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Produced by the NASA Center for Aerospace Information (CASI)
Theoretical Research Program to Predict the
Properties of Molecules and Clusters containing
Transition Metal Atoms


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APPENDIX B - Reprints of papers describing calculations for Transition Metal Hydrides and Dimers.
I. INTRODUCTION

The primary focus of this research has been the theoretical study of transition metal (TM) chemistry. A major goal of this work is to provide reliable information about the interaction of H atoms with iron metal. This information is needed to understand the effect of H atoms on the processes of embrittlement and crack propagation in iron. The method employed in the iron hydrogen studies is the cluster method in which the bulk metal is modelled by a finite number of iron atoms. There are several difficulties in the application of this approach to the hydrogen iron system. First the nature of TM-TM and TM-H bonding for even diatomic molecules was not well understood when these studies were started. Secondly relatively large iron clusters are needed to provide reasonable results. Therefore it is not possible to include all of the valence electrons on each iron atom. In the present calculations only the 4s electron of each iron atom was included directly in the calculation while the Ar core and 3d electrons are incorporated into the effective core potential (ECP) based on the 4s13d7 state of the Fe atom. In order to understand the effects of removing the 3d electrons from the valence space, it is necessary to have detailed information about the nature of TM-TM and TM-H bonding. For these reasons we have carried out in parallel two levels of calculation: i) highly accurate studies of TM dimers and hydrides. (These studies are carried out with large basis sets and include extensive electron correlation). ii) studies of large clusters of Fe atoms with and without H adatoms. [These studies are carried out at the SCF level and make the approximation of incorporating the TM core and 3d electrons into the core (ECP approximation).] The studies of diatomic species provide benchmark calculations which are used to test the approximations in the cluster studies, while the cluster studies on Fe_n are designed to provide potential function input for studies of hydrogen embrittlement.

Since much of the work to be discussed here has been described in manuscripts, relevant manuscripts have been included in the appendices and the reader is referred to these papers and to the publications list for further details. This report concentrates on the TM hydrides, TM
dimers, and Fe\textsubscript{n}H cluster results. The Fe\textsubscript{n}H cluster results are described in detail in a manuscript included as Appendix A. The results for the TM hydrides and dimers are summarized in Sections II and III, respectively; while, Appendix B contains copies of publications on these topics. During the course of this work several other projects were undertaken. These include all-electron calculations on the CsH and Cs\textsubscript{2} molecules, calculations on the alkali dimers, an ab-initio study of core-valence correlation, and studies of atomic correlation and basis sets. References to this work are given in the publications list.
II. TRANSITION METAL HYDRIDES

Fig. 1 shows the relative ordering of the $4s^{2}3d^{n}$ and $4s^{1}3d^{n+1}$ states of the TM atoms. The important features of Fig. 1 are: i) a monatonic decrease in excitation energy from Sc to Cr with $4s^{1}3d^{n+1}$ an excited state for Sc through V but the ground state for Cr. ii) a sharp reversal in the ordering of the states for Mn with $4s^{2}3d^{n}$ again lower, and iii) a monatonic decrease in excitation energy from Mn to Cu with $4s^{1}3d^{10}$ the ground state of Cu. The character of the ground states of the TM hydrides is strongly correlated with the ordering of atomic states. For example, for CrH the ground state is $^{6}E^{+}$ arising from $4s^{1}3d^{5}$ while for MnH the ground state is $^{7}E^{+}$ arising from $4s^{2}3d^{5}$. For elements where the $4s^{2}3d^{n}$ and $4s^{1}3d^{n+1}$ states are closer in energy a strong admixture of states occurs, e.g. for VH the ground state is $^{5}A$ arising from a mixture of $4s^{2}3d^{2}3d_{0}^{1}$ and $4s^{1}3d_{0}^{1}3d^{2}3d_{0}^{1}$ atomic character with a 3d population of $\approx 3.4$.

The ratio of sizes of 4s and 3d orbitals increases monotonically from 2.364 to 3.239 going from Sc to Cu. Because the 4s orbital is so much larger than the 3d orbital we find the bonding in the TM hydrides involves primarily the 4s electrons (with some admixture of 4p character) while the 3d electrons remain essentially atomic like. The one exception is ScH which shows a Sc(3d)-H(ls) bond in the lowest $^{1}E^{+}$ state. Note that Sc is most likely to show 3d bonding since the 4s and 3d orbital sizes are more nearly comparable.

CASSCF/Ci studies have been carried out for TiH, VH, CrH, MnH, FeH, and NiH. These calculations show good agreement with experiment for the $R_{e}$, $\omega_{e}$, and $D_{e}$; thus confirming the theoretical model.

Studies have also been carried out for the $^{5}A$ state of FeH$^{-}$. These calculations show that photodetachment from FeH$^{-}$ leads to a large change in $R_{e}$ for the $^{4}A$ state but little change in $R_{e}$ for the $^{6}A$ state. These results confirm the assignment of Stevens, Fiegerle, and Lineberger (SFL) of the vertical photodetachment transition with a long vibrational progression to $^{4}A$, and hence that the ground state of FeH is $^{4}A$. However the calculations show that the simple theoretical model used by SFL to assign the above transitions is not correct in that the $^{4}A$ state of FeH
and the \( ^5\Delta \) state of FeH\(^-\) have 3d populations of 6.26 and 6.50 respectively, whereas SFL assumed 7.0 for both of these states. Thus the theoretical calculations in conjunction with the experiment by SFL establish that the ground state of FeH is \( ^4\Delta \).
FIG. 1. $4s^{1}3d^{n+1}-4s^{2}3d^{n}$ excitation energies of scandium to copper [$E(3d^{n+1})-E(3d^{n})$]. All units are in eV.
III. TRANSITION METAL DIMERS.

For the TM dimers molecular states may arise from three different atomic asymptotes: \(4s^23d^n + 4s^23d^n\), \(4s^23d^n + 4s^13d^{n+1}\), and \(4s^13d^{n+1} + 4s^13d^{n+1}\). The accessibility of these asymptotes of course depends on the \(4s^13d^{n+1} - 4s^23d^n\) excitation energies (see Fig. 1). Thus for Sc\(_2\) we find that the low-lying states arise from the first two asymptotes with \(4s^13d^{n+1} + 4s^13d^{n+1}\) too high in energy to lead to the ground state while for Ti\(_2\), V\(_2\), and Cr\(_2\) the ground states arise from the \(4s^13d^{n+1} + 4s^13d^{n+1}\) atomic asymptote.

Because the 4s orbital is significantly larger than the 3d orbital the predominant interaction in the TM dimers at large internuclear distance (\(R\)) is between the 4s electrons with very little 3d interaction. For states arising from the \(4s^23d^n + 4s^23d^n\) atomic asymptote this interaction is basically repulsive and only a shallow well at large \(R_e\) (\(\sim 8.0\,a_0\)) arising from the 4s-4p near degeneracy effect is observed. For states arising from the \(4s^23d^n + 4s^13d^{n+1}\) atomic asymptote the 4s interaction is weakly bonding at intermediate \(R\) but is repulsive at small \(R\) leading to intermediate \(R_e\) values (\(\sim 5.0\,a_0\)). At these \(R_e\) values the 3d-3d overlaps (\(S\)) are small which favors one-electron 3d bonds whose bonding terms vary with distance like \(S\) over two-electron 3d bonds whose bonding terms vary with distance like \(S^2\). Finally for states arising from the \(4s^13d^{n+1} + 4s^13d^{n+1}\) atomic asymptote the 4s-4s interaction is attractive and also appears to be relatively flat well inside the optional 4s-4s bonding radius. Thus, states arising from this atomic asymptote are able to move into short \(R_e\) regions where the 3d-3d overlaps are large enough to favor two-electron 3d bonding.

For the TM elements with more than half filled 3d shells, the formation of 3d bonds becomes much less favorable for two reasons. First the 4s to 3d orbital sizes are larger for the right half of the first transition row. Secondly the presence of doubly occupied 3d orbitals leads to repulsive interactions which effectively cancel any bonding interactions from the 3d shell. Thus the bonding here is dominated by the 4s electrons. An example is Cu\(_2\) where the Cu atom has a \(4s^13d^{10}\)
ground state and the bonding is predominantly a $4s$-$4s$ bond with the $3d$ electrons remaining atomic like.

The dominant configurations for important states of those TM dimers which have been studied are:

$$\text{Sc}_2 \quad 3\Sigma^-_u \quad 4s^2 \quad 4s^2 \quad 3d\pi^1_u \quad 3d\pi^1_u$$

$$5\Sigma^-_u \quad 4s^2 \quad 3d\sigma^1_u \quad 4s^1 \quad 3d\pi^1_u \quad 3d\pi^1_u$$

$$\text{Ti}_2 \quad 7\Sigma^+_u \quad 4s^2 \quad 3d\sigma^1_g \quad 4s^1 \quad 3d\pi^1_u \quad 3d\pi^1_u \quad 3d\delta^1_s \quad x^2-y^2$$

$$1\Sigma^+_u \quad 4s^2 \quad 3d\pi^2_u \quad 3d\pi^2_u \quad 3d\pi^2_u \quad 3d\pi^2_u$$

$$\text{V}_2 \quad 3\Sigma^-_g \quad 4s^2 \quad 3d\sigma^2_g \quad 3d\pi^2_x \quad 3d\pi^2_x \quad 3d\delta^1_s \quad x^2-y^2$$

$$\text{Cr}_2 \quad 1\Sigma^+_g \quad 4s^2 \quad 3d\sigma^2_g \quad 3d\pi^2_x \quad 3d\delta^2_s \quad 3d\delta^2_s \quad x^2-y^2$$

$$\text{Cu}_2 \quad 1\Sigma^+_g \quad 4s^2 \quad 3d\sigma^2_g \quad 3d\pi^2_x \quad 3d\delta^2_s \quad 3d\delta^2_s \quad x^2-y^2$$

$$3d\sigma^2_u \quad 3d\pi^2_x \quad 3d\pi^2_x \quad 3d\sigma^2_x \quad 3d\pi^2_y$$

Fig. 2 shows calculated potential curves for low-lying states of Sc$_2$. The initial study of Sc$_2$ by Walch and Bauschlicher found only weakly bound states arising out of the $^2D + ^2D$ asymptote in contrast to mass spectrometric experiments which indicated strong bonding ($D_e = 26 \pm 5$ kcal/mole). A $5\Sigma_u$ state was found which was bound by $\approx 0.8$ eV with respect to $^2D + 4^F(4s^14p^13d^1)$ atomic limit, but unbound with respect to $^2D + ^2D$. However at about the same time that this work was published, matrix isolation studies by Knight, VanZee and Weltner indicated a bound $\Sigma$ state of Sc$_2$. From the ESR studies it appeared that this state arose from the $^2D + 4^F(4s^13d^2)$ atomic asymptote which had not been studied in detail in the previous theoretical studies. A re-examination of this system revealed a new $5\Sigma_u^-$ state which had been missed.
in the previous study because its $R_e$ ($\approx 5.0a_0$) is much shorter than the $R_e$ values for the states studied previously ($\approx 7.0a_0$). The $5\Sigma_u^-$ state turned out to be of considerable theoretical interest because it exhibited multiple 3d bonding (three one-electron bonds) and constituted the first theoretical evidence of multiple 3d bonding in a first row transition metal dimer.

The studies on Sc$_2$ were extended to Ti$_2$, V$_2$ and Cr$_2$. Initially the high spin $7\Sigma_u^+$ state of Ti$_2$ was studied. The Sc$_2$ $5\Sigma_u^-$ and Ti$_2$ $7\Sigma_u^+$ states come from the mixed $(4s^23d^{n+1} + 4s^13d^{n+1})$ asymptote and exhibit multiple one-electron 3d bonding. These states have long bond lengths ($R_e \approx 5.0a_0$) and small vibrational frequencies ($\omega_e \approx 200\text{cm}^{-1}$). The $5\Sigma_u^-$ state of Sc$_2$ is consistent with the $5\Sigma$ state which has been observed in matrix studies by Knight, Van Zee, and Weltner. The bond length here is not known but the calculated vibrational frequency of 184 cm$^{-1}$ is reasonably close to the experimental value of 238.9 cm$^{-1}$.

For Ti$_2$, from reference to Fig 1 one sees that the excitation energy to the $4s^13d^{n+1} + 4s^13d^{n+1}$ atomic asymptote is about half as large as for Sc$_2$. Thus the $1\Sigma_g^+$ state which arises from the $4s^13d^3 + 4s^13d^3$ atomic asymptote becomes a competitor for the ground state of Ti$_2$. The bonding here is a triple two-electron 3d bond ($3d_\sigma$, $3d_{\pi_x}$, $3d_{\pi_y}$). This leads to a short $R_e$ state, $R_e = 3.73a_0$ and $\omega_e = 438\text{cm}^{-1}$. The bond length is not known experimentally but the experimental vibrational frequency is $407.9\text{cm}^{-1}$ which is consistent with the $1\Sigma_g^+$ state of Ti$_2$, but inconsistent with the $7\Sigma_u^+$ state. Based on this we tentatively assign the ground state of Ti$_2$ as $1\Sigma_g^+$.

Fig. 3 shows calculated potential curves for the $3\Sigma_g^-$ state of V$_2$. The $3\Sigma_g^-$ state of V$_2$ has the same triple two-electron 3d bond as in Ti$_2$ with the remaining two electrons in the $3d\delta$ orbitals. Because the $3d\delta$ orbitals still have small overlaps in the region near $R_e$ ($\approx 3.5a_0$), the lowest state is a triplet state arising by forming two one-electron $3d\delta$ bonds. The $R_e$ and $\omega_e$ values obtained from the CASSCF curves are in good agreement with the recent results of Langridge-Smith, Morse, Hansen, Smalley and Merer for the $3\Sigma_g$ ground state of V$_2$. An important feature of Fig. 3 is the large effect of 4f functions, an effect which is also evident in the Cr$_2$ curves.
FIG. 2. Potential energy curves for the low-lying states of Sc$_2$ from CASSCF CI(ST) calculations. The locations of the $2D + 2D$, $2D + 4F(4s^{1}4p^{1}3d^{1})$, and $2D + 4F(4s^{1}3d^{2})$ asymptotes are indicated.
in Fig. 4. Since these states exhibit strong 3d bonding, the large
effect (\approx 1.0\text{ev}) for 4f as a polarization function is not surprising. This
large effect is not observed for the one-electron 3d bonds in the \text{Sc}^5_{2_u} or
\text{Ti}^7_{2_u} states. However, this is expected given the strong \( R \)
dependence of this effect. For example from Fig. 4 one sees that for
\text{Cr}^2 near \( R_e \) the effect of 4f is large but is near zero by 3.75\text{a}_0.

Fig. 4 shows the calculated potential curves for \text{Cr}^2. Here the
3d\( \delta \) orbitals are doubly occupied which is expected to be unfavorable
based on the \text{V}^2 result that the 3d\( \delta \) orbitals were preferentially singly
occupied. This is consistent with the weaker bonding in \text{Cr}^2, \( D_e \approx 1.0\text{ev} \)
as compared to \text{V}^2, \( D_e \approx 2.5\text{ev} \). Because of the weaker bonding in \text{Cr}^2 the
CASSCF potential curve is not bound. However the potential curve does
exhibit a shoulder near the experimental \( R_e \) which is suggestive of an
inner well.

A major problem with the CASSCF studies for \text{V}^2 and \text{Cr}^2 is that
only a small percentage of the binding energy is obtained for \text{V}^2 and no
well is obtained for \text{Cr}^2. This result is not unexpected for CASSCF.
Normally these problems would be corrected by configuration interaction
(CI). However, the CI expansions required for \text{V}^2 and \text{Cr}^2 exceed current
computational capabilities. Several different attempts have been made to
include the missing correlation in other ways. One approach due to Goodgame
and Goddard assumes that the missing correlation serves mainly to correct
the location of the ionic atomic asymptotes. These authors attempt to include
these effects by empirical modification of the integrals to correct the
atomic ionization potentials and electron affinities to agree with experiment.
This method does lead to a reasonable potential curve for \text{Cr}^2 although the
bond length is somewhat too short which suggests that this method over
corrects. Another approach by Walch attempts to include extra correlation
effects by expanding the valence space in the CASSCF calculation. Here
atomic 4p and 3d\( \gamma \) terms are added (where 3d\( \gamma \) is a tight diffuse correlating
orbital for the 3d). This approach should include the principle correlation
effects needed to describe charge transfer within the 4s and 3d shell.
Unfortunately, it is not possible to add all these extra valence orbitals at
Fig. 3. Calculated CAS SCF potential curves for the $3^2\Sigma_g^-$ state of $V_2$. Basis I is the [8s6p4d] basis while Basis II is the [8s6p4d2f] basis.
FIG. 4. Calculated CAS SCF potential curves for the 1E+9 state of Cr$_2$. Basis I and Basis II are the same size as in fig. 1.
once (due to computational limitations) and the extra orbitals are added separately by symmetry blocks. From checks on $H_2$ it appears that there is no real problem with additivity due to this approach. However, checks on $N_2$ and $Ti_2$ indicate that because the method dissociates to SCF atoms certain atomic correlation terms are not included and these terms are more important in the large $R$ region than they are near $R_e$. Thus, the method does overestimate the binding energy that would be obtained in a more complete MCSCF calculation. In spite of these difficulties the method does nearly reproduce the CI potential curves for $H_2$, $N_2$ and $Ti_2$ and therefore we reproduce the estimated potential curve for $Cr_2$ in Fig. 5. Analysis of this potential curve gives (experimental values in parenthesis) $R_e = 1.78\text{Å}(1.68\text{Å})$, $\omega_e = 383\text{cm}^{-1}(480\text{cm}^{-1})$ and $D_e = 0.7\text{eV})$. Note that the long bond length and small $\omega_e$ are consistent with underestimating the binding energy.

A significant feature of the studies of the TM dimers is the presence of outer wells associated with 4s-4s bonding and one-electron 3d bonding in some cases (e.g. the $^7\Sigma_u^+$ state of $Ti_2$ and analogous states in $V_2$), and inner wells associated with two-electron 3d bonding (e.g. the $^1\Sigma^+$ state of $Ti_2$ and the $^3\Sigma_g^-$ state of $V_2$). These types of effects have been observed experimentally for small Fe clusters where the dimer exhibits a bond length of $\approx 3.8\text{Å}$ which presumably involves some 3d bonding but larger clusters exhibit longer bond lengths approaching the nearest neighbor distance in BCC Fe ($\approx 4.7\text{Å}$).
Estimated potential curves for Cr\textsubscript{2} based on extended valence space CASSCF calculations. The effect of 4p is estimated based on calculations on Ti\textsubscript{2}. 

FIG. 5.
IV. \textit{Fe}_n\textit{H} CLUSTER CALCULATIONS

The \textit{Fe}_n\textit{H} cluster calculations are described in detail in a manuscript contained in Appendix A. For a summary of the main results, the reader is referred to the introduction of the above paper.
V. PUBLICATIONS

A. Transition Metal Hydrides

1. On the d-Bond in ScH
   C.W. Bauschlicher, Jr. and S.P. Walch

2. CASSCF/CI Calculations for First Row Transition Metal Hydrides:
   The TiH(4$^+$), VH(5$^+$), CrH(6$^+$), MnH(7$^+$), FeH(4,6$^+$) and NiH(2$^+$)
   States
   S.P. Walch and C.W. Bauschlicher, Jr.

3. On Incorporation of Atomic Correlation in Transition Metal
   Molecular Calculations: NiH
   S.P. Walch and C.W. Bauschlicher, Jr.

4. Theoretical Evidence Supporting the $^4$R Ground State Assignment
   for FeH

B. Transition Metal Dimers

5. CASSCF/CI Calculations for the $^3_{g_2}$, $^1_{g_2}$, $^3_{u_2}$ and $^5_{u_2}$ States
   of Sc$_2$
   S.P. Walch and C.W. Bauschlicher, Jr.

6. Theoretical Evidence for Multiple One-Electron 3d Bonding in a
   First Row Transition Metal Dimer: The $^3_{u_2}$ State of Sc$_2$
   S.P. Walch and C.W. Bauschlicher, Jr.

7. Theoretical Evidence for Multiple 3d Bonding in the V$_2$ and Cr$_2$
   Molecules
   S.P. Walch, C.W. Bauschlicher, Jr., B.O. Roos, and C.J. Nelin

8. Extended CASSCF Calculations for Transition Metal Dimers: the
   Ti$_2$ $^1_{e_2}$, V$_2$ $^3_{e_2}$, and Cr$_2$ $^1_{e_2}$ states

9. On the Nature of the Bonding in Cu$_2$
   C.W. Bauschlicher, Jr., S.P. Walch, and P.E.M. Siegbahn

10. On the Nature of Bonding in Cu$_2$ - An Ab Initio Viewpoint
    C.W. Bauschlicher, Jr., S.P. Walch and P.E.M. Siegbahn
C. Iron Clusters

   S.P. Walch
   Surface Science, in press

D. Alkali Metals and Core-Valence Correlation

12. Ab Initio Calculation of the X_{1\Sigma^+} State of CsH
   B.C. Laskowski, S.P. Walch, and P.A. Christianson

13. All Electron GVB/CI Potential Curves for the X_{1\Sigma^+} State of Cs_2
   S.P. Walch, C.W. Bauschlicher, Jr., P.E.M. Siegbahn, and H. Partridge

14. Electron Affinities of the Alkali Dimers: Na_2, K_2 and Rb_2
   H. Partridge, D.A. Dixon, S.P. Walch, C.W. Bauschlicher, Jr.,
   and J.L. Gole

15. An Ab Initio Study of Core Valence Correlation
   H. Partridge, C.W. Bauschlicher, Jr., S.P. Walch, and Bowen Liu

E. Atomic Calculations and Basis Sets

16. On Correlation in the First Row Transition Metal Atoms
   C.W. Bauschlicher, Jr., S.P. Walch, and H. Partridge

17. On the Electron Affinity of Cu Atom
   C.W. Bauschlicher, Jr., S.P. Walch and H. Partridge

18. On the Choice of Gaussian 4f Functions for Use in Calculations
    on Transition Metal Atoms
    S.P. Walch and C.W. Bauschlicher, Jr.

19. Supplemental Basis Functions for the Second Transition Row
    Elements
    S.P. Walch, C.W. Bauschlicher, Jr. and C.J. Nelin
F. Oxygen on Nickel

20. Comment on "Evidence for Two States of Chemisorbed O on Ni (100)"
C.W. Bauschlicher, Jr., S.P. Walch, P.S. Bagus, and C.R. Brundle
APPENDIX A

The following paper discusses the $\text{Fe}_n\text{H}$ cluster calculations.
Model Studies of the Interaction of 
H Atoms with BCC Iron

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Abstract
Ab Initio/Effective Core Potential cluster studies are reported for the
interaction of H atoms with BCC iron. The calculations use a one-electron 
ECP based on the 4s13d7 state of the Fe atom. Two-fold and four-fold sites 
on the (100) surface as well as octahedral, tetrahedral, and trigonal interior 
sites were studied. Four-fold surface sites are found to be bound by \(\sim 1.5\) eV 
with the H atom \(\sim 0.5\) \(a_0\) above the surface. Penetration of the surface at a 
four-fold site involves movement toward a second layer atom and is expected to 
be unfavorable. Two-fold surface sites have small binding energies \(\sim 0.25\) eV. 
Penetration of the surface at this site involves movement toward a tetrahedral 
interior site and is downhill in energy. Tetrahedral interior sites are found 
to be bound by \(\sim 1.3\) eV and are a minimum on the potential energy surface. 
Octahedral sites are a maximum on the potential energy surface and are estimated 
to be \(\sim 0.2\) eV higher (including lattice relaxation effects). Trigonal sites 
are found to be a saddle point connecting adjacent tetrahedral sites and this 
pathway leads to an estimated barrier to diffusion of \(\sim 0.1\) eV (including lattice 
relaxation effects). The volume expansion for a H atom in a tetrahedral site 
is calculated to be 21%.

* Supported by NASA grant #NCC2-148
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dimers, and $\text{Fe}_n\text{H}$ cluster results. The $\text{Fe}_n\text{H}$ cluster results are
described in detail in a manuscript included as Appendix A. The
results for the TM hydrides and dimers are summarized in Sections II
and III, respectively; while, Appendix B contains copies of publications
on these topics. During the course of this work several other projects were
undertaken. These include all-electron calculations on the CsH and Cs$_2$
molecules, calculations on the alkali dimers, an ab-initio study of core-
valence correlation, and studies of atomic correlation and basis sets.
References to this work are given in the publications list.
I. Introduction

Hydrogen embrittlement of metals is an important technological problem [1]. As part of a program to understand the effect of H atoms on crack propagation in iron we have undertaken a theoretical study of the interaction of H atoms with clusters of iron atoms in the BCC structure (α-Iron). In the studies reported here we first fixed the Fe atoms at the lattice positions of the perfect crystal and studied the interaction with a H atom at two-fold and four-fold sites on the (001) surface and at a series of octahedral, tetrahedral, and trigonal sites interior to the solid. These studies determine the geometry and binding energy at surface chemisorption sites and provide information on the barriers to diffusion within the metal and to penetration of the surface at two-fold and four-fold sites. We then relaxed the geometry of the nearest neighbor Fe atoms for the octahedral, tetrahedral and trigonal interior sites. These studies are important because they further refine the energetics for the diffusion process and because significant expansion of the lattice is found for tetrahedral sites. This expansion could induce stress in the metal leading to fracture.

The computational method employed here is the ab initio SCF method using a one-electron (4s valence) iron effective core potential (ECP) [2] based on the 4s\(^1\)3d\(^7\) state of the Fe atom. Here the Ar core and the 3d\(^7\) configuration are incorporated into the ECP leaving only a single 4s valence electron. The justification for including only the 4s electrons in the valence space comes from all-electron studies of diatomic molecules involving transition metal (TM) atoms. Here it is found that for elements on the right hand side of the first transition row, the bonding in the hydrides [3] and dimers at the nearest neighbor distances in the metal [4-6] involves the 4s,4p electrons with the 3d electrons remaining essentially atomic like. The selection of the 4s\(^1\)3d\(^7\) atomic configuration of the Fe atom is based on experimental bulk magnetic information [7] and on calculations [8] which show that although the 4s\(^2\)3d\(^6\) state is the ground state of the free Fe atom with the 4s\(^1\)3d\(^7\) state 0.88eV higher, in an environment appropriate to Fe metal the 4s\(^1\)3d\(^7\) state becomes the lowest state.
The present calculations involve Fe clusters of up to 66 Fe atoms and show slow convergence with respect to cluster size; cluster edge effects still introduce significant uncertainties even for the largest clusters studied. Important qualitative features of the H-Fe\textsubscript{n} interaction include: i) H atoms are most stable at surface four-fold sites (binding energy \(\sim 1.5\text{eV}\)) with a barrier to movement into the bulk (toward an Fe atom in the second layer). ii) Two-fold sites are only weakly bound but it is downhill from this location to move into the bulk (toward an interior tetrahedral site). iii) Interior octahedral and tetrahedral sites are less stable than four-fold surface sites (binding energy \(\sim 1.3\text{eV}\)) with tetrahedral sites lower in energy (\(\sim 0.23\text{eV}\) separation for the unrelaxed lattice and \(\sim 0.18\text{eV}\) separation for the relaxed lattice based on Fe\textsubscript{66}H). The tetrahedral site is a minimum on the potential energy surface while the octahedral site is a maximum. iv) Tetrahedral interior sites show a large volume expansion \(\sim 21\%\). v) The lowest pathway for T\(\leftrightarrow\)T diffusion involves a trigonal site which is a saddle point on the potential energy surface (Calculated barrier \(\sim 0.17\text{eV}\) for the unrelaxed lattice and \(\sim 0.10\text{eV}\) for the relaxed lattice based on Fe\textsubscript{66}H).

Section II discusses some features of the electronic structure of Fe clusters. Section III discusses the cluster calculations. Section IV discusses the features of the calculated potential, while Section V compares the computed energetics to experiment.
For the TM atoms of the first transition row the 4s orbital is significantly larger than the 3d orbital. As one moves from left to right in the first transition row the ratio \( \frac{\langle r_{4s}\rangle}{\langle r_{3d}\rangle} \) increases monotonically from 2.36 to 3.24 with a value of 2.95 for Fe [9]. Thus, for large bond distances one expects bonding to the 4s orbital to be more favorable than bonding to the 3d orbital with the 4s becoming increasingly favorable on the right side of the row.

For the TM hydrides only ScH [10] shows a short R state involving 3d bonding; whereas the other hydrides including FeH show predominately 4s bonding character with the 3d orbitals remaining quite atomic like [3]. The situation for the dimers is similar with the possibility for elements on the left half of the row of 4s-4s bonding at large R and 3d-3d bonding at small R. Examples of the latter are \( \text{V}_2 \) [11] and \( \text{Cr}_2 \) [11,12]. With more than half filled 3d shells the favorability of 3d bonding decreases since the repulsion between doubly occupied 3d orbitals cancels 3d bonding interactions arising out of the singly occupied 3d orbitals. For \( \text{Cu}_2 \) [4] with a closed 3d shell (for the \( 4s^13d^{10} \) state) the bonding is described as predominately 4s-4s bonding with the 3d orbitals essentially atomic like. Given this, one expects the dominant bonding interactions for Fe-Fe and Fe-H bonds to involve the 4s,4p electrons of the Fe atom with the Fe 3d electrons remaining essentially atomic like.

Fig. 1 shows the results of all-electron calculations for the Fe, molecule. The electronic state considered here arises from the \( 4s^23d^6 + 4s^13d^7 \) atomic limit. The significant feature of Fig. 1 is that there is weak 3d bonding in the small R region as evidenced by the low-spin state (maximum 3d bonding) being lower, but in the large R region the high spin state (no 3d bonding) is lower thus indicating negligible 3d bonding. Similar conclusions have been reached by Shim and Gingerich [6] for states derived from the \( 4s^13d^7 + 4s^13d^7 \) atomic limit. Thus we conclude that at the Fe-Fe distances involved in BCC Fe metal-metal 3d bonding is of negligible importance. (The nearest neighbor distance is 4.68\(a_o\) in BCC Fe [13]). For these reasons we believe it is a reasonable though extreme approximation to include only 4s electrons in the valence shell with the 3d electrons incorporated into the ECP.
The ECP is based on the $4s^13d^7$ Fe atomic configuration. The choice of this configuration is supported by experimental magnetic data [7] which show 2.22 effective Bohr magnetons per Fe atom. Assuming that this magnetic moment arises only from the 3d electrons and that the 3d electrons are completely high spin coupled, this magnetic data is consistent with a mixture of $4s^13d^7$ and $3d^8$. However, this data could also be consistent with $4s^13d^7$ and some low-spin coupling. The choice of $4s^13d^7$ is also supported by calculations in which one Fe atom is placed in the center of a cubic arrangement of eight one-electron $4s^13d^7$ like Fe atoms (BCC unit cell). The result is that the $4s^13d^7$ configuration is 0.25eV below the $4s^23d^6$ configuration in this environment, although for the free atom $4s^13d^7$ is 0.88eV above $4s^23d^6$. Given this choice of atomic configuration with the 3d electrons incorporated into the ECP leaves only one valence electron per iron atom. This approach is very similar to the one-electron Ni cluster studies based on the $4s^13d^9$ Ni atomic configuration [14].

Comparison between ECP and all-electron results can be made for FeH. Here the ECP calculation leads to $R_e = 2.96 \, a_o$ and $D_e = 1.85eV$ whereas the all-electron calculation leads to $R_e = 3.02 \, a_o$ and $D_e = 3.20eV$ for the $^4\Delta$ state of FeH [5]. However, a direct comparison here is not appropriate since the ECP calculation corresponds to pure $4s^13d^7$ atomic character whereas the FeH molecule in the $^4\Delta$ state is a strong mixture of $4s^13d^7$ and $4s^23d^6$. The latter configuration mixing, which occurs in the all-electron calculations, is expected to lengthen $R_e$ (due to more $4s^23d^6$ character) and increase $D_e$ as compared to the ECP calculation; these expectations are borne out by the results quoted above. Based on these results, to the extent that mixing of $4s^13d^7$ and $4s^23d^6$ is important for the cluster, we expect the calculations with the ECP to slightly underestimate FeH bond lengths and to significantly underestimate H atom binding energies. Relative energetics for a given cluster would still be expected to be accurate and the emphasis here is therefore on comparisons of relative energies for different H atom locations within a given cluster.
III. The Cluster Calculations

The basis set for Fe is a (4s3p)/[2slp] basis. The 4s functions are a (31) contraction of the outer four Wachters’ 4s functions [15]. The contraction here is based on an atomic SCF calculation for the 2S state arising from the 4s\(^1\) configuration. Note that this contraction is different from the all electron contraction because the ECP 4s orbital does not have a nodal structure. The 4p function was obtained by optimization of a 3 term GTO fit to a 2p STO [16] for the 2P atomic state arising out of the 4s\(^1\) configuration. The resulting exponents were multiplied by 1.5 to make them more suitable for describing 4s + 4p correlation [17]. The H basis set is a (5slp)/[3slp] basis. The s basis is a (311) contraction of Huzinaga’s 5s set [18], while the 2p functions are a single set of gaussian primitives with exponent 1.0. The one-electron ECP is given in Table I.

As has been well documented [19] 4p functions are very important for describing the bonding in Ni clusters and these effects are also found to be important for Fe clusters. Omission of the 4p functions leads to a loss of most of the metal-metal bonding energy and leads to overestimation of metal-H binding energies due to i) poor description of the metal metal bonds and ii) basis set superposition effects (i.e. the H basis functions mimic the effect of the missing 4p functions and thus lower the cluster energy even without the H atom electron and associated nuclear charge). Thus, unlike Upton and Goddard [14] who omitted the important 4p functions, we have included the 4p functions for those Fe atoms which are within bonding distance of the H atom in any site considered in the cluster. These Fe atoms are denoted as primary (P). To reduce edge effects we have also added the nearest neighbors of the primary atoms. These we denote as secondary (S) atoms. Because these atoms are more distant from the H adatom, the omission of the 4p functions is less serious and we chose to include only the 4s functions on these atoms in order to keep the calculations of more reasonable size. For example, the Fe\(_{66}\) cluster involves 330 basis functions with 4p functions on all centers, but only 198 functions if 22 atoms are primary and the remainder are secondary.
Fig. 2 shows the Fe$_{36}$ cluster which is a representative cluster for interior sites. The primary atoms here consist of eight atoms in an arrangement consisting of two fused tetrahedra. Each primary atom has the full complement of eight nearest neighbors which are included at the secondary level. The locations of the H atoms are also indicated in Fig. 2. The Fe$_{36}$ cluster contains i) octahedral sites which have six nearest neighbor Fe atoms and ii) tetrahedral sites which have four nearest neighbors. (Note that these are not regular octahedra or tetrahedra since they are compressed in one direction.)

Moving from left to right along the H atom positions indicated by open circles one passes alternately through octahedral and tetrahedral sites at separations of $d/4$ where $d$ is the lattice constant. Thus the potential should exhibit a periodicity in the direction indicated with $\lambda = d/2$, i.e. all octahedral sites should be equivalent and all tetrahedral sites should be equivalent. This periodicity is not necessarily present in the clusters due to cluster edge effects and we have used periodicity as a criterion for judging the size of cluster edge effects. Two other clusters were studied which are related to the Fe$_{36}$ cluster. These were the smaller Fe$_{30}$ cluster which is related to the Fe$_{36}$ cluster by deleting two primary atoms and associated secondary atoms from one end of the cluster and a larger Fe$_{48}$ cluster which extends the Fe$_{36}$ cluster by addition of an additional tetrahedron of primary atoms and associated secondary atoms at one end.

The BCC metal also exhibits periodicity in a direction perpendicular to the path discussed above for the Fe$_{36}$ cluster. This path is indicated by the solid circles in Fig. 2. Also illustrated in Fig. 2, by the triangle, is a trigonal site which is found to be a saddle point connecting the two adjacent tetrahedral sites. In order to study the T$\leftrightarrow$T diffusion via the trigonal site we considered additional clusters which are equivalent in the two periodicity directions. The primary cluster here is a 22 atom cluster consisting of four fused BCC unit cells centered about the intersection of the two paths given above. Here we considered an Fe$_{22}$ cluster with all atoms primary and an Fe$_{66}$ cluster which includes in addition the nearest neighbors as secondary atoms.
Fig. 3 shows the Fe\textsubscript{30} cluster for the surface sites. Here we are considering two-fold and four-fold sites. The Fe\textsubscript{30} cluster has six surface and two second layer primary atoms. The secondary atoms consist of ten in the first layer, six in the second layer, and six in the third layer. Note that some of these are at second nearest neighbor distances. The Fe\textsubscript{39} cluster adds to the Fe\textsubscript{30} cluster three additional primary atoms (two in the first layer and one in the second layer) and associated secondary atoms leading to an additional four-fold surface site. For each of these clusters the H atom was moved perpendicular to the surface for the two-fold and four-fold sites.

The ground states of the clusters were obtained by an Aufbau method. The symmetry used in the calculations is C\textsubscript{2v} for the interior site clusters and C\textsubscript{s} for the surface site clusters. The orbitals are filled using the Aufbau principle until the full complement of electrons is present. The cluster configurations for the interior site clusters are as follows: Fe\textsubscript{30} has six a\textsubscript{1}, three b\textsubscript{2}, three b\textsubscript{1}, and two a\textsubscript{2} orbitals doubly occupied and one a\textsubscript{1} and one b\textsubscript{2} orbitals singly occupied which leads to a \textsubscript{3B\textsubscript{2}} state. The triplet state arises here because the singly occupied orbitals belong to an E representation in the full cluster symmetry which is higher than C\textsubscript{2v}. Fe\textsubscript{36} has eight a\textsubscript{1}, four b\textsubscript{2}, four b\textsubscript{1}, and two a\textsubscript{2} orbitals doubly occupied. Fe\textsubscript{48} has eleven a\textsubscript{1}, five b\textsubscript{2}, five b\textsubscript{1}, and three a\textsubscript{2} orbitals doubly occupied. Fe\textsubscript{66} has twelve a\textsubscript{1}, nine b\textsubscript{2}, seven b\textsubscript{1}, and five a\textsubscript{2} doubly occupied. The cluster configurations for the surface site clusters are as follows: Fe\textsubscript{30} has nine a' and six a'' orbitals doubly occupied. Fe\textsubscript{39} has twelve a' and seven a'' orbitals doubly occupied and one a'' orbital singly occupied. The Fe\textsubscript{39}H clusters are all doublet states with the exception of the Fe\textsubscript{30}H interior sites cluster which is a quartet state and Fe\textsubscript{39} which is a singlet state.
IV. Discussion

Fig. 4 shows the binding energies for the Fe$_{30}$H, Fe$_{36}$H, and Fe$_{48}$H clusters. As discussed in Section III, for the solid all tetrahedral sites are equivalent and all octahedral sites are equivalent. This behavior is most closely approximated by the Fe$_{36}$H cluster, where we see pseudo periodic behavior with the tetrahedral sites slightly lower in energy than the octahedral sites. Note that these calculations do not include enough points to demonstrate the shape of the potential (i.e. one would expect an approximately sinusoidal variation between the calculated points). The other clusters, on the other hand, at first appear to exhibit rather different potentials with the Fe$_{30}$H cluster showing a decrease in energy in moving from the center to the edge of the cluster while the Fe$_{48}$H cluster shows an increase in energy for motion along the same path. However, the potentials can be made to look very similar for the three clusters by including a correction term (for edge effects) which is linear with distance. Selecting such a correction term to make the two octahedral sites degenerate leads to the corrected curves in Fig. 4b which show a remarkable similarity to each other. From Fig 3b one sees that in all cases the tetrahedral sites are below the octahedral sites. The calculated separations are 0.21eV for Fe$_{30}$H, 0.30 and 0.10eV for Fe$_{36}$H, and 0.28 and 0.11eV for Fe$_{48}$H. Thus, the calculations can be interpreted to indicate a tetrahedral to octahedral separation of 0.10 - 0.30eV.

Fig. 5a shows two cuts through the potential surface for the Fe$_{60}$H cluster. One path follows one of the periodicity directions in Fig. 1, while the other path is from the central octahedral site toward the trigonal site. Fig. 5b differs from Fig. 5a in that a linear correction has been added to make the potential flat from the center of the cluster to the edge (as was done for Fig. 4). These two cuts through the surface show that the octahedral site is a maximum on the potential energy surface and are consistent with the tetrahedral site being a minimum on the surface with the trigonal site being a saddle point connecting two adjacent tetrahedral sites. A remarkable feature of Fig. 4 is the clearly sinusoidal variation of the energy along the periodicity direction. This result suggests that the Fe$_{60}$H cluster is exhibiting true periodicity although from comparison of Fig. 4a and Fig. 4b there still appears to be a significant edge effect.
From Fig. 5b the tetrahedral to octahedral separation is 0.23eV and the tetrahedral to trigonal separation is 0.17eV (based on the central octahedral site and the adjacent tetrahedral site). These orderings may be understood based on the following simple geometric argument. The octahedral site does not correspond to a regular octahedron but has two shorter FeH distances (2.703\(a_0\)) and four longer FeH distances (3.823\(a_0\)). The tetrahedral site has all FeH distances the same (3.022\(a_0\)) and the trigonal site has two short FeH distances (2.819\(a_0\)) and one longer FeH distance (3.023\(a_0\)). With the one-electron ECP and the same basis set used in the calculations diatomic FeH has a bond length of 2.96\(a_0\). Clearly one expects an H atom in the solid to prefer an FeH distance longer than for the diatomic molecule. Thus, it should be downhill for the octahedral site with two short bonds to distort toward the tetrahedral or trigonal sites. The tetrahedral site is favored over the trigonal site since it has four reasonable FeH bond lengths while the trigonal site still has one compressed bond distance.

For the octahedral, tetrahedral and trigonal sites some relaxation of the lattice was allowed both with and without the H atom present. The clusters here consisted of six, four, and three primary atoms plus the nearest neighbors as secondary atoms. The resulting cluster sizes are Fe\(_{30}\), Fe\(_{24}\), and Fe\(_{20}\), respectively. Fig. 6 shows the distances which were varied in the geometry optimization. Here only the locations of the primary atoms were varied while the secondary atom locations were fixed. For the bare clusters the Fe\(_{30}\) and Fe\(_{24}\) cluster geometries were optimized with the constraint that \(r_1\) and \(r_2\) were varied simultaneously; this lead to geometric expansions compared to the BCC geometry of 3.4% and 3.9% for octahedral and tetrahedral, respectively. For the trigonal cluster \(r_1\) and \(r_2\) were varied separately giving a 2.4% increase in \(r_2\) and a 6.5% increase in \(r_1\). For the clusters with the H adatom the increases compared to the bare clusters were: \(r_1 = +10.2\%\) and \(r_2 = -4.8\%\) for octahedral, \(r_1 = +3.8\%\) and \(r_2 = +12.2\%\) for tetrahedral and \(r_1 = +9.7\%\) and \(r_2 = +1.2\%\) for trigonal. The corresponding increases in binding energy are 0.27eV, 0.22eV and 0.29eV for octahedral, tetrahedral, and trigonal. Applying these corrections to the energies from Fig. 5b leads to an estimated tetrahedral to octahedral separation of 0.18eV and an estimated tetrahedral to trigonal separation of 0.10eV. The volume expansion for the tetrahedral site, which is the only site which represents a minimum on the surface, is +21%.
Fig. 1 shows the potential for moving a H atom perpendicular to the (100) surface for two-fold and four-fold sites of the Fe₃₀H surface cluster. Here we see that surface atoms are much more stable (~1.3 eV at the four-fold site) and have a minimum at ~0.5 \(a_0\) above the surface. We expect a barrier for pushing the H atom beneath the surface for a four-fold site because it would be moving in the direction of a second layer Fe atom. For the two-fold sites, on the other hand, a location in the surface is basically an octahedral location and from the studies of interior sites we expect it to be downhill to move to the adjacent tetrahedral site. Indeed it is found that the H atom will move from this location to the interior. Fig. 5 shows similar calculations for the Fe₃₉H surface cluster. Here we see that the Fe₃₉H cluster shows results which are consistent with the Fe₃₀H cluster. The binding energies here are ~1.7 eV for site A and ~1.3 eV for site B. This difference between the two four-fold sites is another manifestation of cluster edge effects.

As discussed above we expect a large barrier to moving an atom from a four-fold site directly toward a second layer atom. Moving from a four-fold to a two-fold site is uphill by ~1.25 eV but it is downhill from here to an interior site; this implies a barrier of ~0.25 eV in addition to the endothermicity of ~1.0 eV to the process of moving a H atom from a four-fold surface site to an interior site via a two-fold site. However, there may be alternative pathways such as penetrating the surface at a four-fold site followed by sideways movement toward an adjacent tetrahedral site which involves little or no barrier.

From examination of Figs. 5, 7, and 8 we see that the most stable site is the four-fold surface site with an estimated binding energy of 1.3 - 1.7 eV while the two-fold surface site shows essentially zero binding energy (based on the Fe₃₉H cluster). Interior sites are less stable than surface sites being bound by about 1.3 eV (based on Fe₆₆H). This result is consistent with the experimental observation that H atoms are more stable at the surface with only a small fraction of the H atoms moving inside the solid (see section V); however, it is not clear that the binding energies are well enough converged with respect to cluster size to strongly support this conclusion.
V. Comparison to Experiment

The current picture of H₂ chemisorption on an iron surface is that the H₂ molecule first bonds in a weakly bound state which subsequently dissociates leading to two H atoms chemisorbed on the surface[21]. The detailed energetics for H atoms interior to the bulk are not known but overall the interior sites are believed to be less stable than the surface sites [22]. H atoms are known to be quite mobile inside the bulk [20]. The solubility and diffusivity of hydrogen in iron has been reviewed by Kiuchi and McLellan [24]. The quantities which are experimentally accessible (experimental value in parenthesis) are i) the heat adsorption (0.9eV) [22] which is the energy for chemisorption of H₂ on an iron surface (normally as film). Since H₂ is known to dissociate on the surface this quantity is twice the binding energy of an H atom minus the Dₑ of H₂. ii) the heat of solution (0.3eV) [23] which is as in (i) except that the two H atoms are in the bulk. Based on an analysis of non-Arrhenius behavior of the solubility it has been inferred that tetrahedral sites are about 0.23eV more stable than octahedral sites, iii) the activation energy for diffusion in the bulk iron lattice (0.1eV) [20], and iv) the volume expansion for a hydrogen atom in the perfect lattice which is ~0.17 atomic volumes for BCC iron [25].

Using the experimental Dₑ of H₂ in conjunction with the heat of adsorption and the heat of solution leads to binding energies of 2.8eV for one H atom at the surface and 2.5eV for one H atom in the bulk. The best calculated values are less than this being 1.3-1.7eV (four-fold, surface site) and 1.3eV (interior tetrahedral site), respectively. This is not an unexpected result given the SCF model which typically underestimates binding energies and considering that the same ECP and basis set underestimates the diatomic FeH binding energy by 1.4eV.

The activation energy for diffusion is estimated to be 0.10eV based on the Fe₆₆H cluster. One expects that the effective barrier should be lower than this, since tunneling is known to be important for hydrogen [26]. Thus, it appears that the calculations underestimate this barrier since the experimental barrier is thought to be ~0.1eV. Finally, the calculated volume expansion is 21% in reasonable agreement with the experimental estimate of 17%.
These encouraging results indicate that the SCF cluster model in conjunction with the one-electron ECP and basis set used here provides physically reasonable results and can be relied upon to provide useful information in situations which are experimentally inaccessible, e.g. the interaction of H atoms with defects in the solid.

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References


2. L.R. Kahn, unpublished work.


8. S.P. Walch, unpublished work.


17. The 4p function is given by: \( a_i = 0.28016, 0.07190, 0.02442 \) and \( C_i = 0.16239, 0.56617, 0.42231 \).


Table I  Parameters of the GTO Fit of the One-Electron
Fe Effective Core Potential

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*The Fe one-electron ECP was developed by Dr. Louis Kahn [2].
Figure Captions

Fig. 1 Calculated potential curves for Fe states arising from the $4s^23d^6 + 4s^13d^7$ atomic limit. Curve A is for the high spin state which has no 3d bonding, while curve B is for the low spin state which could have maximal 3d bonding.

Fig. 2 The Fe$_{36}$ cluster for interior sites in BCC Iron. The locations of the primary atoms are indicated by the large circles; the locations of the secondary atoms are indicated by the intermediate size circles. The H atom locations for one periodicity direction are indicated by the small open circles; the H atom locations for the other periodicity direction are indicated by the small solid circles, while a trigonal site is indicated by a triangle.

Fig. 3 The Fe$_{30}$ cluster for surface sites. The conventions are as for Fig. 1.

Fig. 4 Calculated binding energies for octahedral (O) and tetrahedral (T) sites in BCC Iron. Fig. 4a shows the calculated points while Fig. 4b shows the effect of adding a correction term (see text) to compensate for cluster edge effects.

Fig. 5 Calculated binding energies for two cuts through the potential energy surface for H in the Fe$_{66}$ cluster. Curve A is for motion along one of the periodicity directions while curve B is for motion in the direction of a trigonal site. Fig. 5b differs from Fig. 5a in that a correction term has been added to compensate for cluster edge effects (see text).

Fig. 6 The geometric parameters which were varied in studying lattice relaxation for H in octahedral, tetrahedral, and trigonal sites.

Fig. 7 Calculated binding energies for two-fold and four-fold sites on the (100) surface of BCC Iron from the Fe$_{30}$H cluster.

Fig. 8 Calculated binding energies for two-fold and four-fold sites on the (100) surface of BCC Iron from the Fe$_{39}$H cluster.
Fig 5a

ORIGINALLY Ig. 11
OF POOR QUALITY

Fig 5b

ORIGINAL FIG. 11
OF POOR QUALITY

![Graph](image-url)
Fig 6

TRIGONAL

TETRAHEDRAL

OCTAHEDRAL

4
Fig 7

(A) TWO-FOLD SITE

(B) FOUR-FOLD SITE
APPENDIX B

The following papers describe the calculations for the TM hydrides and dimers.
CASSCF/CI calculations for first row transition metal hydrides: The TiH (4Φ), VH (5Δ), CrH (4Σ'), MnH (4Σ''), FeH (46Δ), and NiH (5Δ) states

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By consideration of atomic coupling arguments and interaction of 4s3d* and 4s3d*2 derived terms, the ground states of the transition metal hydrides are predicted to be TiH (4Φ), VH (5Δ), CrH (4Σ'), MnH (4Σ''), FeH (46Δ), CoH (4Φ), and NiH (5Δ). All of these systems have been studied by a CASSCF/CI(SD) procedure with the exception of CoH. The calculated parameters derived from the CASSCF/CI(SD) potential curves are in good agreement with the experimental values where known (no information exists for TiH and VH).

Inclusion of atomic correlation leads to significantly better agreement with experiment particularly for R., These improvements are related to a more balanced description of the atomic states in the correlated wave functions.

I. INTRODUCTION

The chemistry of the transition metals (TM) is especially diverse because of the presence of several low-lying atomic states which may be utilized in bonding. For the first transition row the lowest atomic states are derived from the 4s23d2, 4s3d1, and 4s4p3d configurations. As we will see in the present study involves a complex interaction among terms arising out of the various atomic levels. A number of studies1-5 have shown that the separations of the TM atomic states are not well described at the Hartree–Fock (HF) level; however, inclusion of electron correlation does significantly improve the description of the atomic states. Thus, electron correlation has to be included in the molecular calculations.

There have been a number of previous theoretical studies of the TM hydrides. Earlier all-electron studies by Scott and Richards6-8 and Bagus and Schaefer9 used HF wave functions which completely neglect electron correlation. More recently Henderson, Das, and Wahl (HDW)10 and Das11 have carried out limited MCSCF studies of the TM hydrides. In these studies atomic correlation was largely neglected. This was justified in the work of Das11 by the observation that for VH the calculated properties of several states were similar in the GVB/POL-Cl calculations of Walch12 which included limited correlation (4s2-4p5), and in the calculations of HDW which neglected these correlation terms. However, Bauschlicher and Walch13 pointed out that for ScH neglect of 4s2-4p5 near degeneracy terms leads to an incorrect ordering of the 4Σ ' and 3Σ states. Similarly for NiH Walch and Bauschlicher14 found that a correct description of the X2Σ state of NiH required a balanced description of the 4s3d2 and 4s4d3d states of Ni, and consequently an accurate description of electron correlation was necessary. This conclusion is also substantiated for NiH by the CASSCF/CI calculations of Blomberg et al.,15 and had been suggested by the earlier studies of Bagus and Bjorkman16 and R. Martin17 in which limited 3d shell correlation had been included.

For completeness we also mention the work of Goddard et al.18 on NiH in which electron correlation effects for the Ni atom were included in a semiempirical way using a modified effective core potential. This approach led to properties for NiH in good agreement with experiment at the two configuration MCSCF (GVB) level.

In the present study calculations were carried out for the predicted ground states of TiH(4Φ), VH(5Δ), CrH(4Σ'), MnH(4Σ''), and NiH(5Δ). For FeH both the 6Δ and 5Δ states were studied, since both are likely candidates for the ground state. As discussed in Sec. II, the ground state symmetries are predicted based on a combination of atomic coupling arguments and coupling of 4s3d and 4s4d terms in the molecular system. Electron correlation is included by a CASSCF/CI(SD) treatment. The CASSCF includes near-degeneracy effects (4s2-4p5) while correlation of the 3d electrons is included at the CI level.

II. QUALITATIVE FEATURES OF THE BONDING IN TM HYDRIDES

Figure 1 shows the relative ordering of the 4s3d2 and 4s4d3d states for the first transition row.10 The trends in Fig. 1 may be understood in terms of two
TABLE I. Calculated parameters for the TM hydrides.

<table>
<thead>
<tr>
<th>State</th>
<th>( R_e ) (( \text{Å} ))</th>
<th>( \omega ) (( \text{cm}^{-1} ))</th>
<th>( D_e ) (eV)</th>
<th>3d population</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiH ( ^1\text{S} )</td>
<td>PW (^a)</td>
<td>1.83</td>
<td>1407</td>
<td>2.12</td>
</tr>
<tr>
<td></td>
<td>SR (^b)</td>
<td>1.86</td>
<td>1311</td>
<td>1.7</td>
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<tr>
<td></td>
<td>D (^d)</td>
<td>1.91</td>
<td>1331</td>
<td>1.7</td>
</tr>
<tr>
<td>VH ( ^3\Delta )</td>
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<td>1590</td>
<td>2.30</td>
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<tr>
<td></td>
<td>D</td>
<td>1.74</td>
<td>1609</td>
<td>1.77</td>
</tr>
<tr>
<td>CrH ( ^3\Sigma^+ )</td>
<td>PW</td>
<td>1.70</td>
<td>1465</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>1.71</td>
<td>1570</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>Exp. (^d)</td>
<td>1.66</td>
<td>1581</td>
<td>1.77</td>
</tr>
<tr>
<td>MnH ( ^3\Sigma^+ )</td>
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<td>1639</td>
<td>1.71</td>
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<tr>
<td></td>
<td>Exp. (^d)</td>
<td>1.73</td>
<td>1548</td>
<td>1.77</td>
</tr>
<tr>
<td>FeH ( ^1\Delta )</td>
<td>PW</td>
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<td>Exp. (^d)</td>
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<td>1550</td>
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<td>NiH ( ^3\Delta )</td>
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<td></td>
<td>BSR (^f)</td>
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<td>1911</td>
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<td>BB (^g)</td>
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<td>1926</td>
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<td></td>
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<td></td>
<td>Exp. (^d)</td>
<td>1.48</td>
<td>1926</td>
<td>2.76</td>
</tr>
</tbody>
</table>

\(^a\)Present work (PW).
\(^b\)Scott and Richards (SR) Refs. 6-8.
\(^c\)Das (D) Ref. 11.
\(^d\)Reference 28.
\(^e\)Jaffe (J) Ref. 32.
\(^f\)Stevens, Lineberger, and Feigerle Ref. 30.
\(^g\)Davis Ref. 31.
\(^h\)Blomberg, Siegbahn, and Roos (BSR) Ref. 15 CI results. \( D_e \) referenced to 4s^1 3d^6.
\(^i\)Bagus and Bjorkman (BB) Ref. 16. The \( R_e \) value is from CI calculation.

The bonding of a H atom to a transition metal atom may involve either the 4s^1 3d^3 or 4s^1 3d^4 state. For the 4s^1 3d^3 \(^t\) state the bonding involves formation of sp-hybrids arising from interaction of the 4s^1 3d^3 and 4s^1 4p^1 3d^3 atomic configurations. This leads to two orbitals \( s_z \) and \( s \) which have the qualitative character 4s \( + 4p^1 \) and 4s \( - 4p^1 \), respectively. The bonding orbital (two electrons) has the character of a sigma bond between Sc (s_z) and H (1s) while the \( s \) orbital which is singly occupied is hybridized away from the bond pair. For the 4s^1 3d^4 \(^t\) state the bonding involves formation of a simple Sc (4s) \(-\)-(H (1s) bond. We expect the bonding here to be stronger than for the 4s^1 3d^3 state since no promotion energy is involved. This picture is supported by the population analysis (CASSCF/CISD wave functions) which shows that MnH which is predominately 4s^1 3d^3 like has valence s and p populations of 1.04 and 0.66 indicating a strong admixture of 4s^1 4p^1 3d^3 character while CrH which is dominated by 4s^1 3d^3 has...

Competing effects (i) a general stabilization of 3d with respect to 4s with increasing \( Z \), and (ii) a preference for a maximum number of high spin coupled 3d orbitals. For less than half-filled shells both effects tend to stabilize 4s^1 3d^3 \(^t\) with respect to 4s^1 3d^3 for increasing \( Z \), thus the 4s^1 3d^3 \(-\)-4s^1 3d^3 separation decreases monotonically from Sc-Cr. For Mn 4s^1 3d^3 is favored over 4s^1 3d^3 because of the extra high spin coupled 3d orbital. Thus, at Mn there is a discontinuity with 4s^1 3d^3 \(^t\) again becoming lower. For Mn-Cu the 4s^1 3d^3 \(-\)-4s^1 3d^3 separation once again decreases monotonically due to stabilization of 3d with respect to 4s for increasing \( Z \).

In addition to the 4s^1 3d^3 and 4s^1 3d^4 atomic configurations the 4s^1 4p^1 3d^3 configuration is also important. The excitation energy 4s^1 3d^3 \(-\)-4s^1 4p^1 3d^3 increases monotonically with increasing \( Z \) from \(-16\,000\,\text{cm}^{-1}\) for Sc to \(-26\,000\,\text{cm}^{-1}\) for Cu.18
valence s and p populations of 0.77 and 0.11, i.e., very little admixture of 4p character.

Considering these two bonding mechanisms in conjunction with the variation in the 4s\(^2\)3d\(^4\)-4s\(^1\)3d\(^5\) separation (Fig. 1) one expects predominately 4s\(^1\)3d\(^3\) like character for elements where 4s\(^2\)3d\(^3\) is well below 4s\(^1\)3d\(^4\) (e.g., Sc and Mn), predominately 4s\(^1\)3d\(^{5-1}\) character for elements where 4s\(^1\)3d\(^{5-1}\) is well below 4s\(^2\)3d\(^3\) (e.g., Cr and Cu), and mixed character for the other elements with especially strong mixing for elements where 4s\(^1\)3d\(^{5-1}\) is slightly above 4s\(^2\)3d\(^3\) (e.g., V and Co). These expectations are borne out by the 3d populations in Table I where we see TiH is predominately 4s\(^1\)3d\(^3\), VH is a mixture of 4s\(^1\)3d\(^3\) and 4s\(^1\)3d\(^4\), CrH is predominately 4s\(^1\)3d\(^4\), MnH is predominately 4s\(^1\)3d\(^3\), FeH is predominately 4s\(^1\)3d\(^3\), and NiH is a mixture of 4s\(^1\)3d\(^3\) and 4s\(^2\)3d\(^2\).

As pointed out elsewhere, there is an additional complication for ScH where there is a competition between bonding to 5s and 3d\(^1\) for the 4s\(^2\)3d\(^3\) configuration. However, we suspect that a "d-bonded" ground state is peculiar to ScH for the following reasons: (i) As one moves from the left to right side of the first transition row both the 3d and 4s orbitals contract, but the ratio of (r\(\text{d}^2\) / r\(\text{s}\)) increases monotonically from 2.364 - 3.239. Thus bonding to the 4s\(^2\) pair is favored increasingly as one moves from Sc to elements on the right side of the row. (ii) Formation of the "d-bond" results in loss of exchange energy as the number of 3d electrons increases. This effect should be most significant in the center of the row where the maximum number of high spin coupled electrons occurs.

In the previous discussion we considered the interaction between H (1s) and the 4s\(^2\)3d\(^4\) and 4s\(^1\)3d\(^5\) atomic configurations. We now consider how to select the lowest 3d orbital occupancies. As discussed in some detail elsewhere, just as one may write a given atomic state as a mixture of determinants it is possible to express a given determinant as a mixture of atomic states. For example, for the Ti atom in the 4s\(^2\)3d\(^5\) state the configuration 4s\(^2\)3d\(^4\)3d\(^1\) is pure 3F, but the configuration 4s\(^2\)3d\(^3\)3d\(^3\) is a mixture of 40\% \(3^d\) and 60\% \(3^p\). These relationships have been worked out for the 3d, 3d\(^2\), 3d\(^3\), 3d\(^4\), and 3d\(^5\) configurations and are given in Table II. Given this information one then expects for Ti that the 4s\(^2\)3d\(^3\)3d\(^1\) configuration is 0.62 eV above 4s\(^2\)3d\(^4\)3d\(^0\) (i.e., 0.6 < 1.03 where 1.03 is the excitation energy \(3^p - 3^d\)). Thus in the absence of other effects one expects it to be more favorable to have the configuration 3d\(^0\)3d\(^1\) than 3d\(^1\)3d\(^0\) and similarly for the other TM hydrides one may pick likely candidates for the ground states from Table I. Note that here we are making use only of atomic information.

Now consider forming a TM hydride. As a first case consider the state of ScH arising out of 4s\(^2\)3d\(^3\). The SCF configuration here is

\[ b^5s^23d^4\alpha\beta\alpha\alpha, \]  

where b is the bond orbital (\(s^2\) - H1s like) and \(s^2\) is an orbital of \(4s - 4s^2\) character. Looking at Table II we see that the three components of \(2^p\) are degenerate and no direct information as to the favorability of 3d\(e\), 3d\(e\), or 3d\(\alpha\) is obtained from purely atomic information. However in the molecular symmetry 3d\(e\) and 4s mix and in Eq. (1) allowing \(s^2\) to mix in 3d\(\alpha\) character leads to mixing in a piece of 4s\(^1\)3d\(^3\) like character:

- \(\text{b particle}\) \(b^5s^23d^4\alpha\beta\alpha\alpha + \lambda b^53d^0\alpha^2d^1\alpha\beta\alpha\alpha 100\% 3^F\);
- \(\text{F particle}\) \(b^5s^23d^4\alpha\beta\alpha \alpha + \lambda b^53d^0\alpha^2d^1\alpha\beta\alpha\alpha 40\% 3^F\);
- \(\sigma\) \text{ particle} \(b^5s^23d^3\alpha\beta\alpha\alpha\)

Note here that the 3d\(\alpha\) particle leads to 4s\(^2\)3d\(^0\)3d\(^1\) which is pure \(3^F\), the 3d\(\beta\) particle leads to 4s\(^2\)3d\(^1\)3d\(^1\) which is 40\% \(3^F\) and 60\% \(3^P\), while the 3d\(\alpha\) particle leads to no 4s\(^1\)3d\(^2\) term due to the Pauli principle. Thus hybridizing 4s and 3d\(\beta\) is equivalent to mixing 4s\(^1\)3d\(\alpha\) and 4s\(^1\)3d\(\alpha\) character and one expects this process to be more favorable for a 3d\(\alpha\) particle than for a 3d\(\beta\) particle which is in turn more favorable than for a 3d\(e\) particle. On this basis one predicts the molecular ordering \(\Delta < \Pi < \Sigma\) which is in fact the calculated ordering.

Considering now TiH, from Table II the lowest atomic configurations are

\[ b^5s^23d^13d^0\alpha\beta\alpha\alpha \]  

and

\[ b^5s^23d^03d^1\alpha\beta\alpha\alpha \]  

which are pure \(3^F\) for the atomic case. However, Eq. (3) mixes with \(b^53d^1\)3d\(^0\)3d\(^1\) which is pure \(3^F\), while no such mixing is allowed for Eq. (4). Thus one predicts the ground state of TiH is \(3^F\) arising from Eq. (3).
For VH the most favorable choice is
\[ b^7s^213d^613d_{5-3}^13d_{5-3}^1, \] (5)
which mixes with
\[ b^13d_{5-3}^13d_{5-3}^13d_{5-3}^13d_{5-3}^1a\beta\alpha\alpha\alpha, \] (6)
leading to a \( ^1\Delta \) ground state.

For CrH mixing of 4s and 3de couples
\[ b^7s^213d_{5-3}^13d_{5-3}^13d_{5-3}^13d_{5-3}^1a\beta\alpha\alpha\alpha\alpha, \] (7)
and
\[ b^73d_{5-3}^13d_{5-3}^13d_{5-3}^13d_{5-3}^13d_{5-3}^1a\beta\alpha\alpha\alpha\alpha, \]
leading to a \( ^3\Delta^* \) ground state.

For less than half-filled 3d shell the above analysis predicts the ground state spin and spatial symmetry independent of whether the molecular state is predominantly \( 4s^2\ 3d^2 \) or \( 4s^1\ 3d^{m-1} \). On the other hand, for a more than half-filled 3d shell the spin multiplicity depends on whether the atomic character is \( 4s^2\ 3d^2 \) or \( 4s^1\ 3d^{m-1} \) like. Here the low spin states are expected to involve strong coupling of \( 4s^1\ 3d^{m-1} \) and \( 4s^2\ 3d^2 \) derived terms as for the elements with less than half-filled 3d shells, but the high spin states should involve less coupling of \( 4s^1\ 3d^{m-1} \) and \( 4s^2\ 3d^2 \) because the high spin coupling arising from \( 4s^1\ 3d^{m-1} \) is expected to be repulsive. By an argument analogous to the above (substituting holes for particles) one predicts that the ground states of the remaining hydrides are MnH(\( 4s^1\ 3d^2 \)), Fe(\( 4s^1\ 3d^1\ 3d^1\ 4p^1\ 4p^1 \)), CoH(\( 3s^2\ 3p^6\ 3d^6\ 4p^2\ 4p^2 \)), and NiH(\( 3s^2\ 3p^6\ 3d^6\ 4p^2\ 4p^2 \)) where the higher spin multiplicity corresponds to \( 4s^2\ 3d^2 \) and the lower multiplicity corresponds to \( 4s^1\ 3d^{m-1} \).

To further confirm the qualitative arguments made above we also compare the predicted ordering of the low-lying states to the calculated POL-CI ordering\(^{22}\) for VH. Figure 2 shows the molecular terms arising out of the \( 4s^2\ 3d^2 \) and \( 4s^1\ 3d^{m-1} \) atomic states (based on Table II and the experimental atomic separations.\(^{19}\)) The left- and right-hand columns of Fig. 2 show the atomic \( 4s^2\ 3d^2 \) and \( 4s^1\ 3d^{m-1} \) states while the center column (labeled "mixed") shows the calculated molecular ordering. Here the \( ^3\Phi \) mixed energy is fixed at the energy of the \( 4s^2\ 3d^2 \) term since no mixing of atomic states is expected for \( ^3\Phi \) (because only one \( ^3\Phi \) term arises).

The most noticeable feature of Fig. 2 is a large stabilization of the \( ^1\Delta \) and \( ^1\Pi \) states as compared to the atomic \( 4s^2\ 3d^2 \) separation. For the \( ^1\Delta \) state this effect is due to admixture of \( ^1\Delta(21\Pi) \) terms as above. [Note that we use an abbreviated notation for the 3d orbital occupancy here and in Fig. 2, e.g., \( ^1\Delta(21\Pi) \) is equivalent to Eq. (5) and \( ^1\Delta(21\Pi) \) is equivalent to Eq. (6).] This admixture of \( 4s^2\ 3d^2 \) and \( 4s^1\ 3d^{m-1} \) character is associated with a decrease of 0.15\( \alpha_0 \) in \( R_s \) as compared to \( ^3\Phi \), and is also consistent with the CASCF/CII population of 3.42 3d electrons (Table I). For \( ^1\Pi \) the situation is more complex in that there are two major configurational mixing effects. The dominant configuration here is \( ^1\Pi(201) \); however, there is significant admixture of \( ^1\Pi(212) \) and \( ^1\Pi(212) \). The latter configuration mixing \( 4s^1\ 3d^2 \) and \( 4s^1\ 3d^{m-1} \) character and is probably responsible for the decrease in \( R_s \) by 0.04\( \alpha_0 \) as compared to \( ^3\Phi \). Finally, the \( ^5\Sigma^* \) state shows significant coupling of \( ^5\Sigma^*(101) \) and \( ^5\Sigma^*(201) \) leading to stabilization with respect to \( ^5\Phi \) but no admixture of \( 4s^2\ 3d^2 \) and \( 4s^1\ 3d^{m-1} \) character which is consistent with \( ^5\Phi \) and \( ^5\Sigma^* \) having nearly identical \( R_s \) values.

III. CALCULATIONAL DETAILS

The TM basis sets start with Wachters' (14s 9p 5d) primitive set\(^{21}\) augmented with Wachters' two 4p functions, the diffuse 3d function of Hay,\(^{22}\) and a set of \( f \) polarization functions. The \( f \) exponents used were Ti (1.2), V (1.4), Cr (1.6), Mn (1.8), Fe (2.0), Co (2.2), and Ni (2.4). These exponents were selected by linear extrapolation of the optimum CI(5D) values for Fe and Ni.\(^{14,4} \) These values are near the optimum values for a single and double CI when the 3s and 3p are correlated.\(^{14} \) Since we did not correlate the transition metal 3s and 3p electrons a better choice of exponents may have been those optimized for only 3d and 4s correlation.\(^{14} \) However, the \( f \) functions are found to be unimportant for the TM hydrides\(^{15}\) and the 3d correlation energy and atomic splitting are somewhat insensitive to the choice of \( f \) exponent. Thus, this defect in the \( f \) basis is of no serious consequence. This basis set was contracted to [5s 4p 3d1] using the general contraction feature of BIGGOLMOL.\(^{23}\)

The H basis set starts with the (6s 1p) primitive set of van Duijneveldt\(^{16}\) with two additional diffuse s functions added in an even tempered manner, while the p functions were selected as a (211) contraction of a four-term GTO fit\(^{24}\) to an STO 2p with an exponent of 1.0: (8s 4p)/[5s 3p]. The innermost contracted p function is similar in spatial extent to the usual single p function, while the outer two p functions are diffuse functions.
appropriate to $H^-$. This basis set obtains all but $-0.02$ eV of the electron affinity (E.A.) of $H^-$. In the CASSCF calculations the Ar cores of the TM atoms are kept doubly occupied in all configurations; the active space consists of the orbitals derived from the transition metal $4s$, $4p$, and $3d$ orbitals and the $H(1s)$ orbital, i.e., $6s-9s$, $3d-4d$, and $1s$. In the above the $9s$, $3s$, and $1s$ orbitals are transition metal $3d$ like, $6s$ is the bond pair, $7s$ is the $s^2$ orbital, and $8s$ introduces left-right correlation of the bond pair, while $4\sigma$ introduces angular correlation of the bond pair. Note that at $R = 6\sigma$ is a transition metal $4s$ orbital. $7\sigma$ is the $H(1s)$ orbital, and $8\sigma$ and $4\sigma$ are transition metal $4p$ orbitals (near degeneracy effect), while as $R$ decreases the orbitals evolve much as in a $2 -1$ chemical reaction. Note also that for cases where the $3\sigma$ orbital is not occupied (TiH and VH) the $9\sigma$ orbital is mostly $H(2p\sigma)$ like and there is no occupied $3d\sigma$ like orbital. The $4\sigma$ orbital is mostly $H(2p\sigma)$ like, a result which is consistent with the nature of the $9\sigma$ orbital for TiH and VH. Note that the TM hydrides contain a significant component of TM$^+$ character ($H$ population 0.22 for MnH CASSCF CI wave function). Because the CASSCF procedure introduces some ambiguities into the calculations (e.g., the $9\sigma$ orbital is hydrogen like for TiH but is transition metal $3d\sigma$ like for CrH), it is difficult to obtain a consistent description of the bonding in the TM hydrides at the CASSCF level. Therefore, the CASSCF calculations were followed by CISD calculations. The starting set of reference configurations for these calculations were the GVB configurations:

$$
\begin{align*}
6s^2 7\sigma^1 \\
6s^1 8\sigma^1 7\sigma^1 \\
8\sigma^2
\end{align*}
$$

$$
\begin{align*}
3d^1 \text{TM}(4s^2 3d^1) - H \\
3d^{-1} \text{TM}(4s^1 3d^{1*}) - H
\end{align*}
$$

Table III shows the configurations in the CASSCF for the $2^1S$ state of MnH, a case which is predominately $4s^2 3d^1$ like. Here one sees that the dominant correlation terms are the GVB configurations (8a). For the $2^3S$ state of CrH which is derived from $4s^1 3d^1$ the dominant terms in the CASSCF are the GVB configurations (8b). For this reason configurations (8a) were used as reference configurations for TiH and MnH which are predominately $4s^2 3d^1$ like and configurations (8b) were used as reference configurations for CrH which is predominately $4s^1 3d^{1*}$ like. However, for VH and NiH and for the $4^3A$ state of FeH there is a strong admixture of $4s^2 3d^*$/ and $4s^1 3d^{1*}$ character, and more extensive reference lists were used as indicated in Sec. IV.

The CASSCF/CI calculations were carried out with BIGG-MOL32–SWEDEN37 using the NASA Ames CRAY 1S. The calculated $R_e$, $D_v$, and $\omega_e$ values were obtained via a Dunham analysis of the points near $R_e$. In those fits in general only three terms are used. Based on a comparison of three and four term fits for NiH we estimate that use of this small number of computed points leads to errors of $0.01\sigma$ for $R_e$, $50 \text{ cm}^{-1}$ for $\omega_e$, and $0.01 \text{ eV}$ for $D_v$.

### IV. Discussion

#### A. TiH

Table IV presents the CASSCF and CI energies for the $4^3\Phi$ state of TiH, while Table I gives the derived potential curve parameters. The reference configurations for the CI are configurations (8a). Note from Table I that the $3d$ population is 2.26 which is consistent with using a $4s^2 3d^2$ reference. No experimental information exists for TiH, however the calculated results are compared to the calculated results of Das (D)31 and Scott and Richards (SR).4–6 Here one sees that the present results show a shorter bond length and larger binding energy—a result consistent with the higher level of electron correlation included in the present calculation.

#### B. VH

Table V gives the CASSCF and CI energies for the $4^3\Delta$ state of VH obtained using Eq. (8a) as reference configurations. Because of the large amount of $4s^1 3d^*$ character in the CI wave function (see Table I and VIA) more extensive CI calculations were carried out.
TABLE V. Calculated energies for the \( ^4\Delta \) state of VH.

<table>
<thead>
<tr>
<th>( R, \sigma_0 )</th>
<th>CASSCF</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0</td>
<td>-943.40439</td>
<td>-943.42986</td>
</tr>
<tr>
<td>3.50</td>
<td>-943.46991</td>
<td>-943.51013</td>
</tr>
<tr>
<td>3.25</td>
<td>-943.45612</td>
<td>-943.51126</td>
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<tr>
<td>3.00</td>
<td>-943.45613</td>
<td>-943.50535</td>
</tr>
</tbody>
</table>

TABLE VI A. VH extended CI results.

<table>
<thead>
<tr>
<th>Case</th>
<th>Energy</th>
<th>( 3d ) population</th>
<th>% reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4A\sigma, 3 ) reference</td>
<td>-943.51516</td>
<td>3.36</td>
<td>92</td>
</tr>
<tr>
<td>( 4A\sigma, 5 ) reference</td>
<td>-943.51350</td>
<td>3.37</td>
<td>92</td>
</tr>
<tr>
<td>( 5A\sigma, 5 ) reference</td>
<td>-943.51535</td>
<td>3.39</td>
<td>93</td>
</tr>
<tr>
<td>( 5A\sigma, 8 ) reference</td>
<td>-943.51434</td>
<td>3.42</td>
<td>94</td>
</tr>
</tbody>
</table>

TABLE VI B. VH \( 5A\sigma, 8 \) reference CI energies.

<table>
<thead>
<tr>
<th>( R, \sigma_0 )</th>
<th>( E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.50</td>
<td>-943.51215</td>
</tr>
<tr>
<td>3.25</td>
<td>-943.51434</td>
</tr>
<tr>
<td>3.00</td>
<td>-943.51062</td>
</tr>
</tbody>
</table>

From Table VIA we see that the extended CI calculations lead to results rather similar to the calculations using only Eq. (8a) as a reference set. Calculations using a larger V basis set \( \{1s, 1p, 6d, 2f\} \) show a very similar population and this population is only slightly changed by natural orbital iterations. From this we conclude that the strong mixing of \( d^1 \) and \( d^1 \) observed in the current CASSCF/CI (SD) calculations is converged with respect to basis set and level of correlation.

Finally, Table VI B gives energies obtained at the \( 5A\sigma, 8 \) reference CI level. The potential curve parameters given in Table IX are derived from these energies. We note from Table I that the potential curve parameters obtained here are in good agreement with the calculations of Das\(^6\) and the earlier results of Walch\(^,10\)

TABLE VII. Calculated energies for the \( ^2\pi \) state of CrH.

<table>
<thead>
<tr>
<th>( R, \sigma_0 )</th>
<th>GVB</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0</td>
<td>-1043.83314</td>
<td>-1043.90002</td>
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<tr>
<td>3.50</td>
<td>-1043.88385</td>
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<tr>
<td>3.00</td>
<td>-1043.79699</td>
<td>-1043.95150</td>
</tr>
</tbody>
</table>

C. CrH

For CrH the ground \( ^5\Pi \) state is predominantly \( 4s^1 5p^6 \) like, with the CASSCF being based on Eq. (8b) (8b) \( 3\sigma, 1\pi \) active space. The CASSCF was followed by a SDCl using Eq. (8b) as references. We note that the CASSCF in this case has a smaller active space than for the other cases. The smaller active space here omits angular correlation effects; however, these effects are included at the Cl(SD) level and these calculations are consistent with those for the other hydrides. The calculated \( R_1 \) and \( \omega_1 \) are in reasonable agreement with experiment\(^9\), the bond length is too long by \(-0.04 \text{ Å} \) and \( \omega_1 \) is too small by 100 cm\(^{-1}\). The results of the present calculations (Table I and Table VIII) are in good agreement with the results of Das\(^6\) — a not unexpected result given that the MSCF model used by Das is the same as ours for this particular system, and one expects very little mixing of \( 4s^1 3d^1 \).

D. MnH

Table IX gives the calculated CASSCF and CI energies for MnH. The reference configurations for the CI

TABLE VII. Reference configurations for VH extended CI calculations.

<table>
<thead>
<tr>
<th>Reference</th>
<th>( 6\sigma )</th>
<th>( 7\sigma )</th>
<th>( 8\sigma )</th>
<th>( 9\sigma )</th>
<th>( 10\sigma )</th>
<th>( 1\sigma_{2p} )</th>
<th>( 3\sigma_1 )</th>
<th>( 4\sigma )</th>
<th>( 3\pi )</th>
<th>( 3\pi )</th>
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</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
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<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

J. Chem. Phys., Vol. 78, No. 7, 1 April 1983
are Eq. (8a) which is consistent with the 3d population of 5.06. From Table I one sees that the calculated \( R_0 \) is -0.04 Å longer than experiment while the calculated \( \omega_0 \) is 90 cm\(^{-1} \) larger than experiment. \(^{28}\) Comparing our results to Das', \(^ {11} \) we see that his \( R_0 \) is larger than ours by -0.07 Å (and in poorer agreement with experiment), and his \( \omega_0 \) is smaller than experiment by -110 cm\(^{-1} \). Given the longer \( R_0 \) and smaller \( \omega_0 \) in the calculations of Das it is puzzling to note that his \( D_0 \) is larger than ours. Note that in all other cases Das' binding energies are smaller. We suspect that overestimation of \( D_0 \) in this case is due to neglect of \( 4s^2 - 4p^2 \) near degeneracy which is more important for the \( 4s^2 3d^6 \) atomic asymptote than for the molecular region. Another puzzling point here is Das' comment that the HF configuration is not dominant for MnH, since we find that in the CASSCF the HF configuration is dominant for all \( R_0 \). (See Table III.)

E. FeH

Table X gives the calculated CASSCF and CI energies for the \( 5\alpha \) state of FeH. These calculations were carried out in the same way as the MnH calculations. For FeH more extended calculations were also carried out to examine the question of the separation of the \( 5\alpha \) and \( 4\alpha \) states of FeH. The \( 6\alpha \) state of FeH is dominated by

\[
6\sigma 7\sigma 9\sigma 10\sigma \leftarrow 5\pi^1 \leftarrow 3\pi^1 3\pi^1 ,
\]

while we find the \( 4\alpha \) state is a strong mixture of the quartet coupling of Eq. (9) and

\[
6\sigma 9\sigma 10\sigma \leftarrow 4\alpha^1 \leftarrow 3\pi^1 3\pi^1 ,
\]

which is best viewed as the \( 4\alpha \) configuration arising from \( 4s^2 3d^7 \). In the CASSCF calculations the \( 4\alpha \) state has the \( 7\pi \) and \( 9\pi \) orbitals mixed, i.e., \( 7\pi \approx 2\sigma - 3d\pi \) and \( 9\pi \approx 3\sigma - 3d\pi \). With these orbitals the \( 4\alpha \) state has five dominant configurations which are the reference configurations given in Table XI. The dominant configurations for the \( 5\alpha \) state on the other hand, also given in Table XI are more clearly defined consisting of Eq. (9) plus left-right and angular correlation of the bond pair.

Table XII gives the calculated energies for the \( 4\alpha \) and \( 5\alpha \) states of FeH using the reference configurations given in Table XI. Here we find the \( 4\alpha \) state is 0.09 eV below \( 5\alpha \) at the C1SD) plus Davidson's correction level of calculation, while the best experimental estimate\(^{19} \) places \( 4\alpha \approx 0.25 \) eV above \( 5\alpha \).

GVBF-1-2 calculations with the present basis set for Eqs. (9) and (10) at \( R = 20.0 \) give a separation of 1.34 eV as compared to the experimental \( 1F - 1D \) atomic separation of 0.88 eV. Since the \( 4\alpha \) state is a strong mixture of \( 4s^2 3p^4 \) and \( 4s^2 3d^7 \) derived terms, one might expect that further improvement in the \( 1F - 1D \) separation would depress \( 4\alpha \) with respect to \( 5\alpha \). However, the same CASSCF CI (SD) calculation with a larger [6s 5p 4d 1f] basis set,\(^ {29} \) which gives a \( 1F - 1D \) atomic separation of 2.11 eV, leads to the same separation of 0.08 eV with \( 5\alpha \) below \( 4\alpha \), and the 3d population remains the same as with the smaller basis set. This result is consistent with our studies\(^ {14} \) of NiH, where we found a correct mixing of \( 4s^2 3p^4 \) and \( 4s^2 3d^7 \) (as reflected in the bond shortening) at a level of calculation where the separation was still in error by -0.5 eV.

From Table XII one sees that there is a differential Davidson's correction for the \( 4\alpha - 5\alpha \) separation of FeH of 0.19 eV (based on \( 5\alpha \) at 3.25 \( \sigma_0 \) and \( 4\alpha \) at 3.00 \( \sigma_0 \)). This large differential Davidson's correction is consistent with the differential percentage reference in the CI (SD) wave functions (92% for \( 5\alpha \) and 95% for \( 4\alpha \)). Because of the size of the differential Davidson's correction we suspect that the ground state of FeH is \( 4\alpha \) (in agreement with experiment) and that the remaining error in our calculated separation is due to a need for
TABLE XII. Calculated energies for the \( ^3\Delta \) and \( ^1\Delta \) states of FeH.

<table>
<thead>
<tr>
<th>( R, a_0 )</th>
<th>( ^3\Delta ) CASSCF</th>
<th>( ^1\Delta ) CASSCF</th>
<th>( ^3\Delta ) CI</th>
<th>( ^1\Delta ) CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>20, 0</td>
<td>1263.96101</td>
<td>1263.96101</td>
<td>1263.05217*</td>
<td>1263.05217*</td>
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<tr>
<td>3.50</td>
<td>1262.99678</td>
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<td>2.75</td>
<td>1262.99550</td>
<td>1263.12109</td>
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<td>1263.12109</td>
</tr>
</tbody>
</table>

\*From Table X using the GVB reference configurations [Eq. (8a)].

Values in parenthesis indicate Davidson's correction.

Values in parenthesis indicate Davidson's correction.

From a GVB + 1 + 2 calculation for the \( ^1\Delta \) state of FeH.

TABLE XIII. Reference configurations for NiH CI calculations.

<table>
<thead>
<tr>
<th>( \sigma )</th>
<th>( \tau )</th>
<th>( \delta )</th>
<th>( \alpha )</th>
<th>( 1\sigma^2 )</th>
<th>( 1\delta )</th>
<th>( 2\sigma^2 )</th>
<th>( 3\sigma^2 )</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
</tbody>
</table>

TABLE XIV. Calculated energies for the \( ^2\Sigma \) state of NiH.

<table>
<thead>
<tr>
<th>( R, a_0 )</th>
<th>CASSCF</th>
<th>CASSCF</th>
<th>CASSCF</th>
<th>CASSCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.25</td>
<td>-1507.37739</td>
<td>-1507.37739</td>
<td>-1507.37739</td>
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<td>3.00</td>
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<td>-1507.37739</td>
<td>-1507.37739</td>
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<tr>
<td>2.75</td>
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<td>-1507.37739</td>
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<td>-1507.37739</td>
<td>-1507.37739</td>
<td>-1507.37739</td>
<td>-1507.37739</td>
</tr>
</tbody>
</table>

\*The asymptotic energy is \(-1507.37739\) from a GVB + 1 + 2 calculation based on a \( 4s^2 3d^6 \) like GVB solution.

Higher excitations in our CI wave function.

From Table I we see that the calculated \( R_e \) and \( \omega_f \) for the \( ^3\Delta \) state and the calculated \( R_e \) for the \( ^1\Delta \) state are in good agreement with experiment.\( ^{36,31} \) Comparing to other calculated results, Das\(^{31} \) studied only the \( ^3\Delta \) state and finds a longer \( R_e \), smaller \( \omega_f \), and smaller \( D_e \) than in the present calculations. Jaffe\(^{29} \) carried out an ECP CI study of the \( ^3\Delta \) and \( ^1\Delta \) states of FeH. His results show shorter bond lengths for both states (a result which is believed to be due to defects in the ECP); however, the other calculated parameters are in reasonable agreement with the present results.

F. NiH

For NiH the CASSCF calculations converged to a solution somewhat similar to the \( ^3\Sigma \) FeH calculations. The \( 3d \) population here is \(-8.5 \) for \( R = 2.75a_0 \). Attempts to obtain a solution which was dominated by \( 4s^2 3d^6 \) converged to the same result; even when started from \( 4s^2 3d^6 \) like GVB vectors. It was found that correlating the \( 3d \) orbital which stabilizes \( 4s^2 3d^6 \) with respect to \( 4s^2 3d^6 \) lead to stabilization of the \( 4s^2 3d^6 \) like solution. However, for consistency, calculations were carried out using the \( 4s^2 3d^6 \) like orbitals. The GVB–CI calculations were carried out and the natural orbitals were used in a CI using the reference configurations in Table XIII. This calculation leads to a \( 3d \) population of \(-8.7 \) indicating strong mixing between \( 4s^2 3d^6 \) and \( 4s^2 3d^6 \) at the CI level. Note that the results here confirm the conclusion reached in the earlier MCSCF-MC-Cl studies\(^{14} \) of NiH that MCSCF leads to incorrect mixing of \( 4s^2 3d^6 \) and \( 4s^2 3d^6 \), and that this defect is corrected at the CI level. Correlating the \( 3d \) orbitals leads to a \( 4s^2 3d^6 \) like solution as is the case for HF wave functions, while the present CASSCF calculations tend to bias the calculation toward \( 4s^2 3d^6 \).

From Table I we see that the calculated parameters for NiH (derived from the energies given in Table XIV) are in good agreement with experiment.\(^{25} \) Note that the \( D_e \) value is obtained by comparison to a GVB + 1 + 2 calculation for NiH at large \( R \) (\( 4s^2 3d^6 \) like solution). This is the most appropriate state to compare it to since the NiH wave function near \( R_e \) is mostly \( 4s^2 3d^6 \) like. Note also that the calculated \( R_e \) is slightly smaller than experiment, a result that reflects a bias in the present calculations toward \( 4s^2 3d^6 \) like orbitals. By contrast the MCSCF-MC-Cl calculations\(^{14} \) which converged to \( 4s^2 3d^6 \) like orbitals lead to an \( R_e \) somewhat longer than experiment, a result which reflects a corresponding bias toward \( 4s^2 3d^6 \) like orbitals.

The present calculations are in good agreement with the CASSCF–CI calculations of Blomberg et al.,\(^{15} \) in spite of the omission of \( 4f \) functions in the calculations of Ref. 15. This result is consistent with the small importance of \( 4f \) functions in ScH.\(^{13} \) By comparison the calculations of Das\(^{31} \) show an \( R_e \) significantly larger than experiment, which we view as indicative of the need for additional atomic correlation. Interestingly the calculations of GWU\(^{14} \) which are only two configuration MCSCF but incorporate atomic correlation in a semiempirical way are in good agreement with the present calculations.

V. CONCLUSIONS

The bonding in the TM hydrides is found to involve strong admixture of terms from the \( 4s^2 3d^6 \) and \( 4s^2 3d^6 \) states of the TM atoms. The bonding in the \( 4s^2 3d^6 \) state is found to arise by formation of \( sp \) hybrids.
and $s^7$ where $s^1$ is $4s - 4p$ like and $s^6$ is $4s - 4p$ like. The bond pair involves similar sharing of the $s^2$ and $H(1s)$ orbitals while the $s^5$ orbital is singly occupied and hybridized away from the bond pair. The bonding in the $4s^33d^2$ state involves formation of a $4s - H(1s)$ bond pair.

By considering of atomic coupling arguments and interaction of $4s^33d^2$ and $4s^33d^{1-2}$ derived terms, the ground states of the TM hydrides are predicted to be TiH (1f), VH (2f), CrH (3f), MnH (4f), FeH (5f), CoH (6f), and NiH (7f). All of these systems have been studied by a CASSCF CI (SD) procedure with the exception of CoH. In addition studies have been carried out for the $4s$ state of FeH.

We find strong mixing of $4s^33d^2$ and $4s^33d^{1-2}$ for VH and NiH where the $4s^33d^2$ and $4s^33d^{1-2}$ states are close in energy. TiH, MnH, and FeH (5f) are found to be predominantly $4s^33d^2$ like, while CrH is found to be predominantly $4s^33d^{1-2}$ like. These trends are consistent with the ordering of the atomic states.

The calculated $R^*$ and $D_0$ values derived from the CASSCF CI (SD) potential curves are in good agreement with the available experimental information (no information exists for TiH and VH). Inclusion of atomic correlation leads to significantly better agreement with experiment particularly for $R_0$. These improvements are related to a more balanced description of the atomic states in the correlated wave functions.

ACKNOWLEDGMENTS

We thank Bjorn Roos and Per Siegbahn for use of their programs. We thank Rich Jaffe for helpful discussions on FeH.

11. S. P. Walsh, unpublished results quoted in G. Das in Ref. 11.
28. This basis is a (13s12p7d6f) basis set. The primitive $s$ and $p$ basis sets differ from Wachters' in that the $4s$ and $4p$ functions are triple zeta whereas Wachters' basis is double zeta. The $4s$ functions were optimized for $3d^2$ while the $4p$ functions were optimized for $F_2(4d^2)$ and the resulting $4p$ functions were multiplied by 1.5 to make them more suitable for describing $4s - 4p$ correlation. The final exponents are $a_{4s} = 0.1294, 0.05287, 0.03758$ and $a_{4p} = 0.2454, 0.1249, 0.05307$. The $3d$ basis was contracted to four functions. The ${\eta}$ function is a $3 \ell$ term GTO fit to an STO with exponent 3.75.
30. S. Davis (private communication).
THEORETICAL EVIDENCE SUPPORTING THE $^4\Delta$ GROUND-STATE ASSIGNMENT FOR FeH

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The results of GVB/MRSD CI calculations for the $^6\Delta$ state of FeH$^-$ are combined with the results of previous CAS SCF/MRSD CI calculations for the $^4\Delta$ and $^2\Delta$ states of FeH to provide theoretical confirmation of the qualitative arguments used by Stevens, Feigerle, and Lineberger to assign the lowest state of FeH as $^4\Delta$. The calculated electron affinity of FeH and the calculated $R_e$ and $\omega_e$ for the $^4\Delta$ state of FeH$^-$ are in good agreement with experimental estimates.

Recently Stevens, Feigerle and Lineberger [1] (SFL) have reported photodetachment experiments for FeH$^-$ and MnH$^-$. For FeH$^-$ the lowest photodetachment transition exhibits a vibrational progression while a second transition which is 0.24 eV higher exhibits no vibrational progression. SFL interpret these experiments using a theoretical model in which FeH$^-$ has the configuration

$$b^2{s^2}3d^0 3d^3 3d\pi^2$$. (1)

where $b$ is a bond pair orbital and $s^2$ is an sp hybrid directed away from the bond pair [2]. Removing an electron from the above configuration leads to two low-lying FeH neutral states: (i) ionization of the $s^2$ electron leads to a $^4\Delta$ state with the configuration

$$b^2 3d^0 3d^3 3d\pi^2$$. (2)

and (ii) ionization of a $3d\pi$ electron leads to a $^6\Delta$ state with the configuration

$$b^2 s^1 3d^0 3d^3 3d\pi^2$$. (3)

SFL argue that (i) involves ionizing an antibonding orbital ($s^2$) and this involves a significant reduction in equilibrium bond length ($R_e$) while (ii) involves ionizing a non-bonding orbital ($3d\pi$) and should involve little change in $R_e$. Thus SFL assign the lower transition with a long vibrational progression to $^4\Delta$ and the upper vertical transition to $^6\Delta$.

The bond length and vibrational frequency ($\omega_e$) for the $^4\Delta$ state are known directly from experiment [3]. SFL were able to estimate $R_e$ and $\omega_e$ for the $^6\Delta$ state of FeH and the $^5\Delta$ state of FeH$^-$ by comparing computed and experimental spectra.

Previously Walch and Bauschlicher (WB) [2] carried out CAS SCF/CI SD calculations for the $^6\Delta$ and $^4\Delta$ states of FeH. In the present paper GVB CI SD calculations are reported for the $^5\Delta$ state of FeH$^-$. The calculated spectroscopic parameters are compared to experiment in table 1. Here one sees that photodetachment to the $^6\Delta$ state of FeH involves little change in $R_e$ ($<0.01$ Å) while photodetachment to the $^4\Delta$ state involves a large decrease in $R_e$ (0.12 Å). The calculated $R_e$ and $\omega_e$ for the $^6\Delta$ state of the neutral and for the $^5\Delta$ state of FeH$^-$ are in reasonable agreement with the values obtained by SFL. Also the calculated electron affinity (EA) is in good agreement with the value measured by SFL. Thus the present calculations in conjunction with the previous calculations by WB substantiate the assignments of SFL. However the qualitative features of the wavefunctions are different from the simple picture above in that the $^4\Delta$ state of FeH and the $^5\Delta$ state of FeH$^-$ show strong mixing of $3d^6$ and $3d^7$ (see table 1), whereas the analysis of SFL is based on pure $3d^7$ character for these states.

The basis set used for FeH$^-$ is Wachters' [14s9p5d] set [4] augmented with: (i) two diffuse 4s functions selected in an even-tempered fashion, (ii) Wachters'
Table 1
Calculated CAS SCF-CI results for FeH

<table>
<thead>
<tr>
<th>State</th>
<th>$R_e$ (Å)</th>
<th>$\omega_e$ (cm$^{-1}$)</th>
<th>$T_e$ (eV)</th>
<th>3d population</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeH $^6\Delta$</td>
<td>calc. [2]</td>
<td>1.72</td>
<td>1560</td>
<td>-0.08</td>
</tr>
<tr>
<td></td>
<td>exp. [1]</td>
<td>1.77 ± 0.05</td>
<td>1550</td>
<td>0.25</td>
</tr>
<tr>
<td>FeH $^{4}\Delta$</td>
<td>calc. [2]</td>
<td>1.60</td>
<td>1710</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>exp. [3]</td>
<td>1.63</td>
<td>1680</td>
<td>0.00</td>
</tr>
<tr>
<td>FeH$^-$ $^4\Delta$</td>
<td>calc. a)</td>
<td>1.72</td>
<td>1282</td>
<td>-0.78</td>
</tr>
<tr>
<td></td>
<td>exp. [1]</td>
<td>1.79 ± 0.03</td>
<td>1300 ± 140</td>
<td>-0.93</td>
</tr>
</tbody>
</table>

a) Present work. The calculated spectroscopic constants are obtained via a Dunham analysis of the CI plus Davidson's correction energies at 3.00, 3.25, and 3.50 $\mu_0$. The CI energies at 3.25 $\mu_0$ are $-1263.12366 \pm 1263.14914$ where the value in parentheses includes Davidson's correction.

Table 2
Calculation of electron affinity for Fe

<table>
<thead>
<tr>
<th>Basis set</th>
<th>Method</th>
<th>Electron affinity a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[7s5p3d1f]</td>
<td>CV CI</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>MRSD</td>
<td>0.65 (0.78) b)</td>
</tr>
<tr>
<td>[7s5p4d2f]</td>
<td>CV CI</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>exp. c)</td>
<td>1.00</td>
</tr>
</tbody>
</table>

a) $4s^2 3d^7/4s^1 3d^8$.

b) Value in parentheses includes Davidson's correction.

c) Extrapolated based on the error for CV CI for Cu and Ni.

Two 4p functions and one even-tempered 4p diffuse function, (iii) the diffuse 3d function of Hay [5], and (iv) a single set of 4f functions ($\alpha_{4f} = 2.0$). The resulting basis was contracted using the general contraction feature of BIGGMOLI [6]: (16s12p6d1f)/[7s5p3d1f]. The H basis set was the (8s4p)/[5s3p] basis used in ref. [2]. The calculations were carried out using BIGGMOLI—SWEDEN 4.

Before considering FeH$^-$, we first consider the calculated EA for the Fe atom as a function of basis set and level of electron correlation (table 2). Two different types of CI calculations were carried out. The MRSD CI has as reference configurations the SCF configuration for the $4s^1 3d^7$ state of Fe and the SCF plus three components of the $4s^2 \rightarrow 4p^2$ near degeneracy for the $4s^2 3d^7$ configuration of Fe$^-$. All single and double excitations from the above configurations are included in the CI. The core—valence CI (CV CI) [7] has the same set of reference configurations but allows only a single electron outside the 3d$^7$ configuration. The qualitative idea is that the major differential correlation between the $4s^2 3d^7$ and $4s^1 3d^7$ states includes the valence correlation effects due to the 4s electrons and the core—valence correlation effects between the 4s and 3d electrons. The intrapair 3d correlation, on the other hand, remains relatively constant between the two states since they have the same number of 3d electrons. This expectation is substantiated by the results in table 2 where one sees that the CV CI result is in reasonable agreement with the MRSD + Davidson's correction [8] result. The [7s5p3d1f] basis set is the same basis set used for FeH$^-$, while the [7s5p4d2f] basis uses a more flexible [4d] contraction and replaces the single set of 4f functions by a $(3/2)$ 4f basis based on a three-term fit [9] to a Slater 4f with exponent 2.25. This exponent was optimized for the $4s^1 3d^7$ state of the Fe atom at the CV CI level. From table 2 one sees that at the CV CI level the smaller basis set is within 0.04 eV of the larger basis set result for the EA.

No experimental value exists for the EA of Fe atom. The EA reported by Hoton and Lineberger [10], 0.25 eV, is based on SCF calculations plus an estimate of correlation effects. A more reliable estimate may be obtained by noting that CV CI with large basis sets (equivalent to the larger basis set used here) underestimates the EA of Cu [11] and Ni [12] by 0.23 and 0.24 eV, respectively. Assuming the same error for the EA of Fe leads to 1.00 eV with respect

1 SWEDEN is a vectorized SCF MC SCF direct CI written by P.E.M. Siegbahn, B. Roos and C.W. Bauschlicher Jr.
to $4s^1 3d^7$ or 0.12 eV with respect to $4s^2 3d^6$. For the H atom the basis set used here leads to an error of $\approx 0.02$ eV in the EA.

The calculations for FeH$^-$ used a GVB wavefunction to define the orbitals. This calculation was followed by multireference singles and doubles CI (MRSD CI). Given the size of the CI calculations the use of GVB orbitals for FeH$^-$ as compared to CAS SCF orbitals for FeH [2] is expected to be of little importance. In the GVB MRSD CI calculations the Ar cores of the transition metal atoms are kept doubly occupied in all configurations; the active space consists of the orbitals derived from the transition metal 4s, 4po, and 3d orbitals and the H(1s) orbital, i.e. 6o–9o, 3π, and 18. In the above the 9o, 3π, and 18 orbitals are transition metal 3d like, 6o is the bond pair, 7o is the $s^2$ orbital, and 8o introduces left–right correlation of the bond pair. Table 3 gives the reference configurations which were used in the MRSD CI for the $5\Delta$ state of FeH$^-$.

The GVB wavefunction [13] includes the first two configurations in table 3. The first configuration for FeH$^-$ is the SCF configuration which corresponds to eq. (1), while the second configuration introduces left–right correlation of the bond pair. The remaining two configurations correspond to $3d^6$ components of the wavefunction which are found to be sufficiently important that they are included as reference configurations in the MRSD CI.

The molecular constants given in table 1 were obtained via a Dunham analysis of the CI SD plus Davidson's correction energies. As noted in ref. [2] since only three computed points are used in the Dunham analysis, there may be small uncertainties introduced in the derived spectroscopic parameters. These errors are estimated to be $<0.01$ Å for $R_e$ and 50 cm$^{-1}$ for $\omega_e$.

The computed FeH EA is 0.43 eV. These systems have large Davidson's corrections: 0.69, 0.35, and 0.16 eV for FeH$^-$ $5\Delta$, FeH $4\Delta$, and FeH $6\Delta$, respectively. These large Davidson's corrections correlate with the reference in the CI wavefunctions: 88, 92, and 95% for $5\Delta$, $4\Delta$, and $6\Delta$, respectively. Including the differential Davidson's correction leads to 0.78 eV as our best estimate of the EA of FeH. This value is 0.15 eV smaller than experiment. This result is somewhat better than might be expected based on the calculated Fe atom EA, but is consistent with the population analysis which indicates a large amount of H$^-$ character. Thus the error in the FeH EA may be intermediate between the errors for the EAs of the Fe and H atoms.

We conclude that the present calculations in conjunction with the previous results of WB substantiate SFL's assignment of $4\Delta$ as the lowest state of FeH with 6Δ 0.25 eV higher. (Calculations [2] still show the $6\Delta$ state 0.08 eV below $4\Delta$, i.e. an error of 0.33 eV in the $4\Delta$–$6\Delta$ separation.) The key feature here is that photodetachment from the $5\Delta$ state of FeH$^-$ to give the $6\Delta$ state of FeH is calculated to lead to little change in $R_e$ (<0.01 Å) while photodetachment...
to the $^4\Delta$ state of FeH leads to a large decrease in $R_e$ (0.12 Å). Thus the calculations are in agreement with observation of a vibrational progression for photodetachment to $^4\Delta$ but no vibrational progression for photodetachment to $^6\Delta$ as predicted by SFL based on a simple theoretical model. However the qualitative description of the system is more complex than the simple model adopted by SFL in that the $^4\Delta$ state of FeH and the $^5\Delta$ state of FeH$^-$ show strong mixing of 3d⁶ and 3d⁷ character whereas the analysis of SFL is based on pure 3d⁷ character for these states.

The calculated $R_e$ and $\omega_e$ values for the $^4\Delta$ state of FeH are in good agreement with the values measured by Davis [3] while the calculated $R_e$ and $\omega_e$ values for the $^6\Delta$ state of FeH and the $^5\Delta$ state of FeH$^-$ are in reasonable agreement with the values obtained by SFL from comparison of calculated and experimental spectra. Finally the calculated EA of FeH$^-$ is in reasonable agreement with the value reported by SFL.

References

CAS SCF CI CALCULATIONS FOR THE $3\Sigma_g^{-}, 1\Sigma_g^{+}, 3\Sigma_u^{+}$, AND $5\Delta_u$ STATES OF Sc$_2$

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CAS SCF CI(SD) calculations have been carried out for the $3\Sigma_g^{-}, 1\Sigma_g^{+}, 3\Sigma_u^{+}$, and $5\Delta_u$ states of Sc$_2$ using large gaussian basis sets. The $3\Sigma_g^{-}, 1\Sigma_g^{+}$, and $3\Sigma_u^{+}$ states arise from the $2D(4s^2 3d^1) + 2D(4s^2 3d^1)$ limit of Sc$_2$ and are found to be only weakly bound ($D_e = 0.06$ eV and $R_e = 8.0a_0$). The $5\Delta_u$ state arises from the $2D(4s^2 3d^1) + 4F(4s^1 3d^1 4p^1)$ atomic limit. This state is found to be strongly bound relative to its limits ($D_e = 0.8$ eV and $R_e = 7.0a_0$).

1. Introduction

Recently the Sc$_2$ molecule has been the subject of considerable theoretical study [1,2]. The interest in this system arises because of the relevance of metal-metal bonds to problems in materials science and because theoretical studies find only weakly bound states (at least out of the lowest $2D(4s^2 3d^1) + 2D(4s^2 3d^1)$ atomic limit) for Sc$_2$ in contrast to mass spectrometric experiments [3] which had been interpreted to indicate strong bonding.

Das [1] has carried out an MC SCF study of the singlet and triplet states arising out of the $2D(4s^2 3d^1) + 2D(4s^2 3d^1)$ and the $2D(4s^2 3d^1) + 4F(4s^1 3d^2)$ asymptotes of Sc$_2$ using a Slater basis set in conjunction with a pseudopotential. For the $1\Sigma_g^{+}$ state of Sc$_2$ Das finds a $D_e$ of $\approx 4$ kcal mole and an $R_e$ of $\approx 9.5a_0$ which he attributes to van der Waals terms arising primarily out of the $4s^2 \rightarrow 4p^2$ near-degeneracy effect for the $2D(4s^2 3d^1)$ state of Sc. However, as Das points out, by making choices for $R_e$ and the degeneracy factors consistent with the calculations, the mass spectrometric experiments are consistent with a binding energy in the range of 3–5 kcal mole. Das also considered the possibility of bound states arising from the $2D + 4F$ limit but found no significant binding at least for singlet and triplet states (quintet states also arise from this limit but were not considered).

Wood, Doran, Hillier and Guest (WDHG) [2] also carried out MC SCF CI calculations using a small gaussian basis set. They concluded that the lowest state was $5\Sigma_u^{+}$ arising from the $2D + 4F$ asymptote. Their calculations showed a binding energy of 1.12 eV with respect to $2D + 4F$ and 0.55 eV with respect to $2D + 2D$. However, due to basis set deficiencies they find a $4F - 2D$ atomic separation of 0.5 eV compared to an experimental separation of 1.43 eV. Correcting for the error in the asymptotic separation the $5\Sigma_u^{+}$ state is unbound by 0.31 eV with respect to $2D + 2D$ and it does not appear that $5\Sigma_u^{+}$ is the ground state of Sc$_2$ as suggested by WDHG.

The present calculations were undertaken to determine (i) the nature of the bonding and the magnitude of the binding energy for states arising out of the $2D(4s^2 3d^1) + 2D(4s^2 3d^1)$ asymptote and (ii) the nature of the bonding arising out of the $2D(4s^2 3d^1) + 4F(4s^1 3d^2$ or $4s^1 4p^1 3d^1)$ atomic limit. The calculations reported here are more extensive than those of Das or WDHG and involve extensive MC SCF or CAS SCF followed by CI(SD) using large gaussian basis sets. In agreement with Das we find that the states arising out of the $2D + 2D$ limit are weakly bound, however we use the interacting correlated fragments (ICF) method [4] to more accurately determine the binding energy. We have also investigated a $5\Delta_u$ state arising out of the $2D(4s^2 3d^1) + 4F(4s^1 4p^1 3d^1)$ atomic limit. Here we find a binding energy relative to the limits above of $\approx 0.8$ eV at an $R_e$ of $\approx 7.0a_0$. We also estimate a binding energy relative to the corresponding limit of $\approx 0.5$ eV for
2. Calculational details

The Sc basis set starts with the Wachters' (14s9p5d) primitive set [6] augmented with Wachters' two additional 4p functions, the diffuse d function of Hay [7], and a set of f polarization functions ($\alpha = 1.4$). Two different contracted basis sets were constructed from this primitive set. Basis set I was contracted in a segmented fashion for use with MOLECULE [8]. The contraction scheme used here was contraction 3 of Table VI of ref. [6]. This contraction was used for the $s$ and $p$ functions, while the $d$ functions were contracted (3111). In this basis set the $f$ functions were omitted and the 4p functions were scaled by (1.5)$^{1/2}$. Basis set I was used for the CAS SCF calculations.

Table 1
Reference configurations for the CI(SD) calculation

<table>
<thead>
<tr>
<th>State</th>
<th>Configuration</th>
<th>4s 3do 4po u</th>
<th>4s 3do 4po g</th>
<th>3d(\pi_x) g</th>
<th>3d(\pi_y) u</th>
<th>3d(\delta_{xy}) u</th>
<th>3d(\delta_{x^2-\gamma^2}) u</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^3\Delta_u)</td>
<td>2 1 1 1</td>
<td>2 1 0 0</td>
<td>0 0 0 0</td>
<td>1 0</td>
<td>0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^1\Sigma_u^+)</td>
<td>2 1 0 0</td>
<td>2 1 1 0</td>
<td>0 0 0 0</td>
<td>1 0</td>
<td>0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^1\Sigma_u^-)</td>
<td>2 0 0 0</td>
<td>2 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0</td>
<td>0 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The final basis is (14s11p6d)$^7$[8s6p4d]. Basis set II was generally contracted for use with BIGGMOI [9], resulting in a (14s11p6d1f)$^7$[6s6p3d1f] contracted set. Here the 4p functions were left unscaled. This larger basis set was used in the ICF calculations.

The CAS SCF CI calculations were carried out with MOLECULE [8]—SWEDEN [10] using the NASA Ames CRAY 1S. The ICF calculations were carried out with BIGGMOI [9]—noname [11] using the NASA Ames CDC 7600.

In the calculations the 18-electron Ar cores were kept doubly occupied in all configurations. In the CAS SCF calculations these orbitals were optimized at the CAS SCF level, while in the calculations using noname the core orbitals were obtained from a HF calculation on the \(^3\Sigma_u^\pi\) state of Sc$_2$.

3. Discussion

The low-lying states of the Sc atom are the \(^2\Sigma_u^\pi (4s^23d^1)\) state which is the ground state, the \(^4\Sigma (4s^14p^13d^1)\) state which is at 1.43 eV, and the \(^4\Pi (4s^14p^13d^1)\) state which is at 1.96 eV [12] (the...
energy levels are averaged over the \( m_f \) values). As indicated earlier the present calculations concentrate on states arising out of the \( ^2D + ^2D \) and \( ^2D + ^4F \) limits. In these calculations we include the \( 4s, 4p, \) and \( 3d \) electrons in the valence space, thus the \( 4s^2 \rightarrow 4p^2 \) near degeneracy [13] which is important for the \( ^2D \) state is included at the MC SCF level. Correlation of the \( 3d \) orbitals on the other hand is treated at the CI level.

Table 1 shows the dominant configurations for the \( ^3\Sigma_g^-, \ ^1\Sigma_u^+, \ ^3\Sigma_u^+, \ ^5\Delta_u \) states which were considered here. The reference configurations in table 1 are the dominant configurations at all \( R \) as derived from small CI calculations. These configurations may also be understood by considering the degeneracies which occur at large \( R \) (due to the degeneracy of the corresponding \( g \) and \( u \) orbitals at large \( R \)). The \( ^3\Sigma_g^- \) state requires only one reference configuration, the \( ^1\Sigma_u^+ \) and \( ^3\Sigma_u^+ \) states require two reference configurations, and the \( ^5\Delta_u \) state requires eight configurations to dissociate to \( ^2D(4s^23d^1) + ^4F(4s^23d^1) + ^4F(4s^23d^1) + ^4F(4s^23d^1) \). The remaining two \( ^5\Delta_u \) configurations describe the \( ^5\Delta_u \) state arising from \( ^2D(4s^23d^1) + ^4F(4s^23d^1) \). In order to keep the CAS SCF calculations of reasonable size, restrictions were placed on the orbital occupancies as indicated in table 2. These restrictions arise by noting the number of \( \sigma \) and \( \pi \) electrons associated with each state and allowing up to double excitations from the \( \sigma \) and \( \pi \) blocks to the \( \pi \) block. These excitations correspond to \( 4s^2 \rightarrow 4p^2 \) atomic excitations. Note that for the \( ^5\Delta_u \) state an additional restriction that the \( \sigma \) plus \( \pi \) block contain five electrons could have been imposed. The CAS SCF calculations in each case were followed by CI(SD) calculations from the reference configurations in table 1.

The calculated energies for the CAS SCF CI(SD) calculations are given in table 3, while fig. 1 shows the calculated potential curves [CAS SCF CI(SD) calculations] for the \( ^3\Sigma_g^-, ^1\Sigma_u^+, ^3\Sigma_u^+ \), and \( ^5\Delta_u \) state. Qualitatively the \( ^1\Sigma_u^+ \) and \( ^3\Sigma_u^+ \) states arise from \( ^2D(4s^23d^1) + ^2D(4s^23d^1) \) with singlet and triplet pairing of the \( 3d \) orbitals, while the \( ^3\Sigma_g^- \) state arises from \( ^2D(4s^23d^1) + ^2D(4s^23d^1) \) and the \( ^5\Delta_u \) state arises out of \( ^2D(4s^23d^1) + ^4F(4s^24p^13d^1) \).

Concentrating first on the states which arise out of the \( ^2D + ^2D \) limit, the basic feature of the calculated curves is very weak binding at large \( R \) (\( \approx 8.0 \ a_0 \)) and repulsive behavior at smaller \( R \). The weak binding at large \( R \) appears to arise from the \( 4s^2 \rightarrow 4p^2 \) near degeneracy, i.e. \( 4s\rightarrow 4p_x \times 4s \rightarrow 4p_y \). The binding energy at the CI level for \( R = 8.0 \ a_0 \) is \( \approx 0.045 \ eV \) for the \( ^3\Sigma_u^+ \) state, \( \approx 0.045 \ eV \) for the \( ^3\Sigma_u^+ \) state, and \( \approx 0.029 \ eV \) for the \( ^3\Sigma_g^- \) state. Note that the CAS SCF curves are repulsive at all \( R \). Note also that in the van der Waals region (i.e. \( \approx 8.0 \ a_0 \)) the states arising from the various occupancies of the \( 3d \) electrons are very close in energy. However, at small \( R \) the \( 3d \) orbital occupancies do split the curves significantly. At small \( R \) one sees that \( ^3\Sigma_g^- \) is significantly below \( ^3\Sigma_u^+ \) indicating some \( 3d \rightarrow 3d \) bonding character. However it appears that the repulsion between the \( 4s^2 \) pairs becomes large before sufficient \( 3d \rightarrow 3d \) overlap is obtained to stabilize this state. Given that we are in the small overlap region it appeared likely that a one-electron bond which varies with distance like \( S \) would be more favorable than a two-electron bond which varies with distance like \( S^2 \). The \( ^3\Sigma_g^- \) state may be thought of as having two one-electron \( \pi \) bonds and indeed at small \( R \) this state drops below \( ^1\Sigma_u^+ \) although \( ^1\Sigma_u^+ \) and \( ^3\Sigma_u^+ \) are nearly degenerate at \( R \) values near the van der Waals minimum.

Looking now at the \( ^5\Delta_u \) state, the bonding here arises basically out of the \( 4s^2 + 4s^1 \) interaction. Based on our studies of the transition metal hydrides [14] we expect this to be an attractive interaction. The reason for this attractive interaction is the presence of the low-lying \( 4s^14p^13d^n \) states of the transition metal atom (e.g. in Sc \( 4s^14p^13d^1 \) is at 1.96 eV). Interaction of \( 4s^23d^n \) and \( 4s^13d^n4p^1 \) leads to the formation of sp hybrids one of which has the character \( s + z^2 \) denoted by \( sz \) and the other of which has the character \( s - z \).
Table 3
Calculated CAS CI (SD) energies for various states of Sc₂ a)

<table>
<thead>
<tr>
<th>State</th>
<th>( R = 6.0 )</th>
<th>( R = 6.5 )</th>
<th>( R = 7.0 )</th>
<th>( R = 7.5 )</th>
<th>( R = 8.0 )</th>
<th>( R = 100.0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 2^3\Delta_u )</td>
<td>CAS b)</td>
<td>-0.36792</td>
<td>-0.37342</td>
<td>-0.37616</td>
<td>-0.36977</td>
<td>-0.36927</td>
</tr>
<tr>
<td>CI</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>( 5\Delta_u )</td>
<td>CAS</td>
<td>-0.43128</td>
<td>-0.43829</td>
<td>-0.43943</td>
<td>-0.43727</td>
<td>-0.43346</td>
</tr>
<tr>
<td>CI</td>
<td>-0.44667</td>
<td>-0.45304</td>
<td>-0.45344</td>
<td>-0.45071</td>
<td>-0.44652</td>
<td>-0.42288</td>
</tr>
<tr>
<td>( 3\Sigma_u^+ )</td>
<td>CAS</td>
<td>-0.4423</td>
<td>-0.46732</td>
<td>-0.46754</td>
<td>-0.48270</td>
<td>-0.48575</td>
</tr>
<tr>
<td>CI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( 1\Sigma_g^+ )</td>
<td>CAS c)</td>
<td>-0.47578</td>
<td>-0.48488</td>
<td>-0.48632</td>
<td>-0.48632</td>
<td>-0.48463</td>
</tr>
<tr>
<td>CI</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>( 3\Sigma_g^- )</td>
<td>CAS</td>
<td>-0.46023</td>
<td>-0.47010</td>
<td>-0.47346</td>
<td>-0.47346</td>
<td>-0.47595</td>
</tr>
<tr>
<td>CI</td>
<td>-0.47934</td>
<td>-0.48514</td>
<td>-0.48594</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) In Hartree relative to \(-1519.0\).
b) Higher root from the \( 5\Delta_u \) CAS calculation.
c) \( 3\Sigma_g^+ \) vectors were used for the CI.

Fig. 1. Potential energy curves for the low-lying states of Sc₂ from CAS SCF CI (SD) calculations. The locations of the \( 2D + 2D \) and \( 2D + 4F(4s^1\,4p^1\,3d^1) \) asymptotes are indicated.

denoted by \( \tilde{z} \). This leads in the case of the transition metal hydride to an \( \tilde{z} - H(1s) \) bond and a singly occupied \( \tilde{z} \) orbital, and in the case of the transition metal dimers to states which may be represented by the following structures:

In the case of the \( 5\Delta_u \) state the remaining electrons are in 3d₀, 4p₀, 3d₀ \( x^2-y^2 \) orbitals which are orthogonal to the bond orbitals and therefore the high spin (i.e. quintet state) is favored.

From fig. 1 one sees that the \( 5\Delta_u \) state is bound by \( \approx 0.8 \text{ eV} \) with respect to \( 2D(4s^2\,3d^1) + 4F(4s^1\,4p^1\,3d^1) \). The atomic asymptote here is calculated to be at 1.68 eV (1.96 eV experimental). Note that experimentally the \( 4F(4s^1\,3d^2) \) state is below the \( 4F(4s^1\,4p^1\,3d^1) \) state, while in the calculations the \( 4F(4s^1\,4p^1\,3d^1) \) state is lower at both the CAS SCF and CI levels. This results from the larger 3d correlation \( [15] \) in the \( 4F(4s^1\,3d^2) \) state. Since 3d correlation is not included in the CAS SCF calculations the \( 4F(4s^1\,4p^1\,3d^1) \) state is lower at the CAS SCF level and the resulting orbital bias makes this state also at the CI level. This problem makes it difficult to study the corresponding \( 4s^1\,3d^2 \) derived state. However, this state is observed as a higher root in the CAS SCF (\( 2^5\Delta_g \) state in table 3) and using these CI energies the binding energy is predicted to be \( \leq 0.3 \text{ eV} \) smaller for the \( 5\Delta_g \) state derived from \( 2D + 4F(4s^1\,3d^2) \) than for the \( 5\Delta_g \) state derived from \( 2D + 4F(4s^1\,4p^1\,3d^1) \). Thus we predict a \( D_e \) of \( \geq 0.5 \text{ eV} \) for the \( 5\Delta_g \) state derived from \( 2D + 4F(4s^1\,3d^2) \).

Assuming this and noting that the \( 4s^1\,3d^{n+1} - 4s^2\,3d^n \) separations for Ti and V are 0.81 and 0.25 eV, resi
pectively [12], we predict that the mixed state will be unbound by $\leq 0.3$ eV with respect to the $4s^23d^9 + 4s^23d^8$ limit for $T_1$ and bound by $\geq 0.25$ eV for the same limit in $V_2$. Indeed the lowest state in $V_2$ is found to arise from this atomic limit [5]. At the other end of the row the mixed states are expected to be important for Fe and Co.

Comparing to WDHG, their calculations show a deeper well and shorter $R_e$ for the $2^3\Sigma_u^+$ state ($R_e = 4.86\ a_0$ and $D_e = 1.12$ eV) than do our calculations for the $2^3\Delta_u$ state ($R_e \approx 7.0\ a_0$ and $D_e \approx 0.8$ eV). We have also studied states of $2^3\Sigma_u^+$ symmetry at the MC SCF POL CI level [16] and find two states, one of which is derived from $4F(4s^24p^13d^1) + 4F(4s^24p^13d^1)$, and the other of which is derived from $2^2D(4s^23d^9) + 2^2D(4s^23d^9)$. Both states are bound by $\approx 0.8$ eV with the first state having an $R_e$ of $\approx 6.5\ a_0$ and the second state having an $R_e$ of $\approx 7.0\ a_0$. It is not clear why the results of WDHG are so different from ours. We do note however that their total energies for Sc2 are more than 3.0 hartree more positive than ours and suspect that some of the difference may arise from basis set deficiencies in the calculations of WDHG (e.g. basis set superposition error).

Now we consider the calculation of the binding energy of the states arising out of the $2^2D(4s^23d^9) + 2^2D(4s^23d^9)$ limit. The calculations consisted of MC SCF followed by POL CI [4] calculations. The ICF method has been shown to lead to reliable binding energies for weakly bound systems, e.g. Be$_2$ [4]. Since the minimum in the van der Waals binding curve for Sc2 occurs at $R > 8.0\ a_0$ and the 3d interactions are small at this distance, we arbitrarily studied the $2^3\Sigma_u^+$ and $1^3\Sigma_u^+$ states which arise from $4s^23d^9 + 4s^23d^8$ (see table 4).

In these calculations the orbitals were obtained from MC SCF calculations with the $4s$, $4p$ and $3d$ in the valence space. The MC SCF configurations consisted of all single and double excitations within the valence space from the reference configurations in table 1 (one for $2^3\Sigma_u^+$ and two for $1^3\Sigma_u^+$). These MC SCF calculations were then followed by CI. The POL CI calculations include single and double excitations from the reference configurations but with no more than one electron outside the valence space. To approximate the ICF method the orbitals were localized using the transformation $\phi_e = 2^{-1/2}\phi_6 + 2^{-1/2}\phi_u$. The $\phi_e = 2^{-1/2}\phi_6 - 2^{-1/2}\phi_u$.

And in addition to the POL CI list configurations of the form $\phi_e \to \nu \times \phi_e \to \nu ,$

which allows two electrons into the virtuals were also included. (Note that this calculation was carried out for the $2^3\Sigma_u^+$ state since for this state the energy is invariant to the transformation given above.) From table 5 we see that the ICF method gives a binding energy of 0.046 eV (1.1 kcal/mole) while the POL CI method leads to 0.041 eV (for the $[6s6p3d1f]$ basis set). Combining this result with the POL CI estimate of the separation between $2^3\Sigma_u^+$ and $1^3\Sigma_u^+$ leads to an estimated binding energy of 0.061 eV (1.4 kcal/mole) for the $2^3\Sigma_u^+$ or $1^3\Sigma_u^+$ state of Sc2.

Das using an MC SCF model obtains a $D_e$ of $\approx 4$ kcal/mole, whereas we obtain no binding at the table.

Table 4
Calculated MC SCF POL CI energies for the $2^3\Sigma_u^+$ and $1^3\Sigma_u^+$ states of Sc2

<table>
<thead>
<tr>
<th>$R$</th>
<th>MC SCF</th>
<th>POL CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^3\Sigma_u^+$</td>
<td>$^1\Sigma_u^+$</td>
</tr>
<tr>
<td>20.0</td>
<td>-0.50699</td>
<td>-0.50699</td>
</tr>
<tr>
<td>10.0</td>
<td>-0.50679</td>
<td>-0.50679</td>
</tr>
<tr>
<td>9.0</td>
<td>-0.50614</td>
<td>-0.50614</td>
</tr>
<tr>
<td>8.0</td>
<td>-0.50390</td>
<td>-0.50390</td>
</tr>
<tr>
<td>7.5</td>
<td>-0.50287</td>
<td>-0.50287</td>
</tr>
<tr>
<td>7.0</td>
<td>-0.49815</td>
<td>-0.49815</td>
</tr>
<tr>
<td>6.0</td>
<td>-0.48773</td>
<td>-0.48773</td>
</tr>
</tbody>
</table>

$^a$) In hartree relative to $-1519.0$.

Table 5
Calculated MC SCF POL CI energies for the $2^3\Sigma_u^+$ state of Sc2

<table>
<thead>
<tr>
<th>$R$</th>
<th>MC SCF</th>
<th>POL CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[6s6p3d]</td>
<td>[6s6p3d]</td>
</tr>
<tr>
<td></td>
<td>[6s6p3d1f]</td>
<td>[6s6p3d1f]</td>
</tr>
<tr>
<td>20.0</td>
<td>-0.50833</td>
<td>-0.50947</td>
</tr>
<tr>
<td></td>
<td>0.000 eV</td>
<td>0.000</td>
</tr>
<tr>
<td>8.0</td>
<td>-0.50934</td>
<td>-0.51099</td>
</tr>
<tr>
<td></td>
<td>-0.027</td>
<td>-0.041</td>
</tr>
</tbody>
</table>

$^a$) In hartree relative to $-1519.0$. 
CAS SCF level. Das' MC SCF differs from ours in that he includes only the dispersion terms $4s \rightarrow 4p \times 4s \rightarrow 4p$, while we include all valence configurations among the $4s$, $4p$, and $3d$ orbitals. Including these additional terms tends to decrease the importance of the dispersion terms and we see a repulsive curve at the CAS SCF level but obtain a $D_e$ of 1.4 kcal/mole at the ICF level. We suspect that Das' MC SCF potential curve is too attractive, although his conclusion that the experimental results may be reinterpreted in terms of a weak bonding model remains valid.

4. Conclusions

We have studied the $3\Sigma^+_g$, $1\Sigma^+_g$, $3\Pi_u$, and $5\Delta_u$ states of $Sc_2$ using CAS SCF CI(5D) wavefunctions in a large gaussian basis set. We find that the states arising out of the $2D(4s^23d^1) + 2D(4s^23d^1) + 2D(4s^23d^1)$ limit show only weak bonding ($\approx 0.06$ eV at $R \approx 8.0 a_0$). At this distance $3d$ electrons are only weakly coupled and the bonding appears to be largely of the van der Waals type arising out of the $4s^2 \rightarrow 4p^2$ near degeneracy.

The $5\Delta_u$ state which arises out of the $2D(4s^23d^1) + 4F(4s^14p^13d^1)$ limit is found to be strongly bound with respect to $2D + 4F(4s^14p^13d^1)$ ($\approx 0.8$ eV at $R \approx 7.0 a_0$). The bonding in this state is a result of interaction between the $4s$ orbital of the $4s^13d^14p^1$ configuration and sphybrids arising out of the $4s^23d^1$ and $4s^13d^14p^1$ states. States arising out of $2D(4s^23d^1) + 4F(4s^13d^2)$ are predicted to be bound by $\leq 0.3$ eV less with respect to $2D + 4F(4s^13d^2)$. While this atomic asymptote is too high ($1.43$ eV) in $Sc_2$ for this state to drop below the $2D(4s^23d^1) + 2D(4s^23d^1)$ asymptote, the corresponding asymptote is at $0.25$ eV leading to states from this mixed asymptote being the lowest state. WDHG report a significantly shorter $R_e$ ($4.86 a_0$) and somewhat deeper $D_e$ ($1.12$ eV) for a $3\Sigma^+_u$ state. However, our calculations indicate similar results for $3\Sigma^+_u$ and $5\Delta_u$. We suspect that the differences between our results and those of WDHG are at least partly due to basis set deficiencies in the calculations of WDHG.

We have also studied the binding energy of the $3\Sigma^+_u$ state using the ICF method. This leads to the estimate of $D_e = 0.046$ eV for $3\Sigma^+_g$ and $0.061$ eV for $1\Sigma^+_g$ or $3\Sigma^+_g$. This result is in agreement with the weak bonding model proposed by Das.

Acknowledgement

We thank Björn Roos for helpful discussions and thank Björn Roos and Per Siegbahn for use of their programs.

References

Theoretical evidence for multiple one-electron 3d bonding in a first row transition metal dimer: The \( ^3\Sigma_u^- \) state of Sc\(_2\)

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Recently, the Sc\(_2\) molecule has been the subject of considerable theoretical study.\(^1\) The interest in this system arises because previous theoretical studies have found only weakly bound states for Sc\(_2\) in contrast to experimental evidence for a bound state of Sc\(_2\) involving two one-electron 3d orbitals. Experimental studies have indicated a bound \( ^3\Pi \) state of Sc\(_2\),\(^5\) This state appears to be bound with respect to the \( ^3D + ^1D \) atomic limit, but clearly cannot arise from this asymptote. Walch and Bauschlicher\(^7\) indicated that states arising from the \( ^3D + ^1D \) atomic limit were closely spaced and only weakly bound with large \( R \) values (\( \approx 8.0\) a.u.).

Previous studies of Sc\(_2\) by Das\(^3\) and by Walch and Bauschlicher\(^7\) indicated that states arising from the \( ^3D + ^1D \) atomic limit were closely spaced and only weakly bound with respect to the \( ^2D - ^2D \) limit were bound with respect to the \( ^2D - ^2D \) limit.

Reinterpreting the mass spectrometric experiments using a larger molecular degeneracy and larger \( R \) (the original analysis used \( R = 5.14\) a.u., \( \omega = 230 \) cm\(^{-1}\), and \( g = 5 \)), Das concluded that the mass spectrometric results were consistent with weak binding. However, more recently matrix isolation studies have indicated a bound \( ^3\Pi \) state of Sc\(_2\).\(^5\) This state appears to be bound with respect to the \( ^3D + ^1D \) atomic limit, but clearly cannot arise from this asymptote. Walch and Bauschlicher\(^7\) indicated that states arising from the \( ^3D + ^1D \) atomic limit were closely spaced and only weakly bound with respect to the \( ^2D + ^1D \) atomic limit. States arising out of the \( ^3D + ^1D \) atomic limit were not studied in detail; however, given the experimental evidence for a bound \( ^3\Sigma_u^- \) state of Sc\(_2\) with a 3d population of \( \approx 3 \), together with a known computational bias toward the \( ^3F(4s^1 4p^1 3d^1) \) state relative to the \( ^3P(4s^1 3p^1 3d^1) \) state,\(^6\) a re-investigation of the \( ^3\Sigma_u^- \) state arising from \( ^3D + ^1D \) was carried out.

In this communication we report extensive CAS/CASSCF/CI(SD) calculations which show that this \( ^3\Sigma_u^- \) state is bound with respect to the \( ^3D + ^1D \) atomic limit. We find that the bonding in this state involves three one-electron 3d bonds and believe this to be strong theoretical evidence of multiple 3d bonding in a first row transition metal dimer.

The \( ^3\Sigma_u^- \) state had previously been suggested as the ground state of Sc\(_2\) by Wood, Moran, Hillier, and Guest.\(^1\) However, this assignment was not convincing because correcting for their asymptotic error the \( ^3\Sigma_u^- \) state was not bound with respect to the lowest limit.

The basis set was the \([14s11p6d]/[8s6p4d]\) basis set described in Ref. 3. An extended basis \([14s12p6d3f]/[8s7p4d5f]\) was also used. This basis has three 4p functions\(^1\) optimized for the \( ^4F(4s^1 4p^1 3d^1) \) state of Sc and two 4f functions obtained as a (21) contraction of a three-term GTO fit to a Slater 4f with exponent \( 1.6 \). The extended basis gave an energy improvement of 0.003 39\( h \) = 0.092 eV for the CASSCF of the \( ^3\Sigma_u^- \) state at \( R = 5.0\) a.u.

As in the previous calculations,\(^1\) the CASSCF space consisted of the orbitals derived from the atomic 4s, 4p, and 3d orbitals. The dominant configuration \( c_1 = 0.85 \) for CASSCF at \( R = 5.0\) a.u. for the \( ^3\Sigma_u^- \) state is

\[
4s^1 3d^1 4s^1 3d^1 3d^1. \tag{1}
\]

Constraints were placed on the orbital occupancies; here the \( \sigma \) block had four electrons, the \( \pi \) block had two electrons, and the \( \delta \) block had zero electrons in all configurations. The reference configurations for the CI(SD) were selected as those configurations (ten) with CI coefficients \( > 0.05 \) in the CASSCF wavefunction near \( R \).

This leads to a \( 86\% \) reference in the CI(SD) wave function for the \( ^3\Sigma_u^- \) state at \( R = 5.0\) a.u. as compared to \( 88\% \) reference for the large \( R \) asymptote, the \( ^3\Sigma_u^- \) state at \( R = 50.0\) a.u. The valence populations derived from the CASSCF/CI(SD) calculation are \( 4s = 2.60, 4p = 0.83, \) and \( 3d = 2.57 \).

Figure 1 shows the calculated CASSCF/CI(SD) potential curve for the \( ^3\Sigma_u^- \) state together with the states which were previously computed.\(^3\) The \( ^3\Sigma_u^- \) state is most closely related to the \( ^3\Sigma_u^- \) state which has the configuration

\[
4s^2 4s^1 4s^1 3d^1 3d^1. \tag{2}
\]

As discussed elsewhere,\(^3\) for the states derived from the \( ^3D + ^1D \) asymptote, the 3d overlap is small and in the small \( S \) region one expects one-electron bonds which vary with distance like \( S \) to be more favorable than two-electron bonds which vary with distance like \( S^2 \). Thus the \( ^3\Sigma_u^- \) state which involves two one-electron \( \pi \) bonds is more favorable than the \( ^3\Sigma_u^- \) state which has a single
two-electron σ bond. Promoting an electron of the $^3\Sigma_u^+$ state from the 4$s\gamma$ antibonding orbital to the 3$d\sigma$ orbital leads to the $^1\Sigma_u^+$ state which has an additional one-electron 3$d\sigma$ bond and reduced 4$s$ repulsion due to removal of an electron from the 4$s\gamma$ orbital. Given these factors, it is not surprising that the $^5\Sigma_u^+$ state has a smaller $R_e$ and is more stable than the $^3\Sigma_u^+$ state.

A Dunham analysis of a parabolic fit to the $^1\Sigma_u^+$ potential leads to $R_e = 5.27\text{a}_0$ and $\omega_e = 184\text{ cm}^{-1}$. The binding energy is estimated to be 0.44 eV (10.1 kcal/mol) including (i) a small differential Davidson’s correction (-0.03 eV), (ii) a correction for the error in the asymptotic separation (+0.26 eV), and (iii) a correction for the energy improvement with the extended basis (+0.09 eV). The calculated $R_e$ and $\omega_e$ values are very close to the assumed values. In the limit of no 3$d$ interactions $^4F \to ^3D$ leads to a molecular degeneracy of 280 which would lead to an -16 kcal/mol decrease in the experimental estimate of $D_e$, and excellent agreement with experiment. However, the actual degeneracy will be much lower than this, possibly approaching 5, and thus the calculated $D_e$ is smaller than current experimental estimates by at least 10 kcal/mol. The calculated $\omega_e$ is slightly smaller than the current estimate$^5$ of 238.9 cm$^{-1}$ which is consistent with the underestimation of $D_e$.

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Fig. 1. Potential energy curves for the low-lying states of Sc$^+$ from CASSCF (CHSD) calculations. The locations of the $^1D\to^3D$, $^1D\to^3F(4s\gamma 4p\gamma 3d\gamma)$, and $^3D\to^3F(4s\gamma 3d\gamma)$ asymptotes are indicated.
Extended CASSCF Calculations for Transition Metal Dimers:

the Ti$_2$$^1\Sigma^+$, V$_2$$^3\Sigma^-$, and Cr$_2$$^1\Sigma^+$ States

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The results of extended active space CASSCF calculations are reported for Ti$_2$, V$_2$, and Cr$_2$. Molecular orbitals derived from atomic 4p and 3d' are found to be very important leading to improved binding energies for Ti$_2$ and V$_2$ and to a bound curve for Cr$_2$. The Cr$_2$ calculated spectroscopic parameters are (experimental values in parenthesis) $R_e = 1.78$ Å (1.68 Å), $\omega_e = 383$ cm$^{-1}$ (480 cm$^{-1}$) and $D_e = 0.71$ eV (1.56 eV).

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Recently the transition metal dimers have been of considerable experimental [1-5] and theoretical [6-10] interest both because of the diverse nature of the bonding in the transition metal dimers and because of the difficulty in calculating accurate potential curves for these dimers which exhibit multiple two-electron 3d bonding (especially Cr$_2$). To date the most extensive study of V$_2$ and Cr$_2$ has been carried out by Walch et al. [6]. These calculations were CASSCF calculations with the 4s and 3d transition metal orbitals in the active space. This choice of the active space is appropriate for the states considered, V$_2$ $^3\Sigma^{-}$ and Cr$_2$ $^1\Sigma^{+}$, since they arise from the 4s$^1$3d$^n$ + 4s$^1$3d$^n$ atomic asymptotes. The calculated CASSCF curve for V$_2$ gave good $R_e$ and $\omega_e$ values and also these authors correctly predicted the ground state of V$_2$ to be $^3\Sigma^{-}$ prior to experimental determination [4]. However, the calculated binding energy for V$_2$ was only 0.33 eV (relative to 4s$^2$3d$^4$ + 4s$^2$3d$^4$) compared to the current experimental value of 1.8 eV [4] and Cr$_2$ did not give a bound curve although a shoulder was observed near the region of the experimental $R_e$.

The usual approach to correcting those defects is the use of configuration interaction (CI). However, the brute force application of CI techniques to V$_2$ and Cr$_2$ is not practical due to the large size of the CI expansions encountered. For example, Walch et al. [6] estimate ~57 million configurations are needed to describe the potential curve for the Cr$_2$ molecule, whereas the current computational capability is only about one million configurations. Walch et al. were able to carry out a CI calculation for the $^1\Sigma^{+}$ state of Ti$_2$ which exhibits a triple two-electron 3d bond (\(\sigma, \pi_x, \pi_y\)) and used this result to estimate the binding energies of V$_2$ and Cr$_2$ assuming a triple bonded picture for V$_2$, i.e., that the 3d$^5$ orbitals are nonbonding. The preliminary estimate [6] was an increase in binding energy of ~2.0 eV which has now been refined to 1.57 eV leading to predicted $D_e$'s of ~1.7 eV for V$_2$ (relative to 4s$^2$3d$^3$ + 4s$^2$3d$^3$) and 0.2 eV for Cr$_2$ (relative to 4s$^1$3d$^5$ + 4s$^1$3d$^5$). This model is probably realistic for V$_2$ where the 3d$^5$ orbitals are singly occupied leading to only weak one-electron bonds but we now believe it is not reasonable for Cr$_2$ where the 3d$^5$ orbitals are double occupied (vide infra).

In order to get around these difficulties we have used a CASSCF approach to estimate the dominant correlation effects missing in the CASSCF calculations with only 4s and 3d in the active space. For the transition metal atoms we find that the most important additional terms are derived from 3d' and 4p and these are also found to be the most important additional molecular correlation terms. Here 3d' is a tight diffuse correlating orbital for the 3d. Table 1 shows the effect of including these
additional correlation terms for the Ti atom. Concentrating on the description of the $4s^23d^2 \rightarrow 4s^13d^3$ excitation energy we see that SCF underestimates
the excitation energy. Including the 4p orbital lowers $4s^2$ relative to $4s^1$ and leads to an overestimation of the excitation energy, while inclusion of $3d'$ lowers $3d^3$ relative to $3d^2$ leading to a calculated separation that is close to the CI value when both 4p and $3d'$ are included. The remaining 0.2 eV discrepancy with experiment is due to core-valence correlation involving the 3p shell [11]. Thus inclusion of 4p and $3d'$ enables an accurate description of the relative energies of atomic states involving different numbers of $4s$ and $3d$ electrons. This improved atomic description has been shown to be important for describing molecular potential curves [12]. An analogous argument for the importance of $3d'$ has been made by Dunning, Botch, and Harrison [13].

To the extent that charge transfer terms are important for the transition metal dimers, we also expect 4p and $3d'$ to be important since 4p improves the description of terms arising from

$$3d^n + 4s^23d^n$$ (1)

while $3d'$ improves the description of terms arising from

$$4s^13d^{n-1} + 4s^13d^{n+1}$$ (2)

Indeed, Goodgame and Goddard [14] have suggested that the difficulty in describing the transition metal dimers arises from difficulties in describing the ionic terms [especially (2)]. If this explanation is correct our calculations include directly the correlation corrections which they include by empirical modification of the integrals.

The dominant configurations [6] for the molecules considered here are:

$$\text{Ti}_2 \quad 1s^2 4s^2 2g 3d^2 3d\pi_{xu} 3d\pi_{yu}$$ (3)

$$\text{V}_2 \quad 1s^2 4s^2 2g 3d\pi_{xu} 3d\pi_{yu} 3d\delta 3d\pi_{x-y}$$ (4)

$$\text{Cr}_2 \quad 1s^2 4s^2 2g 3d\pi_{xu} 3d\pi_{yu} 3d\pi_{x-y} 3d\delta$$ (5)

The calculations use the [8s6p4d2f] basis set described previously [6] and the MOLECULE-SWEDEN programs [15]. As in the previous calculations the occupations are constrained by symmetry. For example for Ti$_2$, the dominant configuration has four electrons in sigma, two in $\pi_x$, and two in $\pi_y$. 


For the CASSCF within the 4s and 3d orbitals we impose the constraints that four electrons be distributed among 4s\textsubscript{g}, 4s\textsubscript{u}, 3d\textsubscript{g}, and 3d\textsubscript{u}, two electrons be distributed among 3d\textsubscript{xy} and 3d\textsubscript{yz}, and two electrons be distributed among 3d\textsubscript{xz} and 3d\textsubscript{y}. This set of constraints leads to a CASSCF which mimics the GVB wavefunction \cite{16}. Here we use GVB in the more general sense of allowing all possible spin couplings of the 4s and 3d atomic like orbitals with simultaneous orbital optimization. The active space was then augmented by

addition of 3d\textsuperscript{t} and 4p. Here the additional active orbitals were added separately by symmetry blocks. For Ti\textsubscript{2}, 3d\textsuperscript{t}, 3d\textsuperscript{t} plus 4p\textsubscript{t}, 3d\textsubscript{t}, 3d\textsuperscript{t} plus 4p\textsubscript{t}, were added in separate calculations. The same occupation constraints were imposed except that in the calculation with 3d\textsubscript{t} plus 4p\textsubscript{t}, the sigma block was constrained to two to four electrons and the pi block to two to four electrons thus allowing the 4s\textsuperscript{2} + 4p\textsuperscript{2} near degeneracy terms. These orbital constraints in addition to keeping the calculations of tractable size also lead to a wavefunction which dissociates to Hartree-Fock atoms (for the 4s\textsuperscript{1}3d\textsuperscript{t} + 4s\textsuperscript{1}3d\textsuperscript{t} limit considered here). For Cr\textsubscript{2} and V\textsubscript{2}, 3d\textsuperscript{t}, 3d\textsubscript{t} and 3d\textsuperscript{t} were added in separate calculations. For the Ti\textsubscript{2} calculations the 4p\textsuperscript{t} contribution was obtained as the 3d\textsuperscript{t} plus 4p\textsuperscript{t} contribution minus the 3d\textsuperscript{t} contribution and similarly for the 4p\textsubscript{t} contribution. The 3d\textsuperscript{t}, 4p\textsuperscript{t}, and 3d\textsuperscript{t} contributions were calculated as twice the 3d\textsubscript{t}, 4p\textsubscript{t} and 3d\textsuperscript{t} contributions, respectively. The CASSCF energies and energy contributions for each of the added active space orbitals are given in Table 2, Table 3, and Table 4 for Ti\textsubscript{2}, V\textsubscript{2}, and Cr\textsubscript{2}, respectively.

Figure 1 shows the calculated potential curves for the \textit{Eg} state of the Ti\textsubscript{2} molecule. The CI calculation was a multireference singles and doubles CI from nine references leading to \approx 180,000 CSFs. For comparison to the CASSCF curves the CI energies are shifted to make the asymptotic CI energy equal to the asymptotic SCF energy for the 4s\textsuperscript{1}3d\textsuperscript{3} + 4s\textsuperscript{1}3d\textsuperscript{3} limit (i.e. we are comparing binding energies). From Fig. 1 it is clear that both 3d\textsuperscript{t} and 4p make important contributions to the binding energy with 3d\textsuperscript{t} somewhat more important than 4p. It is also evident from Fig. 1 that the extended CASSCF procedure used here obtains a very large percentage of the extra binding energy obtained in the CI. However, estimating \Delta E 3d\textsuperscript{t} by summing the separately calculated 3d\textsuperscript{t} and 3d\pi components as was done here overestimates the effect of 3d\textsuperscript{t} as compared to a calculation in which all the 3d\textsuperscript{t} components are included in one calculation. For Ti\textsubscript{2} including 3d\textsuperscript{t}, 3d\textsuperscript{t}, and 3d\textsuperscript{t} in one calculation with occupation constraints as above increases \Delta E 3d\textsuperscript{t} by 0.01446h for the molecule at R = 3.75\textsubscript{a}\textgreek{i} and by 0.03852h for the separated atoms; thus the differential effect of 3d\textsuperscript{t} is reduced from \approx 32mh to \approx 8mh. The dominant atomic correlation terms are of the form

\begin{equation}
3d\textsubscript{t} \rightarrow 3d\textsubscript{t} \times 3d\textsubscript{j} \rightarrow 3d\textsubscript{j}
\end{equation}
This result indicates that these terms may not be viewed as "atomic correlation" because they are less important for the molecule than for the atom. On the other hand, the 4p correlation does not contribute for the 4s\(^1\)3d\(^n\) state of the atom and we do not expect the 4p correlation effect to be significantly reduced by a more extensive MCSCF calculation. Given these results we must view as fortuitous the good \(D_e\) for Ti\(_2\) obtained by including 3d' and 4p correlation estimates based on calculations which dissociate to SCF atoms. However, our intention here is to use this method to extrapolate from the Ti\(_2\) case where we are able to do an adequate CI treatment to the V\(_2\) and Cr\(_2\) cases where the calculations exceed present computational capabilities. We believe that the correlation effects which are included in these calculations will be the most important differential effects between molecules in this series. For simplicity in performing the extrapolation we use the extended CASCF results directly since the \(D_e\) obtained for Ti\(_2\) in this way is within 0.08 eV of the CI value.

Table 5 shows the calculated spectroscopic parameters for Ti\(_2\) (obtained via a Dunham analysis of the points in Table 2). Here we see that the calculated \(\omega_e\) is in good agreement with experiment. The calculated \(D_e\) is smaller than the mass spectrometrically determined \(D_e\) but the experimental value may be too large as is the case for V\(_2\) where a more recent determination via predissociation reduces \(D_e\) by \(~0.7\) eV.

Table 6 shows the calculated spectroscopic constants for V\(_2\). Here the effect of 4p was estimated from the Ti\(_2\) calculations. This was done by shifting the \(\Delta E\) 4p curves for Ti\(_2\) toward shorter \(R\) by 0.36 \(\alpha_0\) which is twice the difference between \(<r_{4s}>\) for Ti 4s\(^1\)3d\(^3\) and V 4s\(^1\)3d\(^4\)\([11]\). From Table 6 we see that \(R_e\), \(D_e\), and \(\omega_e\) are all in good agreement with experiment for V\(_2\). In particular the calculated \(D_e\) is in good agreement with the recent experimental value determined from predissociation \([4]\) but is considerably smaller than the mass spectrometric value \([17]\).

Fig. 2 shows calculated potential curves for Cr\(_2\). Here as for V\(_2\) the effect of 4p was estimated from the Ti\(_2\) results but shifted toward shorter \(R\) by 0.64 \(\alpha_0\) which is twice the difference between \(<r_{4s}>\) for Ti 4s\(^1\)3d\(^3\) and Cr 4s\(^1\)3d\(^5\) \([11]\). The most significant feature of Fig. 2 is the appearance of a well in the region where a shoulder had been observed in the CASSCF curve \([6]\). Thus, Cr\(_2\) exhibits rather different behavior from Ti\(_2\) or V\(_2\) in that 3d' correlation in Ti\(_2\) and V\(_2\) deepened the well but did not significantly change \(R_e\) or \(\omega_e\), while for Cr\(_2\) 3d' correlation converts a shoulder on the curve into a well. This behavior implies considerable \(R\) dependence in the 3d correlation as is evident from Fig. 3 where the 3d\(_\sigma\), 3d\(_\pi\), and 3d\(_\delta\) components of the 3d' correlation are plotted. The 3d\(_\delta\) component shows an especially strong \(R\) dependence and it is this term which is mainly respon-
possible for the difference between \( \text{Cr}_2 \) and \( \text{V}_2 \) or \( \text{Ti}_2 \). In fact from Table 3 one sees that for \( \text{V}_2 \) the \( \Delta E \) 3d\( \sigma \) is small (\( \sim 0.010 \)) and not strongly \( R \) dependent. Thus a triple bond model based on \( \text{Ti}_2 \), as used in ref 6, is an appropriate zero order approximation for \( \text{V}_2 \) but not for \( \text{Cr}_2 \).

From Fig. 2 one sees that there is some anharmonicity in the calculated \( \text{Cr}_2 \) curve. However, this anharmonicity decreases as the calculation is improved and neither the CASSCF + 3d' nor the CASSCF + 3d' + 4p curves show any resemblance to the very peculiar potential curve obtained in the recent local spin density (LSD) calculations [20]. Also the LSD wavefunction is described as antiferromagnetic even near \( R_e \) whereas our wavefunction shows this spin coupling at large \( R \) but becomes a multiple 3d bond near \( R_e \).

Table 7 shows the calculated spectroscopic constraints for \( \text{Cr}_2 \). Here the best calculation has \( R_e \) too long by 0.10 \( \text{Å} \) and \( \omega_e \) too small by 97 cm\(^{-1}\). This result is consistent with underestimating the binding energy. However, it seems probable based on what is known about the binding energy of \( \text{V}_2 \) that \( \text{Cr}_2 \) is bound by considerably less than 1.56eV. The most likely source of error in the \( \text{Cr}_2 \) potential curve is the estimation of the \( \Delta 4p \) using the \( \text{Ti}_2 \) results. Shifting the \( R_e \) by 0.64\( \text{Å} \) based on the relative 4s sizes for the Ti and Cr atoms is a somewhat arbitrary assumption although the potential is not particularly sensitive to the choice of this parameter since very similar spectroscopic parameters are obtained for a shift of 0.50. It is also possible that the \( \Delta 4p \) is slightly larger for \( \text{Cr}_2 \) than for \( \text{Ti}_2 \) due to the smaller 4s orbital size. However Bagus and Bauschlicher report that 4s\(^2 \rightarrow 4p^2 \) is nearly constant for the atoms varying from 0.76 for Sc to 0.85 for Cu [11]. Unfortunately, the calculation of \( \Delta 4p \) by the technique used for \( \text{Ti}_2 \) would involve a very large CASSCF calculation (which we may carry out in the future) since the \( \text{Cr}_2 \) CASSCF for 3d\( \sigma' \) involves \( \sim 20,000 \) configurations.

One further possible source of error in the \( \text{Cr}_2 \) calculation is core-valence correlation [21] involving the 3p shell. This effect would be more likely to be important for Cr than for V or Ti since \( <r_{3d}>/<r_{3p}> \) is only 1.39 for Cr while the corresponding ratio is 1.47 for V and 1.56 for Ti [11]. However, calculations on the 4s\(^1\)3d\(^5 \) state of the Cr atom [22] show that singles and doubles CI out of the 4s and 3d electrons leads to a slight contraction (\( \delta <r> = -0.09\text{\( \text{Å} \)} \)) of the 4s and a slight expansion (\( \delta <r> = 0.04\text{\( \text{Å} \)} \)) for the 3d, while simultaneous inclusion of single excitations out of the 3p has little additional effect. This result makes a significant core-valence effect due to the 3p shell seem unlikely.
We conclude that inclusion of 3d' and 4p in the valence space leads to a very significant improvement in the potential curves for Ti₂, V₂, and Cr₂. The calculated $R_e$, $D_e$, and $\omega_e$ are in excellent agreement with experiment for V₂. For Ti₂, the calculated $\omega_e$ is in excellent agreement with experiment but the calculated $D_e$ is $\sim 0.3 \text{eV}$ (with respect to $4s^23d^2 + 4s^23d^2$) which is smaller than the mass spectrometric value of $\sim 1.3 \text{eV}$. However, based on previous experience with the mass spectrometric $D_e$ for V₂ which has been shown to be too large by $\geq 0.68 \text{eV}$, we believe the calculated $D_e$ is more reliable. We predict an $R_e$ for Ti₂ of 1.97 Å. To date no experimental determination of this quantity exists. For Cr₂ we report the first variational calculations with proper dissociation which have the inner multiple 3d bonded well. The $R_e$ is too long by $\sim 0.10 \text{Å}$ and the $\omega_e$ is too small by $\sim 97 \text{ cm}^{-1}$ but this still represents a significant improvement over previous calculations. The calculated $D_e$ is 0.71 eV which is smaller than the mass spectrometric estimate of 1.56 eV. Given the large $R_e$ and small $\omega_e$ in the Cr₂ potential curve it is quite likely that the true $D_e$ is larger than the calculated $D_e$ although we doubt that it is as large as 1.56 eV.

Acknowledgments

I would like to acknowledge very helpful discussions with Dr. Bowen Liu.

Dr. Charles Bauschlicher, Jr. has made numerous improvements to the CASSCF program which contributed significantly to this work, also Dr. Bauschlicher and Dr. Constance Nelin redimensioned the CASSCF program to permit these calculations.

I would also like to thank Dr. Charles Bauschlicher, Jr., Prof. William A. Goddard III, Dr. Marvin Goodgame, Dr. Stephen Langhoff, and Dr. Constance Nelin for helpful discussions.
References

15. SWEDEN is a vectorized SCF MCSCF direct CI written by P.E.M. Siegbahn, B.O. Roos, and C.W. Bauschlicher, Jr.
22. C.W. Bauschlicher, Jr., unpublished results.
Table 1. CASSCF/CI Calculations for the Ti Atom

<table>
<thead>
<tr>
<th></th>
<th>4s(^2)3d(^2) state</th>
<th>4s(^1)3d(^3) state</th>
<th>∆E (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCF</td>
<td>-.37208</td>
<td>-.35146</td>
<td>0.56</td>
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<tr>
<td>CASSCF ((4s,4p,3d))</td>
<td>-.40292</td>
<td>-.35146</td>
<td>1.40</td>
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<td>CASSCF ((4s,4p,3d,3d'))</td>
<td>-.40756</td>
<td>-.37072</td>
<td>1.00</td>
</tr>
<tr>
<td>CASSCF ((4s,4p,3d,3d',4f))</td>
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<td>-.38366</td>
<td></td>
</tr>
<tr>
<td>CI (^a)</td>
<td>-.42234 (-.42649)</td>
<td>-.38981 (-.39093)</td>
<td>.89 (0.97)</td>
</tr>
<tr>
<td>exp</td>
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<td></td>
<td>0.81</td>
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</table>

\(^a\)Values in parenthesis include Davidson's correction
Table 2. Energy Contributions and CASSCF Energies for Ti$_2$ $^1Σ^+_g$

<table>
<thead>
<tr>
<th></th>
<th>R = 3.50</th>
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<th>4.25</th>
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<tr>
<td>CASSCF$^a$</td>
<td>-.71240</td>
<td>-.71684</td>
<td>-.71051</td>
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<tr>
<td>$ΔE$ 3dσ$^t$</td>
<td>0.01323</td>
<td>0.01238</td>
<td>0.01094</td>
<td>0.01105</td>
</tr>
<tr>
<td>$ΔE$ 4pσ</td>
<td>0.00749</td>
<td>0.00773</td>
<td>0.00829</td>
<td>0.00810</td>
</tr>
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<td>2x $ΔE$ 3dπ$^t_X$</td>
<td>0.01700</td>
<td>0.01970</td>
<td>0.02364</td>
<td>0.02840</td>
</tr>
<tr>
<td>2x $ΔE$ 4pπ$^t_X$</td>
<td>0.01504</td>
<td>0.01476</td>
<td>0.01320</td>
<td>0.01100</td>
</tr>
</tbody>
</table>

$^a$The CASSCF energies are referenced to -1969.0 hartree
Table 3. Energy Contributions and CASSCF Energies for V$_2$ $^3\Sigma_g^-$

<table>
<thead>
<tr>
<th></th>
<th>$R = 3.15$</th>
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<th>3.50</th>
<th>3.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASSCF a</td>
<td>-.69183</td>
<td>-.69666</td>
<td>-.69407</td>
<td>-.68236</td>
</tr>
<tr>
<td>$\Delta E$ 3d$^0$</td>
<td>0.00987</td>
<td>0.00997</td>
<td>0.00932</td>
<td>0.00769</td>
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<tr>
<td>$2x \Delta E$ 3d$^\pi_{x}$</td>
<td>0.01726</td>
<td>0.01854</td>
<td>0.02194</td>
<td>0.02478</td>
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<tr>
<td>$2x \Delta E$ 3d$^\delta_{xy}$</td>
<td>0.00870</td>
<td>0.00924</td>
<td>0.01058</td>
<td>0.01156</td>
</tr>
</tbody>
</table>

*The CASSCF energies reported here are slightly lower than the values reported in ref. 6 which suffered from incomplete orbital optimization. The CASSCF energies are referenced to -1885.0 hartree.*
Table 4. Energy Contributions and CASSCF Energies for Cr$_2$ $^1$Σ$^+$

<table>
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<tr>
<th></th>
<th>$\mathbf{F = 3.00}$</th>
<th>$3.25$</th>
<th>$3.35$</th>
<th>$3.50$</th>
<th>$3.75$</th>
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</thead>
<tbody>
<tr>
<td>CASSCF</td>
<td>-$0.3455$</td>
<td>-$0.54502$</td>
<td>-$0.54764$</td>
<td>-$0.55206$</td>
<td>-$0.56157$</td>
</tr>
<tr>
<td>$\Delta E$ $3d\sigma^\prime$</td>
<td>$0.01136$</td>
<td>$0.01120$</td>
<td>$0.01087$</td>
<td>$0.01011$</td>
<td>$0.00834$</td>
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<tr>
<td>$2x \Delta E$ $3d\pi_x^\prime$</td>
<td>$0.01930$</td>
<td>$0.02158$</td>
<td>$0.02178$</td>
<td>$0.02118$</td>
<td>$0.01804$</td>
</tr>
<tr>
<td>$2x \Delta E$ $3d\delta_{xy}^\prime$</td>
<td>$0.02950$</td>
<td>$0.02978$</td>
<td>$0.02856$</td>
<td>$0.02560$</td>
<td>$0.01936$</td>
</tr>
</tbody>
</table>

$^a$The energies reported here are slightly lower than the values reported in ref. 6 which suffered from incomplete orbital optimization. The CASSCF energies are referenced to $-2086.0$ hartree.
Table 5. Calculated Spectroscopic Constants for Ti₂

<table>
<thead>
<tr>
<th></th>
<th>CAS</th>
<th>CAS+3d¹</th>
<th>CAS+3d¹+4p</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rₑ, Å</td>
<td>1.97</td>
<td>2.00</td>
<td>1.99</td>
<td>1.97</td>
</tr>
<tr>
<td>Dₑ, eV</td>
<td>0.37</td>
<td>1.25</td>
<td>1.86</td>
<td>1.94</td>
</tr>
<tr>
<td>ωₑ, cm⁻¹</td>
<td>436</td>
<td>423</td>
<td>442</td>
<td>438</td>
</tr>
</tbody>
</table>

*aMass spectrometric value (ref. 17) energy referenced to 4s¹3d³ + 4s¹3d³  
*bref. 19
Table 6. Calculated Spectroscopic Constants for \( V_2 \)

<table>
<thead>
<tr>
<th></th>
<th>CAS</th>
<th>CAS+3d'</th>
<th>CAS+3d'+4p (est.)</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_e ), Å</td>
<td>1.76</td>
<td>1.79</td>
<td>1.79</td>
<td>1.76(^a)</td>
</tr>
<tr>
<td>( D_e ), eV</td>
<td>0.60</td>
<td>1.68</td>
<td>2.29</td>
<td>2.29(^a), 2.97(^b)</td>
</tr>
<tr>
<td>( \omega_e ), cm</td>
<td>564</td>
<td>533</td>
<td>545</td>
<td>537.5(^c)</td>
</tr>
</tbody>
</table>

\(^{a}\text{ref.} \& \text{The } D_e \text{ value is from predissociation}\)

\(^{b}\text{mass spectrometric value (ref. 17) referenced to } 4s^{1}3d^{4}+4s^{1}3d^{4}\)

\(^{c}\text{ref. 19}\)
<table>
<thead>
<tr>
<th></th>
<th>CAS</th>
<th>CAS+3d'</th>
<th>CAS+3d' +4p (est.)</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_e, \AA )</td>
<td>---</td>
<td>1.81</td>
<td>1.78</td>
<td>1.68 \textsuperscript{a}</td>
</tr>
<tr>
<td>( D_e, \text{eV} )</td>
<td>-1.4</td>
<td>0.13</td>
<td>0.71</td>
<td>1.56 \textsuperscript{b}</td>
</tr>
<tr>
<td>( \omega_e, \text{cm}^{-1} )</td>
<td>---</td>
<td>308</td>
<td>383</td>
<td>480  \textsuperscript{c}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Ref. 1-3.

\textsuperscript{b} Mass spectrometric value (ref. 18)

\textsuperscript{c} Ref. 19
Figure Captions

Fig. 1. Calculated potential curves for the $^{1}_{\Sigma_{g}^{+}}$ state of Ti$_2$.

Fig. 2. Calculated potential curves for the $^{1}_{\Sigma_{g}^{+}}$ state of Cr$_2$.

Fig. 3. Calculated energy contributions for 3d$^4$ orbitals for Cr$_2$. 
Fig. 2

ENERGY, hartrees

- 6.0

- 6.5

- 7.0

R, au

3.0

3.5

4.0

4.5

5.0

CASSCF

4s\(^1\) 3d^5 + 4s\(^1\) 3d^5

CASSCF + 3d'

CASSCF + 3d' + 4p (est.)
Fig. 3

ORIGINAL RESULTS
OF POOR QUALITY

ENERGY, Hartree

0.00  0.020  0.020  0.010

R, au

3.00  3.25  3.50  3.75  4.00
THEORETICAL EVIDENCE FOR MULTIPLE 3d BONDING IN THE V₂ AND Cr₂ MOLECULES

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Received 29 September 1982; in final form 13 October 1983

Calculated CAS SCF potential curves are reported for the $3\Sigma^-$ state of $\text{V}_2$ and the $1\Sigma^+$ state of $\text{Cr}_2$. At the CAS SCF level the $3\Sigma^-$ state of $\text{V}_2$ is calculated to be bound ($R_c = 1.77$ Å, $\omega_e = 593.6$ cm$^{-1}$, $D_e = 0.33$ eV) and to involve a triple 3d bond, while the $\text{Cr}_2$ potential curve is not bound but shows a shoulder near the experimental $R_e$ and the wavefunction shows multiple 3d bonding in this region.

It is now clear from experimental work that the $\text{Cr}_2$ molecule has a very short bond length [1], 1.68 ± 0.01 Å. This short bond has generally been thought to involve a quintuple 3d bond arising out of the 3d$\pi$, 3d$\sigma$, and 3d$\delta$ orbitals of the $\text{Cr}_2$ 4s$^1$3d$^5$ + 4s$^1$3d$^5$ asymptote. Given the $\langle \sigma \rangle$ for the Cr atomic orbitals [2] $\langle \sigma \rangle = 1.94$ Å, $\langle 3d \rangle = 0.72$ Å one sees that at the equilibrium bond distance ($R_e$) of $\text{Cr}_2$ the 3d orbitals are at a reasonable distance for bonding but that this $R$ value is well inside the optimal bonding radius for the 4s electrons and they are expected to be non-bonding or antibonding.

At larger $R$ values one would expect the spin coupling to change from predominately 3d–3d bonding to 4s–4s bonding, since at large $R$ the 4s orbitals have a much larger overlap than the 3d orbitals. The situation at large $R$ is expected to be somewhat complex because the ground state of the Cr atom is high-spin 6S arising out of 4s$^1$3d$^5$. As pointed out by Goodgame and Goddard [3], forming a 4s–4s bond with the remaining electrons high-spin-coupled results in the loss of a large amount of exchange interaction. As a result the lowest molecular state in the large $R$ region is found to be an antiferromagnetic singlet state which couples the two Cr atoms into a singlet but still preserves the maximum number of atomic exchange interactions.

For $\text{Mo}_2$ Goodgame and Goddard [3] found an inner and outer well with the inner well corresponding to multiple 3d bonding while the outer well corresponded to the antiferromagnetic coupling. The perplexing problem is why the Goodgame and Goddard $\text{Cr}_2$ calculation did not show a similar 3d bonding solution in the inner region.

In this paper we present complete active space self-consistent field (CAS SCF) calculations [4] with large...
gaussian basis sets for the $^3\Sigma^+_e$ state of V$_2$ and the $^1\Sigma^+_e$ state of Cr$_2$. These calculations show very clear evidence for a triple 3d bond in V$_2$, the bonding involves $3d\sigma$ and $3d\pi$ two-electron bonds with the remaining two electrons involved 3d8 one-electron bonds. The bond length here is 1.77 Å compared to an experimental value [5] of 1.757 Å and the vibrational frequency is 593.6 cm$^{-1}$ compared to an experimental value [6] of 537.5 cm$^{-1}$. The calculated binding energy at the CAS SCF level is only 0.33 eV compared to 2.48 eV for experiment [7]. For Cr$_2$, while the wavefunction shows clear evidence of quintuple 3d bonding at small R (<1.85 Å), the calculated potential curve shows only a marked shoulder at ≈1.7 Å and is still repulsive by ≈1.4 eV compared to current interpretations [8] of the experimental estimate of $D_e$(1.0 ± 0.3 eV). At the present time it is not computationally feasible to do configuration interaction (CI) calculations for the $^3\Sigma^+_e$ state of V$_2$ or for the $^1\Sigma^+_e$ state of Cr$_2$ at the level of our previous calculations on Sc$_2$ [9,10]. An idea of the size of the CI for Cr$_2$ may be obtained by noting that a multi-reference singles and doubles CI (MRSD CI) for Cr$_2$ using the basis set with 4f functions and the 3086 configuration CAS SCF defined below as reference configurations leads to 57 million configurations in $D_{2h}$ symmetry. However, less extensive MRSD CI calculations [11] have been carried out for a $^1\Sigma^+_e$ state of Ti$_2$ which shows triple 3d bonding, $3d\sigma$ and $3d\pi$ as in V$_2$ and Cr$_2$, respectively. Here we find an increase in $D_e$ of ≈2.0 eV for CI as compared to CAS SCF. Applying this correction to the V$_2$ and Cr$_2$ CAS SCF results leads to 2.3 and 0.6 eV as our best estimates of the $D_e$ of V$_2$ and Cr$_2$, respectively. We believe that these calculations provide the first convincing theoretical evidence for multiple two-electron 3d bonding in a first-row transition metal dimer. Multiple one-electron 3d bonding had been observed previously for Sc$_2$ by Wallach and Bauschlicher [9].

The spd basis sets used here were the (14s11p6d)/[8s6p4d] segmented sets which have been described previously [10]. These basis sets were augmented with two 4f functions. The 4f functions were optimized based on SDCI calculations for the 4s$^1$3d$^4$ and 4s$^1$3d$^6$ configurations of the V and Cr atoms using a (14s11p6d3f)[8s6p4d1f] basis set. The optimum exponents (STO) were 2.7 and 3.2 for V and Cr, respectively. The [2f] contraction is a (21) contraction based on Stewart’s [12] three-term fit of a 176 gaussian f function to a Slater 4f.

The CAS SCF space for these calculations consisted of the orbitals derived from the atomic 4s and 3d orbitals. Constraints were placed on the orbital occupancies. For V$_2$ the o block had four electrons, $\pi_x$ and $\pi_y$ had two electrons each, and $\delta_{xy}$ had one electron each. For Cr$_2$ the $\delta_{xy}$ and $\delta_{xy}$ blocks had two electrons each and the other occupancies were the same as for V$_2$. These constraints basically correspond to a generalized valence bond (GVB) treatment of these systems. Here we use GVB in the more general sense of allowing all possible spin couplings of the 4s and 3d atomic like orbitals with simultaneous orbital optimization. For Cr$_2$ these orbital constraints reduce the CAS SCF calculation from 28784 configurations to 3088 configurations in $D_{2h}$ symmetry. The dominant configurations in the small R region are the SCF configurations:

$$4s_2^2d_{x^2}^1d_{y^2}^1d_{xy}^1d_{yz}^1d_{zx}^13d_{x^2}^13d_{y^2}^13d_{xy}^1$$ (1)

for V$_2$ and

$$4s_2^2d_{x^2}^1d_{y^2}^1d_{xy}^1d_{yz}^1d_{zx}^13d_{x^2}^13d_{y^2}^1$$ (2)

for Cr$_2$. At R = 3.00 $a_0$, the percent SCF ($C^2$) in the CAS SCF wavefunction is 76% for V$_2$ and 56% for Cr$_2$. This clearly indicates the need for an MC SCF treatment of these systems.

Table 1 gives the natural orbital occupancies of the CAS SCF wavefunctions for V$_2$ and Cr$_2$ at R = 3.0 and 3.5 $a_0$. In discussing the results in table 1 it is useful to consider an analogy to the H$_2$ molecule. Here including only left-right correlation leads to a two-configuration MS SCF.

$$C_1|1s_2^2 + C_2|1s_2^2$$ (3)

Near $R_e$ the 1s$^2$ (SCF) configuration dominates but at large R, $C_1 \approx C_2$. As discussed elsewhere, in terms of the generalized valence bond (GVB) wavefunction [13], the relative weights of the two configurations are related to the overlap of the two H(1s) like GVB orbitals $\phi_1$ and $\phi_2$, with $C_1$ dominant indicative of a large overlap ($\phi_2$, $\phi_1$) while $C_1 \approx C_2$ implies a very small overlap. In interpreting table 1 we can thus compare the overlaps of each pair by comparing the natural orbital occupancies of the bonding and antibonding combinations of each atomic like orbital.

Looking first at Cr$_2$, where each possible 3d pair is doubly occupied, we see that the above analysis indicates the 3d overlaps are in the order...
Table 1

<table>
<thead>
<tr>
<th>State</th>
<th>R</th>
<th>Natural orbital occupation a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>4s</td>
</tr>
<tr>
<td>V₂  2Σ⁺</td>
<td>3.00</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td>3.50</td>
<td>1.93</td>
</tr>
<tr>
<td>Cr₂  1Σ⁺</td>
<td>3.00</td>
<td>1.90</td>
</tr>
<tr>
<td></td>
<td>3.50</td>
<td>1.85</td>
</tr>
</tbody>
</table>

a) The 4s and 3d natural orbitals are a mixture of 4s and 3d at R = 3.00 a₀ but show only slight amounts of mixed character at R = 3.5 a₀.

\[(3d\pi | 3d\pi) \approx (3do | 3do) > (3d\delta | 3d\delta).\]  

Given this analysis one expects the lowest state in V₂ to arise by distributing two electrons among the 3d\delta orbitals since the 3do and 3d\pi orbitals are in the large overlap region near Rₑ and the 3d\delta orbitals have much smaller overlaps in this region. Thus it is favorable for the 3do and 3d\pi electrons to form two-electron bonds. Furthermore, the small overlap of the 3d\delta orbitals makes one-electron bonding more favorable than two-electron bonding [10]. Thus the 2Σ⁺ state arising from 3d\delta₁₃, 3d\delta₂₂₋₂₋₂ is expected to be below the 1Σ⁺ and 1Π states arising out of 3d\delta₂₂ and 3d\delta₂₂₋₂₋₂. These arguments are consistent with the observation of a 2Σ ground state with a short bond length for V₂ [5] and are also consistent with the much weaker bonding in Cr₂ as compared to V₂ due to the necessity of two-electron 3d\delta bonding (unfavorable in the small overlap region) in Cr₂.

Table 2

<table>
<thead>
<tr>
<th>State</th>
<th>R</th>
<th>CAS SCF energy a,b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[8s6p4d]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V₂ 4Σ⁺</td>
<td>3.00</td>
<td>-0.64007</td>
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<td></td>
<td>3.15</td>
<td>-0.67119</td>
</tr>
<tr>
<td></td>
<td>3.25</td>
<td>-0.67716</td>
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<td></td>
<td>3.50</td>
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<td>-0.67798</td>
</tr>
<tr>
<td></td>
<td>4.00</td>
<td>-0.67051</td>
</tr>
</tbody>
</table>

a) In au relative to -1885.0.
b) The asymptotic energies (based on atomic SCF calculations) are 4s³4p² + 4s³4p² - 1885.6858 eV, 4s³4p² + 4s³4p² - 1885.68076 eV, and 4s³4p² + 4s³4p² - 1885.67566 eV.

Tables 2 and 3 give the CAS SCF energies for V₂ and Cr₂ while the results are plotted in figs 1 and 2. A very striking feature of these calculations is the large effect of 4f functions in the basis set. This effect has also been noted by McLean and Liu [14] for SCF calculations on Cr₂ using a large Slater basis set. Table 4 shows the change in SCF energy at R = 3.0 a₀ as a function of the completeness of the 4f basis set. The contractions shown in table 4 are based on the gaussian fits of Stewart [12] for an STO of 3.2. The largest basis set is the basis set used in the molecular calculations. The total effect of 4f functions for this basis is 1.17 eV as compared to 1.11 eV in the calculations of McLean and Liu. The slightly larger effect of 4f functions in our calculations probably reflects a slightly better spd basis in our calculations. A surprising feature of table 4 is the relatively good results with much less complete 4f basis sets. In particular a single set of 4f primitives obtains 1.01 eV of...
the 1.17 eV effect obtained with the best 4f basis set. From table 4 one sees that the effect of 4f functions is slightly smaller at the CAS SCF level than at the SCF level.

An interesting feature of fig. 1 is that the effect of 4f functions is very $R$ dependent and shifts the $R_e$ value of $V_2$ to smaller $R$. From fig. 2 one also sees that the addition of 4f basis functions results in a distinct shoulder on the Cr$_2$ potential curve in the region of the experimental $R_e$. While this feature is not evident in the calculation without 4f functions, the nearly linear behavior from 4.00 to 3.25 a$_0$ is indicative of some additional bonding interaction occurring in this region.

Comparing to Goodgame and Goddard we note that our configuration space contains all the configurations included in the GVB wavefunction. Our basis set is more extensive than that of Goodgame and Goddard which is only double zeta in the 3d space and has no 4f functions. As pointed out by McLean and Liu [14] a major weakness in the Goodgame and Goddard calculations is the very limited basis set and this clearly accounts for missing the shoulder on the Cr$_2$ curve at small $R$.

Kok and Hall [15] claim to obtain a correct bond length for Cr$_2$ using essentially a perfect pairing GVB wavefunction [13]. However this result is clearly an artifact of the failure of their wavefunction to dissociate properly.

We conclude that the ground states of both V$_2$ and Cr$_2$ are characterized by multiple 3d bonding. Given this, it is not surprising that 4f functions are found to be very important in the basis set. This new theoretical result demonstrates the diverse nature of transition metal bonding in that Sc$_2$ has been shown to have multiple one-electron 3d bonding [9], V$_2$ and Cr$_2$ are now shown to have multiple two-electron 3d bonding, and Cu$_2$ [16] has been shown to be predominately 4s–4s bonding with the 3d electrons essentially atomic like.

Table 4
Comparison of 4f basis sets for Cr$_2$ $^1\Sigma^+_g$

<table>
<thead>
<tr>
<th>4f basis</th>
<th>SCF energy</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-2085.82353</td>
</tr>
<tr>
<td>(1) [1]</td>
<td>-2085.86064</td>
</tr>
<tr>
<td>(2) [1]</td>
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</tr>
<tr>
<td>(3) [1]</td>
<td>-2085.86550</td>
</tr>
<tr>
<td>(3) [2]</td>
<td>-2085.86640</td>
</tr>
</tbody>
</table>
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to be published.


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On the nature of the bonding in Cu₂

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Per E. M. Siegbahn

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The ground state of Cu₂ is found to arise from the ¹S(4s⁴3d⁶) + ¹S(4s⁴3d⁶) limit and to involve a 4s-4s sigma bond pair. The dominant bond pair correlations are left-right and angular, with the former lengthening the bond and the latter contracting the bond, so that at the two-electron MCSCF level the R, is slightly longer (0.02a₀) than at the SCF level. Correlation of the 3d electrons shortens the bond by 0.19a₀, leading to a final bond length of 4.35a₀, which is 0.1a₀ longer than experiment. This error is of the same magnitude as twice the relativistic contraction of the 4s orbital of the ¹S state of the Cu atom (0.13a₀) and most of the remaining error in R, is thought to be due to this relativistic contraction.

INTRODUCTION

Since the ground state of the Cu atom is ¹S(4s⁴3d⁶), the bonding in Cu₂ is expected to involve a 4s-4s bond, giving rise to a ¹S₂ ground state with all orbitals fully occupied. This makes Cu₂ one of the simplest transition metal dimers. It is also one of the few transition metal dimers for which there is an accurate determination of the bond length (4.20 bohr). For these reasons, Cu₂ serves as an important benchmark for theoretical calculations on transition metal bonding. There have been several previous calculations on Cu₂ (see Ref. 2 and references therein) and probably the best is that of Pelissier,² who used effective core potentials (ECP's), a reasonable valence basis, and a nonvariational CI treatment. One interesting feature of this work was the bond shortening at the CI level when the d electrons are correlated. Bagus and Björkman observed this for NH₃,³ and we have observed it for NH₂, CoH, and CuH. This bond shortening and its implications for the nature of the transition metal bond are discussed in this article.

COMPUTATIONAL DETAILS

The basis set is the ¹4s9p5d basis of Wachters,³ optimized for the ¹S state, and augmented with the Hay⁴ diffuse d and Wachters'² two diffuse 4p functions, optimized for ¹P, scaled by √7.28 to make them more suitable for a ground state. This basis is contracted in a segmented manner to [14s11p6d/8s6p4d]. The 3s combinations of the d's are excluded. In some of the calculations, an f polarization function is added. This is a 3 GTO fit to an STO with l = 5.0. The f exponent was chosen by extrapolation of the optimum values for the Fe and Ni atoms. When the f function is used, only seven components are retained.

All calculations were performed with MOLECULE—noname—Siegbahn CI,¹ using either the NASA Ames 7600 or CRAY 15.

Cu ATOM

In these calculations, symmetry and equivalence restricted SCF calculations were performed. These were followed by CI calculations including all single and double excitations from all valence configurations with the correct symmetry. The 3d and 4s valence orbitals are included in all calculations, while in the more extensive calculations, the 3s and 3p semicore electrons are also included. The calculations in which the 3s and 3p are included are denoted as CI(3p) and CI(3s3p), respectively. The results of these calculations are summarized in Table I. CI-3f denotes that the f function has been uncontracted.

From Table I, one sees that the SCF separation differs from numerical HF (NHF) by 0.07 eV, while at the CI (3s3p) + f level, the agreement with experiment is within 0.01 eV. However, when the f function is uncontracted, 3d⁴4s⁴ is stabilized by ~0.1 eV with respect to 3d⁴4s⁵, thus worsening the agreement with experiment. This is consistent with our previous work,⁸ which indicated that the 3d⁴4s⁵ states of the transition metal atoms are stabilized relative to the 3d⁴4s⁴ states upon uncontracting the f function. Including relativistic effects stabilizes 4s⁴3d⁶ by 0.45 eV with respect to 4s⁵3d⁶. Thus, it is not surprising that improvement in the calculation leads to 4s⁵3d⁶ too high with respect to 4s⁴3d⁶. However, we note here that the molecular calculations neglect relativistic effects, and a good description of the ¹S-¹D separation is obtained at the CI (3s3p) + f level. Thus, we chose to use this basis set for the molecular calculations.

<table>
<thead>
<tr>
<th>Calculation</th>
<th>¹S(4s⁴3d⁶)</th>
<th>¹D(4s⁴3d⁵)</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCF</td>
<td>-1638.813826</td>
<td>-1628.796907</td>
<td>0.44</td>
</tr>
<tr>
<td>CI</td>
<td>-1638.054659</td>
<td>-1629.015096</td>
<td>1.35 (1.30)</td>
</tr>
<tr>
<td>CI + f</td>
<td>-1639.153825</td>
<td>-1629.129928</td>
<td>1.59 (1.55)</td>
</tr>
<tr>
<td>CI(3p) + f</td>
<td>-1639.380301</td>
<td>-1629.327964</td>
<td>1.43 (1.41)</td>
</tr>
<tr>
<td>CI(3s3p) + f</td>
<td>-1639.436391</td>
<td>-1629.380992</td>
<td>1.51 (1.50)</td>
</tr>
<tr>
<td>CI + 3f</td>
<td>-1639.217307</td>
<td>-1629.155872</td>
<td>1.67 (1.65)</td>
</tr>
<tr>
<td>CI(3p) + 3f</td>
<td>-1639.430515</td>
<td>-1629.374116</td>
<td>1.54 (1.53)</td>
</tr>
<tr>
<td>CI(3s3p) + 3f</td>
<td>-1639.494822</td>
<td>-1629.435222</td>
<td>1.62 (1.63)</td>
</tr>
<tr>
<td>EXP⁹</td>
<td>1.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NHF</td>
<td>0.37</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CU2 CALCULATIONS**

The calculated bond lengths for Cu2 are summarized in Table II. The separation between computed points was 0.9 bohr, so the reported $R_b$ values are expected to be within 0.02 bohr of the true minima of the model used.

The first calculation is a single configuration SCF

\[ \ldots \delta_{6s}^2(3d)^7(4s-4p \text{ bond}) \delta_{6s}^2(3d)^3(3d)^3(3d)^3(3d)^3(3d)^3 \times 16(3d). \]

Using these SCF orbitals, a series of CI calculations were carried out including single and double excitations from the SCF configuration with progressively more electrons being correlated. The CI's include a 2 el CI ($7o^2$), a 6 el CI ($6s_1, 7o^3, 6o_1$), a 14 el CI ($6o_2, 7o^3, 6o_3, 3p_1, 3p_2, 3d_1, 3d_2$), a 22 el CI which includes all 3d and 4s electrons, and a 34 el CI which includes the 3p as well as the 3d and 4s electrons. For each point, Davidson's correction was computed, added to the computed energy, and the minima redetermined. These results are reported in parenthesis in Table II.

In addition to these CI calculations, a series of MCSCF calculations were performed. They included a two-configuration MCSCF, which included only $7o^2$ and $7o^4$, which allows proper dissociation. A three-configuration MCSCF which, in addition to the $7o^2$ and $7o^4$ configuration, includes $7o^4$ reduces the importance of $7o^2$ which is a bond lengthening excitation, and moves a pair of electrons into the $4p$ bonding orbital.

**DISCUSSION**

At the SCF level, the $R_b$ is more than 0.3 bohr longer than experiment even when $f$ functions are included in the basis. Considering first correlations of the 4s and 4p electrons, inclusion of the 7o orbital lengthens the bond. This is typical of an MCSCF which includes the bonding and antibonding orbitals. The inclusion of $7o^2$ reduces the importance of $7o^4$, which is a bond lengthening excitation, and moves a pair of electrons into the $4p$ bonding orbital.

Considering now correlation of the 3d electrons, the inclusion of only the 3do electrons has only a small effect, as is shown by the 6 el CI. The inclusion of the 3s's (3d), the 14 el CI, shows a large bond shortening of 0.14 bohr, while inclusion of the 16 orbitals (22 el CI) leads to an additional 0.05 bohr shortening, or about 1/3 of the change of going from 6 to 14 el CI's. When the 3p electrons are also included (24 el CI), virtually no additional shortening occurs.

The large bond shortening due to correlation of the 3s electrons is thought to result from three effects: (i) the correlation resulting from the 4s-3s interaction, due to the importance of the $7o^2$-4s interaction; (ii) orbital relaxation effects included in the CI (vide infra), and (iii) reduction of d-d repulsion between the centers.

Effects (ii) and (iii) are also present when the 1o orbitals are correlated, while for 3do correlation only effect (ii) is present; thus, the smaller bond contraction due to correlation of these orbitals may be rationalized.

In Cu2, the atoms are 3d$^8$4s$^1$ like, and evaluating the SCF energy of the 3d$^8$4s$^2$ state using the 3d$^8$4s$^1$ orbitals leads to an excitation energy of 4.70 or -3.2 eV larger than experiment, whereas individual SCF calculations yield a separation of 0.37 eV. The inclusion of configuration interaction improves the separation through orbital relaxation and correlation, thus lowering the 3d$^8$4s$^2$ state relative to the 3d$^8$4s$^1$ state. This is opposite to the effect if separate SCF calculations are carried out for each state. This reduction of the separation allows an increased 3d$^8$4s$^1$ interaction or some d-d bonding. We note here that Pelisser stated that CI would not mix in more 3d$^8$4s$^1$ since CI increased the separation. This was based upon separate orbitals for each state and therefore does not apply in Cu2. Similar effects have been observed for NiH.
It is interesting to note that Pelissier's\textsuperscript{2} nonvari-
ation 22 el Cl leads to an $\alpha$, 0.14 bohr shorter than our result. If the shortening we observe by including $f$ functions at the 22 el Cl level ($\sim 0.04$ bohr) were subtracted from his result, he would be in excellent agreement with experiment. However, in our lab, we have found a useful estimate of the relativistic bond shortening is obtained from the relativistic contraction of the valence orbitals observed by Desclaux.\textsuperscript{13} For Cu, this is 0.064 bohr or an expected bond shortening for Cu of $\sim 0.13$ bohr. If this estimate is used, our 22 el Cl with $f$'s would be corrected from 4.35 to 4.22 bohrs. Considering the approximate nature of this relativistic shortening and the use of Davidson's correction to compute the bond length, this must be somewhat fortuitous. However, it does lead us to believe that there are potential problems with the ECP of Pelissier, which does not include relativistic effects. It is clear that to resolve this problem, 2 ECP's must be developed, one with and the other without relativistic effects included at the same level of treatment, i.e., basis set and correlation. The nonrelativistic ECP should be able to reproduce our all-electron result.

A final point is the mechanism by which 3$d^14s^2$ allows $d-d$ interactions. One might assume that a 4$s^1$ atom would form a repulsive state; however, we have shown in ScH\textsuperscript{14} that the 4$s-4p$ near degeneracy allows a 4$s^2-4p^2$ excitation which polarizes the 4$s$ electrons into the $\pi$ orbital, moving them out of the bonding region and allowing an increased 3$d$ interaction.

CONCLUSION

The Cu atoms in Cu\textsubscript{2} are best described as 3$d^94s^1$ with $\sim 4s-4s$ bond. The important correlation effects for the 4$s$ electrons are the usual bonding to antibonding excitation and a bonding to $4\pi-4p$ bonding orbital. We attribute this to the near degeneracy of the 4$s-4p$ orbitals. This effect has been seen in other systems, such as Li\textsubscript{2}, Cr\textsubscript{2}, and Cs\textsubscript{2}. We expect this to be a common feature of transition metal–transition metal bonds.

We see a large bond length contraction at the CI level when the 3$d$ electrons are correlated. We attribute this in part to an improved description of the $3d^94s^1-3d^94s^1$ separation, as a result of orbital relaxation and correlation overcoming the strong orbital bias in favor of $3d^94s^1$. This allows an increased involvement of $3d^94s^1$ and the possibility of $3d-3d$ interactions. Our best bond length is $\sim 0.15$ bohr longer than experiment and we attribute most of this to relativistic effects, based upon atomic calculations of Desclaux. This is different from Pelissier's calculations, which appear to show little relativistic effect. The question of relativistic bond shortening is left as an unresolved problem.

\textsuperscript{7}Molecule is a Gaussian integral program written by J. Almlof. "Noname" is a general SCF MCSCF open-ended CI program written by C. W. Bauschlicher, Jr. and B. H. Lengsfield III. Siegbahn CI is the Unitary-Group CI of Per Siegbahn which was converted to CRAY and CDC by C. W. Bauschlicher.
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