow \mathrm{P}_{4} \mathrm{O}_{10}(\mathrm{~s}) & \Delta \mathrm{H}=-2967.3 \mathrm{~kJ} \\
\mathrm{PCl}_{3}(g)+\mathrm{Cl}_{2}(g) \rightarrow \mathrm{PCl}_{5}(g) & \Delta \mathrm{H}=-84.2 \mathrm{~kJ} \\
\mathrm{PCl}_{3}(g)+1 / 2 \mathrm{O}_{2}(g) \rightarrow \mathrm{Cl}_{3} \mathrm{PO}(g) & \Delta \mathrm{H}=-285.7 \mathrm{~kJ}
\end{array}
$$

b. How much heat is absorbed or released when 50.0 g of $\mathrm{PCl}_{5}$ reacts completely?
4. (22 pts) The over-the-counter remedy called "milk of magnesia" contains magnesium hydroxide, which neutralizes hydrochloric acid in the stomach. Suppose that you carry out the following reaction in a coffee-cup calorimeter to determine the heat flow involved:

$$
2 \mathrm{HCl}(a q)+\mathrm{Mg}(\mathrm{OH})_{2}(a q) \rightarrow \mathrm{MgCl}_{2}(a q)+2 \mathrm{H}_{2} \mathrm{O}(l)
$$

You add 250.0 mL of 4.00 M HCl to enough $\mathrm{Mg}(\mathrm{OH})_{2}$ to make 500.0 total grams of solution. Initially, you measure a temperature of $23.6^{\circ} \mathrm{C}$; after reaction is complete, the temperature is $50.3^{\circ} \mathrm{C}$. Calculate $\Delta \mathrm{H}_{\mathrm{rxn}}$ in kJ per mole of $\mathrm{MgCl}_{2}$ formed. The specific heat of solution 4.18 $\mathrm{J} / \mathrm{g}{ }^{\circ} \mathrm{C}$. [Hint: Start by calculating the heat of reaction.]
5. (12 pts) Another important industrial process is the production of lime (a.k.a. calcium oxide, CaO ) from limestone (calcium carbonate, $\mathrm{CaCO}_{3}$ ); the US produces approximately 20 million metric tons per year. Under typical industrial conditions, $\Delta \mathrm{H}_{\mathrm{rxn}}=+178 \mathrm{~kJ}$ for this process.

$$
\mathrm{CaCO}_{3}(\mathrm{~s}) \rightarrow \mathrm{CaO}(\mathrm{~s})+\mathrm{CO}_{2}(\mathrm{~g}) \quad \Delta \mathrm{H}=+178 \mathrm{~kJ}
$$

a. Please predict the sign of $\Delta \mathbf{S}$ for this reaction. Briefly explain your reasoning. [Note: No calculations are needed here.]
b. Under what temperature conditions do you expect this process to be spontaneous?
(Choose from: No T, Low T, High T, or All T). Explain your reasoning. You should refer to a mathematical equation in your answer, but you need not calculate anything.

Thermodynamic Data:
Substance
$\mathrm{CH}_{3} \mathrm{OH}(g)$
$\mathrm{CO}(g)$
$\mathrm{H}_{2}(g)$
$\underline{\Delta \mathrm{H}^{\circ}}{ }_{f}(\mathrm{~kJ} / \mathrm{mol})$
-201.0
-110.5
0

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If there is material to be graded here, make sure that it is clearly labeled, and that your name is written on top of this page.

## Constants, Conversion Factors and Equations

## Constants and Conversion Factors:

$h=6.626 \times 10^{-34} \mathrm{~J} \cdot \mathrm{~s}$
$c=2.9979 \times 10^{8} \frac{\mathrm{~m}}{\mathrm{~s}}$
$1 \mathrm{~J}=1 \frac{\mathrm{~kg} * \mathrm{~m}^{2}}{\mathrm{~s}^{2}}$
$N_{\mathrm{A}}=6.022 \times 10^{23}$
$R=0.08206 \frac{\mathrm{~L} * \mathrm{~atm}}{\mathrm{~mol} * \mathrm{~K}}$
$1 \mathrm{cal}=4.184 \mathrm{~J}=1 \times 10^{-3} \mathrm{Cal}$
$1 \mathrm{~atm}=760 \mathrm{Torr}=760 \mathrm{~mm} \mathrm{Hg}=1.013 \mathrm{bar}$

## Equations:

$d=\frac{m}{\mathrm{~V}}$
$v=\frac{c}{\lambda}$
$E_{\text {photon }}=h v$
$E_{\mathrm{K}}($ ejected electron $)=E_{\text {photon }}-\phi$
$\Delta E=-2.18 \times 10^{-18} \mathrm{~J}\left(\frac{1}{\mathrm{n}_{\mathrm{f}}^{2}}-\frac{1}{\mathrm{n}_{\mathrm{i}}^{2}}\right) \quad E_{\text {photon }}=|\Delta E|$
$\lambda_{\text {matter }}=\frac{h}{m \mathrm{v}}$
$M_{\mathrm{i}} V_{\mathrm{i}}=M_{\mathrm{f}} V_{\mathrm{f}}$
$P V=n R T$
$P M=d R T$
$P_{\mathrm{A}}=\chi_{\mathrm{A}} P_{\text {total }}$

$$
\chi_{\mathrm{A}}=\frac{\mathrm{n}_{\mathrm{A}}}{\mathrm{n}_{\text {total }}}
$$

$\mathrm{E}_{\mathrm{K}}=\frac{1}{2} \mathrm{mv}^{2}$
$\overline{\mathrm{E}_{\mathrm{K}}}=\frac{3}{2} \mathrm{RT}$
$\mathrm{v}_{\mathrm{rms}}=\sqrt{\frac{3 \mathrm{RT}}{\mathrm{M}}}$
$\Delta G=\Delta \mathrm{H}-\mathrm{T} \Delta \mathrm{S} \quad \Delta S^{\circ}{ }_{\mathrm{rxn}}=\Sigma\left[\mathrm{n} S^{\circ}{ }_{m}\right.$ (products) $]-\Sigma\left[\mathrm{n} S^{\circ}{ }_{m}\right.$ (reactants)] (similar for $\Delta \mathrm{G}^{\circ}{ }_{f}, \Delta \mathrm{H}^{\circ}{ }_{f}$ )
$q=m C_{s} \Delta T$
$q_{\mathrm{rxn}}=-q_{\text {soln }}$
$\Delta H=q_{\mathrm{P}}$

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| $\begin{gathered} 1 \\ 1 \mathrm{~A} \end{gathered}$ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| $\begin{gathered} 1 \\ \mathrm{H} \\ \text { 1.0794 } \\ \hline \end{gathered}$ | $2{ }_{2}^{2}$ |  |  |  |  |  |  |  |  |  |  | $\begin{array}{r} 13 \\ 3 \mathrm{~A} \\ \hline \end{array}$ | $\begin{array}{r} 14 \\ 4 \mathrm{~A} \\ \hline \end{array}$ | $\begin{array}{r} 15 \\ 5 \mathrm{~A} \\ \hline \end{array}$ | $\begin{aligned} & 16 \\ & 6 \mathrm{~A} \\ & \hline \end{aligned}$ | $\begin{aligned} & 17 \\ & 7 \mathrm{~A} \\ & \hline \end{aligned}$ | $\begin{array}{\|c} \hline \begin{array}{c} 2 \\ \mathrm{He} \\ 4.00260 \\ \hline \end{array} \\ \hline \end{array}$ |
| $\stackrel{3}{\mathrm{Li}}$ | $\begin{gathered} 4 \\ \hline \mathrm{Be} \end{gathered}$ |  |  |  |  | nsitio | meta |  |  |  |  | $\begin{gathered} 5 \\ \mathbf{B} \\ 10.81 \end{gathered}$ | $\underset{12.011}{\stackrel{6}{\mathrm{C}}}$ | $\begin{array}{\|c\|} \hline 7 \\ \mathrm{~N} \\ 14.0067 \end{array}$ | $\begin{gathered} 8 \\ \mathrm{O} \\ 15.999 \end{gathered}$ | $\begin{array}{\|c\|} \hline 9 \\ \hline \text { F } \\ \hline 1899403 \\ \hline \end{array}$ | $\begin{gathered} 10 \\ \mathrm{Ne} \\ 20.1797 \end{gathered}$ |
| $\begin{gathered} 6.941 \\ \hline 11 \\ \mathrm{Na} \\ 22.98977 \end{gathered}$ | $\begin{gathered} 9.01218 \\ \hline \begin{array}{c} 12 \\ \mathbf{2 4 g} \\ 24.305 \end{array} \end{gathered}$ | $\stackrel{3}{3 B}$ | $\begin{gathered} 4 \\ 4 \mathrm{~B} \end{gathered}$ | $\begin{gathered} 5 \\ 5 \mathrm{~B} \end{gathered}$ | $\begin{gathered} 6 \\ 6 \mathrm{~B} \end{gathered}$ | $\begin{gathered} 7 \mathrm{7} \end{gathered}$ | 8 | $\begin{gathered} 9 \\ 8 \mathrm{~B} \end{gathered}$ | 10 | $\begin{aligned} & { }_{1 B}^{11} \end{aligned}$ | $\begin{aligned} & 12 \\ & 2 \mathrm{~B} \end{aligned}$ | 13 <br> Al <br> 26.98154 | $\begin{array}{\|c} 14 \\ \mathrm{Si} \\ 28.0855 \\ \hline \end{array}$ | $\begin{array}{\|c\|} \hline 15 \\ \mathbf{P} \\ 30.97376 \\ \hline \end{array}$ | $\begin{gathered} 16 \\ \mathrm{~S} \\ 32.066 \\ \hline \end{gathered}$ | $\begin{gathered} 17 \\ \mathrm{Cl} \\ 35.453 \end{gathered}$ | $\begin{gathered} 18 \\ \mathrm{Ar} \\ 39.948 \\ \hline \end{gathered}$ |
| $\begin{gathered} 22.98977 \\ \hline 19 \\ \mathbf{3 9 . 0 9 8 3} \end{gathered}$ | $\begin{gathered} 24.305 \\ \hline 20 \\ \mathrm{Ca} \\ 40.078 \end{gathered}$ | $\begin{array}{\|c\|} \hline \text { SD } \\ \hline \text { Sc } \\ \text { Sc.959 } \\ \hline \end{array}$ | $\begin{gathered} 22 \\ { }_{4 i}^{\text {Ti.88 }} \\ 47 \end{gathered}$ | $\begin{array}{c\|} \hline 23 \\ \mathbf{V} \\ 50.9415 \end{array}$ | $\begin{gathered} 24 \\ { }^{24} \mathrm{Cr} \\ 51.996 \end{gathered}$ |  | $\begin{gathered} 26 \\ \text { Fe } \\ 55.847 \end{gathered}$ |  | $\begin{aligned} & \hline 28 \\ & \mathrm{Ni} \\ & 58.69 \end{aligned}$ | $\begin{array}{\|c\|} \hline 29 \\ \mathrm{Cu} \\ 63.546 \\ \hline \end{array}$ | $\begin{aligned} & 30 \\ & \mathrm{Zn} \\ & 65.39 \end{aligned}$ | $\begin{array}{\|c\|} \hline 20.71 \\ \hline \mathrm{Ga} \\ \hline 69.72 \\ \hline \end{array}$ | $\begin{gathered} 32 \\ \mathbf{G e} \\ 72.61 \end{gathered}$ | $\begin{array}{\|c\|} \hline 33 \\ \text { As } \\ 74.9216 \\ \hline \end{array}$ | $\begin{gathered} 34 \\ \mathrm{Se} \\ 78.96 \end{gathered}$ | $\begin{gathered} 35 \\ \mathrm{Br} \\ 79.904 \end{gathered}$ | $\begin{gathered} 36 \\ \mathrm{Kr} \\ 83.80 \end{gathered}$ |
| $\begin{array}{\|c\|} \hline 39.0985 \\ \hline \text { Rb } \\ 85.4678 \end{array}$ | $\begin{gathered} 38 \\ \mathrm{Sr} \\ \mathrm{S7} .62 \end{gathered}$ | $\begin{gathered} 44.959 \\ \hline \mathbf{3 9} \\ \mathbf{8} \\ \hline 8.959 \end{gathered}$ | $\begin{gathered} 47.88 \\ \mathbf{4 0} \\ \mathbf{Z r} \\ 91.224 \end{gathered}$ | $\begin{gathered} \stackrel{41}{\mathrm{Nb}} \\ 92.9064 \end{gathered}$ | $\begin{gathered} 42 \\ \hline \begin{array}{c} \text { Mo } \\ 95.94 \end{array} \end{gathered}$ | $\begin{aligned} & 43 \\ & \mathrm{Tc}_{\mathrm{C}} \\ & (98) \end{aligned}$ | $\begin{gathered} 44 \\ \mathrm{Ru} \\ 101.07 \end{gathered}$ | $\begin{gathered} 45 \\ \text { Rh } \\ 102.9055 \end{gathered}$ | $\begin{gathered} 46 \\ \text { Pd } \\ 106.42 \end{gathered}$ | $\begin{gathered} 47 \\ \text { Ag } \\ 107.8682 \end{gathered}$ | $\begin{gathered} 48 \\ \mathrm{Cd} \\ 112.41 \end{gathered}$ | $\begin{gathered} \hline 49 \\ \text { In } \\ 114.82 \\ \hline \end{gathered}$ | $\begin{array}{\|c\|} \hline 50 \\ \mathrm{Sn} \\ 118.710 \end{array}$ | $\begin{array}{\|c\|} \hline 51 \\ \mathrm{Sb} \\ 121.757 \\ \hline \end{array}$ | $\begin{gathered} 52 \\ \mathrm{Te} \\ 127.60 \\ \hline \end{gathered}$ | $\begin{array}{\|c\|} \hline 53 \\ I \\ 126.9045 \\ \hline \end{array}$ | $\begin{gathered} 54 \\ \chi \mathrm{e} \\ 131.29 \\ \hline \end{gathered}$ |
| $\begin{gathered} 85.4678 \\ \hline 55 \\ \hline \begin{array}{c} \text { Cs } \\ 132.954 \end{array} \end{gathered}$ | $\begin{gathered} 56 \\ \text { Ba } \\ 137.33 \end{gathered}$ | $\begin{array}{c\|} \hline \begin{array}{c} 57 \\ { }^{5} \mathrm{La} \\ 138.9055 \end{array} \\ \hline \end{array}$ | $\begin{array}{\|c\|} \hline 72 \\ \mathrm{Hf} \\ 178.49 \end{array}$ | $\begin{gathered} 92.9004 \\ \hline \begin{array}{c} 73 \\ \text { Ta } \\ 180.9479 \end{array} \end{gathered}$ | $\stackrel{74}{\underset{W}{W}} \underset{183.85}{ }$ | $\begin{array}{\|c\|} \hline 75 \\ \hline \text { Re } \\ 186.207 \end{array}$ | $\begin{gathered} 76 \\ \text { Os } \\ 1000 \end{gathered}$ | $\begin{gathered} 77 \\ \text { Ir } \\ 192.22 \end{gathered}$ | $\begin{gathered} 78 \\ \mathrm{Pt} \\ 195.08 \end{gathered}$ | $\begin{gathered} \mathrm{79} \\ \mathrm{Au} \\ 196.9665 \end{gathered}$ | $\begin{array}{\|c} 80 \\ \hline \mathbf{H g} \\ 200.59 \\ \hline \end{array}$ | 81 <br> Tl <br> 204.383 | $\begin{gathered} 82 \\ \mathrm{~Pb} \\ 207.2 \end{gathered}$ | 83 <br> $B i$ <br> 208.9804 | $\begin{aligned} & 84 \\ & \text { Po } \\ & \text { Po } 209 \end{aligned}$ | $\begin{gathered} 85 \\ \text { At } \\ (210) \end{gathered}$ | $\begin{aligned} & 86 \\ & \mathrm{Rn} \\ & (222) \\ & (22) \end{aligned}$ |
| $\begin{gathered} 132.9054 \\ \hline 87 \\ \mathrm{Fr} \\ (223) \end{gathered}$ | $\begin{gathered} 88 \\ \text { Ra } \\ 226.0254 \end{gathered}$ | $\begin{gathered} { }^{89}{ }^{+1}{ }^{\mathrm{Ac}} \\ 227.0278 \end{gathered}$ | $\begin{aligned} & 104 \\ & \text { Rf } \\ & (261) \end{aligned}$ | $\begin{array}{\|c\|} \hline 10595 \\ \hline \text { Db } \\ (262) \\ \hline \end{array}$ | $\stackrel{\substack{106 \\ \text { Sg } \\(263)}}{ }$ | $\begin{aligned} & \begin{array}{l} 107 \\ \text { Bh } \\ (262) \end{array} \end{aligned}$ | $\begin{aligned} & 108 \\ & \text { Hs } \\ & \text { (265) } \\ & \hline \end{aligned}$ | $\begin{aligned} & \begin{array}{l} 109 \\ \text { Mt } \\ (266) \end{array} \end{aligned}$ | $\begin{array}{\|l\|l\|} \hline 110 \\ \text { Uun } \end{array}$ | $\begin{gathered} 111 \\ \text { Uuu } \\ \hline \end{gathered}$ | $\begin{array}{\|c\|} \hline 112 \\ \text { Uub } \end{array}$ |  | $\begin{gathered} 114 \\ \text { Uuq } \end{gathered}$ |  | $\begin{aligned} & 116 \\ & \text { Uuh } \end{aligned}$ |  |  |


| *Lanthanide series | $\begin{array}{\|c\|} \hline 58 \\ \mathrm{Ce} \\ 140.12 \end{array}$ | $\begin{array}{c\|} \hline 59 \\ \mathrm{Pr}_{140.9077} \end{array}$ | $\begin{gathered} \stackrel{60}{\mathrm{Nd}} \\ 144.24 \end{gathered}$ | $\begin{gathered} 61 \\ \mathrm{Pm}_{1} \\ (145) \end{gathered}$ | $\begin{gathered} \mathrm{Cm}_{\substack{2 \\ \mathrm{Sm} \\ 150.36}} \end{gathered}$ | $\begin{gathered} 63 \\ \text { Eu } \\ 151.96 \end{gathered}$ | $\begin{gathered} 64 \\ \text { Gd } \\ 157.25 \end{gathered}$ | $\begin{gathered} 65 \\ \text { Tb } \\ \text { T58.9254 } \end{gathered}$ | $\begin{gathered} 66 \\ \text { Dy } \\ 162.50 \\ \hline \end{gathered}$ | $\begin{gathered} 67 \\ \text { Ho } \\ \text { H64.930 } \\ \hline \end{gathered}$ | $\begin{gathered} 68 \\ \text { Er } \\ \text { E67.26 } \end{gathered}$ | $\begin{gathered} 69 \\ \mathrm{Tm} \\ \text { 168.932 } \\ \hline \end{gathered}$ | $\begin{gathered} 70 \\ \mathrm{Yb} \\ 173.04 \end{gathered}$ | $\begin{gathered} 71 \\ \mathrm{Lu} \\ 174.967 \\ \hline \end{gathered}$ |
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| ${ }^{\dagger}$ Actinide series | $\begin{gathered} 90 \\ \text { Th } \\ \text { T32.0381 } \end{gathered}$ | $\begin{gathered} 91 \\ \mathrm{~Pa} \\ 231.0359 \end{gathered}$ | $\begin{gathered} 9^{92} \\ \mathbf{U} 8.0289 \end{gathered}$ | $\begin{gathered} 93 \\ \stackrel{93}{\mathrm{~Np}} \\ 237.048 \end{gathered}$ | $\begin{gathered} 94 \\ \mathrm{Pu} \\ (244) \\ \hline \end{gathered}$ | $\begin{gathered} 95 \\ { }_{(243)}^{(24)} \end{gathered}$ | $\begin{aligned} & 96 \\ & \mathrm{Cm}_{2} \\ & (247) \end{aligned}$ | $\begin{gathered} 97 \\ \text { Bk } \\ (247) \end{gathered}$ | $\begin{gathered} 98 \\ \text { Cf } \\ \text { (251) } \end{gathered}$ | $\begin{aligned} & \begin{array}{c} 99 \\ \text { Es } \\ (2522) \end{array} \end{aligned}$ | $\begin{aligned} & 100 \\ & \mathrm{Fm} \\ & (257) \end{aligned}$ | 101 Md $(258)$ | $\begin{aligned} & 102 \\ & \text { No } \\ & \text { (259) } \\ & \hline \end{aligned}$ | $\begin{gathered} 103 \\ \mathbf{L r} \\ (260) \\ \hline \end{gathered}$ |

