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3 **Structures and Heats of Formation of Simple Alkaline Earth Metal Compounds II:**
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5 **Fluorides, Chlorides, Oxides, and Hydroxides for Ba, Sr, and Ra**
6

7 Monica Vasiliu,¹ J. Grant Hill,² Kirk A. Peterson,³ and David A. Dixon^{1,*†}
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10 ¹ Chemistry Department, Shelby Hall, The University of Alabama, Shelby Hall, Box 870336,
11 Tuscaloosa, AL 35487-0336
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13

14 ² Department of Chemistry, University of Sheffield, Sheffield S3 7HF, U.K.
15
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17 ³ Department of Chemistry, Washington State University, Pullman, Washington 99164-4630
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21 **Abstract**
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24 Geometry parameters, vibrational frequencies, heats of formation, bond dissociation
25 energies, cohesive energies, and selected fluoride affinities (difluorides) are predicted for the late
26 alkaline earth (Sr, Ba and Ra) oxides, fluorides, chlorides, and hydroxides at the coupled cluster
27 theory [CCSD(T)] level. Additional corrections (scalar relativistic and pseudopotential
28 corrections, vibrational zero-point energies, and atomic spin-orbit effects) were included to
29 accurately calculate the total atomization energies and heats of formation following the Feller-
30 Peterson-Dixon methodology. The calculated values are compared to the experimental data
31 where available. In some cases, especially for Ra compounds, there are no experimental results
32 or the experimental energetics and geometries are not reliable or have very large error bars. All
33 of the Sr, Ba and Ra difluorides, dichlorides and dihydroxides are bent structures with the OMO
34 bond angles decreasing going down the group. The cohesive energy of bulk Be dihalides are
35 predicted to be quite low while those of Ra are relatively large. The fluoride affinities show that
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56 [†] Email: dadixon@ua.edu
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3 the difluorides are moderately strong Lewis acids and that such trifluorides may form under the
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5 appropriate experimental conditions.
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Introduction

Simple alkaline earth compounds play an important role in flame chemistry^{1,2,3} and in other high temperature regimes such as magnetohydrodynamic (MHD) plasmas⁴ and stellar atmospheres.⁵ Molecules containing Sr and Ba have also been observed in atmospheric release experiments.⁶ Important species include the metal monohydroxides⁷ and the oxides.⁸ Severe nuclear accidents can release a wide range of species, and BaO and SrO are among those that have been considered in the gas phase from the interaction of the core with concrete.⁹ The alkaline earth hydroxides may also play a role. Furthermore, molten salt nuclear reactors may generate various gas phase alkaline earth fluorides or chlorides depending on the anion used in the salt and the nuclear fission products, and thermodynamic information about these materials is needed.^{10,11,12,13,14} In addition, one can obtain information about cohesive energies of solid materials by combining the calculated heats of formation of the gaseous species with the experimental heats of formation of the solid.^{15,16}

Reliable structural, spectroscopic and thermodynamic information about alkali and alkaline earth compounds have previously been predicted using accurate computational chemistry methods^{17,18} based on the Feller-Peterson-Dixon (FPD) composite approach.^{19,20,21} The FPD approach is based on correlated molecular orbital theory using coupled cluster methods starting at the CCSD(T) level^{22,23,24,25} extrapolated to the complete basis set (CBS) limit using the correlation consistent basis sets with additional corrections.^{26,27,28,29,30,31} Additional high level calculations for the alkaline earth hydroxides, oxides, fluorides, and chlorides up to Ca have been previously reported.^{32,33,34,35,36,37,38,39,40} Martin and co-workers³⁷ emphasized the need to include the core electrons in the correlation calculations. Recently, Neese and co-workers⁴¹ have reported results at the CCSD(T) and DLPNO-CCSD(T) level for SrF₂, SrCl₂, BaF₂, BaCl₂,

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3 and BaO. They calculated a range of reaction energetics and compared them to experimental
4 values and also emphasized the need to correlate the outer core electrons. In addition,
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8 The recent design of systematically convergent, correlation consistent basis sets for the
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10 third, fourth and fifth row main group and transition elements using relativistic effective core
11 potentials^{42,43,44,45,46} has been essential to the application of highly accurate correlation methods.
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13 With the new basis sets developed by Hill, Peterson, and co-workers^{47,48} for M = Sr, Ba and Ra,
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15 we can expand our predictions of the thermodynamic properties of the alkaline earth metals.
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17 Herein, we report the properties of M = Sr, Ba, and Ra halides (chlorides and fluorides), oxides
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19 and hydroxides.
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24 **Computational Methods**

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26 We used the coupled-cluster method at the CCSD(T) level including core-valence (CV)
27 correlation corrections with the aug-cc-pVnZ (H)/aug-cc-pwCVnZ (O, F, Cl)/aug-cc-pwCVnZ-
28 PP (Sr, Ba, Ra) basis sets for $n = D, T, Q$ and 5 (abbreviated as awCVnZ) to predict the structural
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30 characteristics and thermodynamic properties of the alkaline earth compounds for M = Sr, Ba,
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32 and Ra fluorides, chlorides, oxides and hydroxides.^{26,27,47,49} The 28 electrons in the
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34 1s2s2p3s3p3d orbitals of Sr, the 46 electrons in the 1s2s2p3s3p3d4s4p4d orbitals of Ba, and the
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36 78 electrons in the 1s through 5d orbitals of Ra are replaced by relativistic energy-consistent
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38 pseudopotentials (PPs).⁵⁰ Equilibrium geometries were optimized at the CCSD(T)(CV)/awCVnZ
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40 level with $n = D$ and T , except for the diatomic compounds which were optimized with $n = D, T$
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42 and Q . The CCSD(T) total energies were extrapolated to the CBS limit by using Eq. 1^{51,52} for
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49 basis sets with $n = 4$ and 5 (awCVQZ and awCV5Z)

$$51 \quad E(n) = E_{\text{CBS}} + A/[n + 0.5]^4 \quad (1)$$

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We label the values obtained from Eq. 1 as CBS-Q5. Alternative extrapolated values using a mixed Gaussian/exponential (Eq. 2) for $n=2-4$.⁵³

$$E(n) = E_{\text{CBS}} + B \exp[-(n - 1)] + C \exp[-(n - 1)^2] \quad (2)$$

are given in the Supporting Information.

The harmonic frequencies (ω_e) and anharmonic constants ($\omega_e x_e$) of the diatomic molecules were obtained at the CCSD(T)/awCVQZ level using a 7-point Dunham expansion.^{54,55}

Harmonic vibrational frequencies for the remaining alkaline earth compounds were calculated at the CCSD(T)/awCVTZ level. The anharmonic corrections^{56,57,58} of the closed shell polyatomic molecules were calculated via 2nd-order vibrational perturbation theory at the MP2^{59,60}/awCVTZ/wCVTZ-PP(Sr,Ba,Ra) level using Gaussian09 (Supporting Information).⁶¹

For the MOH compounds, the anharmonic corrections were obtained from analytical fits (polynomials in simple displacement coordinates) to the near-equilibrium potential energy surfaces (defined by 50 symmetry-unique geometries) at the MP2/awCVTZ/wCVTZ-PP(Sr,Ba,Ra) level using Molpro^{62,63} and the SurfIt program.⁶⁴ The appropriate frequencies were used in the zero point energy (ZPE) corrections to the total atomization energy.

Total atomization energies (TAEs or ΣD_0) at 0 K were calculated from the following expression (Eq. 3) with ΔE referring to the difference between the molecule (reactant) and the atomic products for each energy component:

$$\Sigma D_0 = \Delta E_{\text{CBS}} + \Delta E_{\text{rel}} + \Delta E_{\text{ZPE}} + \Delta E_{\text{SO}} \quad (3)$$

Additional corrections to the CCSD(T)/CBS energy (ΔE_{CBS}) are necessary to reach chemical accuracy (± 1 kcal/mol). Scalar relativistic corrections for light elements together with corrections for the PP approximation, ΔE_{rel} , were obtained using the 2nd or 3rd order Douglas-Kroll-Hess (DKH) Hamiltonian at the CCSD(T)/aug-cc-pwCVTZ-DK^{48,65} level of theory (abbreviated as

awCVnZ-DK). The atomic spin-orbit corrections, $\Delta E_{\text{SO}} = \{\sum_J[(2J + 1) \cdot E(J)]\} / [\sum_J(2J + 1)]$, were calculated from the experimental values for the ground states of the atoms using Moore's tables⁶⁶ ($\Delta E_{\text{SO}}(\text{O}) = -0.22$, $\Delta E_{\text{SO}}(\text{F}) = -0.39$, $\Delta E_{\text{SO}}(\text{Cl}) = -0.84$ kcal/mol and 0 kcal/mol for H, Sr, Ba and Ra).

Heats of formation at 0 K were calculated by combining our computed ΣD_0 values with the known enthalpies of formation at 0 K for the elements⁶⁷ [$\Delta H_{\text{f},0\text{K}}(\text{O}) = 58.98 \pm 0.02$, $\Delta H_{\text{f},0\text{K}}(\text{F}) = 18.47 \pm 0.07$, $\Delta H_{\text{f},0\text{K}}(\text{Cl}) = 28.59$, $\Delta H_{\text{f},0\text{K}}(\text{H}) = 51.63$, $\Delta H_{\text{f},0\text{K}}(\text{Sr}) = 39.3 \pm 0.4$, and $\Delta H_{\text{f},0\text{K}}(\text{Ba}) = 43.0 \pm 1.2$ kcal/mol]. Two values for $\Delta H_{\text{f},0\text{K}}(\text{Ra})$ of 36.35 kcal/mol⁶⁸ and 38.95 ± 2.0 kcal/mol⁶⁹ have been reported. Since we cannot distinguish which one is better without reliable data for other Ra containing compounds determined independently of this gas phase value, we report results using both atomic heats of formation. Heats of formation at 298 K were calculated by following the procedures outlined by Curtiss et al.⁷⁰

The CCSD(T) calculations were performed with the MOLPRO 2012.1 program package.^{62,63} The open-shell calculations were done with the R/UCCSD(T) approach where a restricted open shell Hartree-Fock (ROHF) calculation was initially performed and the spin constraint was then relaxed in the coupled cluster calculation.^{24,71,72,73} The calculations were mainly performed on Linux clusters at The University of Alabama.

Results and Discussion

Geometries The optimized geometries of the diatomic Sr, Ba and Ra compounds are reported in Table 1 and compared to the available experimental values. The M-A bond distances of the diatomics where M = Sr, Ba or Ra and A = O, Cl or F are in good agreement with experiment.^{74,75,76,77,78,79,80,81,82,83,84,85} In general, the calculated Sr-O and Ba-O bond distances are longer than experiment by about 0.01 Å suggesting that a similar error is likely for Ra-O,

where the experimental data has not been reported. The Ba-O bond is only slightly longer than the SrO bond and there is a much larger difference between RaO and BaO for the bond distance. The monofluorides and monochlorides exhibit a similar difference of 0.01 Å between the CCSD(T) values and experiment for Sr and Ba. The trends in the M-X bond distances are different from the M-O bond distances as there is an approximately equal spacing between the Sr-F, Ba-F and Ra-F bonds and a similar but larger spacing between the M-Cl bonds.

Table 1. CCSD(T) Calculated and Experimental Bond Distances in Å for the Alkaline Earth Metal Oxides, Monochlorides and Monofluorides.

Molecule	awCVQZ	awCV5Z	awCVQZ-DK ^a	Expt.
SrO ($^1\Sigma^+$)	1.935	1.929	1.927	1.919809 ^{77,78,80,85}
BaO ($^1\Sigma^+$)	1.947	1.943	1.950	1.939630 ^{74,75,77,78,80,81,85}
RaO ($^1\Sigma^+$)	2.061	2.052	2.052	
SrF ($^2\Sigma^+$)	2.085	2.082	2.082	2.07537 ^{84,85}
BaF ($^2\Sigma^+$)	2.172	2.168	2.177	2.163 ^{77,85}
RaF ($^2\Sigma^+$)	2.262	2.256	2.253	
SrCl ($^2\Sigma^+$)	2.588	2.584	2.599	2.576 ^{80,83,84}
BaCl ($^2\Sigma^+$)	2.701	2.694	2.700	2.682765(10)
RaCl ($^2\Sigma^+$)	2.801	2.794	2.802	

^a Using DKH2 for Sr compounds and DKH3 for Ba and Ra compounds. The O and F 1s, and Cl 2s and 2p orbitals have been rotated into the correlated electron space.

Based partially on the diatomic results above, the current predicted geometries for the triatomic dihalides (Table 2) should be more reliable than the estimated values reported in the JANAF Tables.⁶⁷ The values in the JANAF Tables are not directly measured for the isolated molecules but are derived from krypton matrix isolation infrared spectroscopy measurements in combination with a normal coordinate/force field analysis.^{86,87} We now discuss the periodic trends in the bending angle in the Group 2 dihalides. BeF₂ is a linear molecule from both

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3 experiment and theory.^{18,88} MgF₂ is predicted at the CCSD(T)/awCVTZ level¹⁸ to be linear in
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5 contrast to some of the experimental data. Krypton matrix isolation infrared spectroscopy
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7 measurements have been interpreted to show that the molecule is bent with an $\angle\text{FMgF} = 158^\circ$ ⁸⁹
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9 but electron diffraction⁹⁰ and beam deflection measurements⁹¹ suggest a linear structure,
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11 consistent with the CCSD(T) one. The low calculated bending frequency of 154 cm⁻¹ suggests
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13 that the Kr matrix is causing a bent structure. Hassett and Marsden⁴⁰ examined the effect of the
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15 basis set and correlation level on the bending frequency for linear MgF₂ and found modest
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17 effects. CaF₂ is predicted¹⁸ to have a bent structure with $\angle\text{FCaF} = 157^\circ$, consistent with the
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19 experimental result that CaF₂ has a permanent electric dipole moment.^{88,92} As found for MgF₂,
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21 the experimental $\angle\text{FCaF}$ angle of $135 \pm 7^\circ$ derived from a Kr matrix isolation experiment is 20°
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23 smaller than our calculated value.⁸⁶ Hassett and Marsden⁹³ examined the effect of the basis set
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25 on the angle for CaF₂ at the Hartree-Fock level and found that large d-orbital basis sets are
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27 needed to find a bent structure. Kaupp et al.⁹⁴ predicted that CaF₂ is bent with a bond angle of
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29 157.5° at the CISD+Q (configuration interaction single and doubles with the Davidson
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31 correction) level with a 6s6p5d1f valence basis set with a pseudopotential on the Ca. The trend in
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33 the difluorides being bent beginning at CaF₂ continues for the heavier Group 2 elements with the
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35 bond angle decreasing from Sr to Ra, with a much smaller difference between Ba and Ra than
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37 between Sr and Ba. Kaupp et al.⁹⁴ predict SrF₂ and BaF₂ to be bent with bond angles of 138.8°
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39 and 123.0° at the level given above consistent with our CCSD(T) results.
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47 BeCl₂, MgCl₂, and CaCl₂ are all predicted¹⁸ to be linear molecules in agreement with
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49 experiment.^{67,95,96} and the results of Kaupp et al.⁹⁴ at the CISD+Q level. The potential energy
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51 surface for bending in SrCl₂ is very flat and the linear structure is only 0.04 kcal/mol above the
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53 structure with an angle of 160°. This leads to a very anharmonic bend with a very low bending
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frequency of 7 cm^{-1} as compared to a harmonic value of 26 cm^{-1} . Hargittai and co-workers⁹⁷ have studied SrCl_2 in detail experimentally using high temperature (1500 K) electron diffraction and computationally at the MP2 level including all electrons with large basis sets. They also checked their MP2 results with limited CCSD(T) calculations. They describe SrCl_2 as being quasilinear and having a complex bending potential. They also showed that the angle is very temperature dependent. They predict the molecule to be bent with a bond angle between 155° and 160° . They predict a harmonic bending frequency of 25.5 cm^{-1} as predicted by us with a barrier to linearity of 0.1 kcal/mol . They solved for the frequencies in a one-dimensional approximation but did not report the values for the bend except to note that the results show splitting due to the presence of the small barrier and that the ZPE is quite low. All of the results for SrCl_2 point to a very low frequency bend with a contribution to the ZPE of $< 0.05\text{ kcal/mol}$. The bond angles for BaCl_2 and RaCl_2 are significantly smaller, both near 130° and the molecules are clearly bent. The bond angles for the chlorides are larger than for the fluorides. The CISD+Q results of Kaupp et al.⁹⁴ are consistent with our results for the bond angles of SrCl_2 and BaCl_2 .

Table 2. Calculated [CCSD(T)/awCVTZ] and Experimental Bond Distances and Angles for the Alkaline Earth Fluorides and Chlorides.

Molecule	CCSD(T) M-X (Å)	Expt. ⁶⁷ M-X (Å)	CCSD(T) $\angle\text{XMX}$ (°)	Expt. ⁶⁷ $\angle\text{XMX}$ (°)
SrF_2 (${}^1\text{A}_1, \text{C}_{2v}$)	2.139	2.20 ± 0.03	136.4	108
BaF_2 (${}^1\text{A}_1, \text{C}_{2v}$)	2.246	2.32 ± 0.03	123.1	[95]
RaF_2 (${}^1\text{A}_1, \text{C}_{2v}$)	2.321		120.7	
SrCl_2 (${}^1\text{A}_1, \text{C}_{2v}$)	2.635	2.67 ± 0.03 2.625 ± 0.010^a 2.606 ± 0.008^a	161.4	120 ± 20 142.4 ± 4.0^a
BaCl_2 (${}^1\text{A}_1, \text{C}_{2v}$)	2.761	2.82 ± 0.03	133.5	100 ± 20
RaCl_2 (${}^1\text{A}_1, \text{C}_{2v}$)	2.845		130.4	

^a Ref. 97. First bond distance is measured value at 1500 K. Second bond distance is thermally corrected value. The angle is the value at 1500 K.

The geometry parameters for the mono and dihydroxides are reported in Table 3. The triatomic monohydroxides are linear.^{98,99,100,101,102} The M-O bond distances (Table 3) follow the same patterns as for the fluorides. The bond distances are in reasonable agreement with the values reported in the JANAF Tables.⁶⁷ The dihydroxides are bent with larger OMO bond angles than found for the difluorides but smaller than for the dichlorides. The M-OH bond angles for the dihydroxides are no longer linear and deviate by about 5 - 10° from linearity. The bond distance down the column increases from Sr to Ra following the pattern of the difluorides.

Table 3. Calculated [CCSD(T)/awCVTZ] and Experimental Bond Distances and Angles for the Alkaline Earths Hydroxides.

Molecule	CCSD(T) M-O (Å)	CCSD(T) O-H (Å)	CCSD(T) ∠OMO (°)	CCSD(T) ∠MOH (°)	Expt. ⁶⁷ M-O (Å)
SrOH ($^2\Sigma^+$, $C_{\infty v}$)	2.118	0.955		180.0	2.111
BaOH ($^2\Sigma^+$, $C_{\infty v}$)	2.220	0.957		180.0	2.201
RaOH ($^2\Sigma^+$, $C_{\infty v}$)	2.306	0.957		180.0	
Sr(OH) ₂ (1A_1 , C_{2v})	2.176	0.955	151.0	174.5	
Ba(OH) ₂ (1A_1 , C_{2v})	2.291	0.957	128.9	169.8	
Ra(OH) ₂ (1A_1 , C_{2v})	2.365	0.957	125.6	169.7	

Vibrational Frequencies The vibrational frequencies for the diatomics are given in Table 4. The frequencies for SrO and BaO are less than experiment by 5-15 cm⁻¹ for ω_e due to the predicted bond lengths being longer than the experimental values. The values for $\omega_e x_e$ are larger than experiment by about 1 cm⁻¹ for SrO^{77,78,80} and essentially identical to experiment for BaO.^{74,75,77,78,80,81} The value for $\omega_e x_e$ for RaO is predicted to be larger than for BaO.

Table 4. CCSD(T) Calculated and Experimental Harmonic Frequencies (ω_e) and Anharmonicities ($\omega_e x_e$) in cm^{-1} for the Alkaline Earth Metal Oxides, Monochlorides and Monofluorides.

Molecule	ω_e				$\omega_e x_e$			
	awCVQZ	awCV5Z	awCVQZ-DK ^{a,b}	Expt.	awCVQZ	awCV5Z	awCVQZ-DK ^{a,b}	Expt.
SrO ($^1\Sigma^+$)	639.4	647.0	646.0	653.49 ^{77,78,80}	5.00	4.58	4.64	3.96
BaO ($^1\Sigma^+$)	660.3	663.3	666.0	669.76 ^{74,75,77,78,80,81}	1.98	1.92	1.99	2.028
RaO ($^1\Sigma^+$)	596.5	603.2	611.9		2.98	2.58	2.61	
SrF ($^2\Sigma^+$)	499.5	500.6	500.6	502.4 ⁸⁴	2.17	2.19	2.47	2.27
BaF ($^2\Sigma^+$)	463.4	465.9	465.1	468.9 ⁷⁷	1.84	1.84	1.86	1.79
RaF ($^2\Sigma^+$)	432.8	435.0	434.6		1.65	1.70	1.51	
SrCl ($^2\Sigma^+$)	300.8	301.4	290.0	302.3 ^{80,83,84}	1.10	0.96	1.30	0.95
BaCl ($^2\Sigma^+$)	276.3	278.4	276.9	279.3 ⁸⁵	0.79	0.84	0.96	0.89
RaCl ($^2\Sigma^+$)	253.6	254.5	250.5		0.70	0.73	0.73	

^a Using DKH2 for Sr compounds and DKH3 for Ba and Ra compounds.

^b The O and F 1s, and Cl 2s and 2p orbitals have been rotated into the correlated electron space.

Table 5. Calculated [CCSD(T)/awCVTZ] and Experimental Vibrational Frequencies in cm^{-1} for the Alkaline Earth Dihalides.

Molecule	Symmetry	Calculated CCSD(T)/awCVTZ	Anharm corrected ^a	Expt. ⁶⁷
SrF ₂ (¹ A ₁)	v ₁ (sym stretch - b ₂)	478.3	473.7	443
	v ₂ (asym stretch - a ₁)	469.9	465.2	442
	v ₃ (bending - a ₁)	75.9	72.7	82
BaF ₂ (¹ A ₁)	v ₁ (sym stretch - a ₁)	437.4	433.7	413
	v ₂ (asym stretch - b ₂)	418.5	414.8	390
	v ₃ (bending - a ₁)	88.0	86.3	[64]
RaF ₂ (¹ A ₁)	v ₁ (sym stretch - a ₁)	418.4	415.2	
	v ₂ (asym stretch - b ₂)	397.4	394.3	
	v ₃ (bending - a ₁)	79.8	78.0	
SrCl ₂ (¹ A ₁) ^b	v ₁ (asym stretch - b ₂)	313.0	310.9	300
	v ₂ (sym stretch - a ₁)	262.7	260.1	270
	v ₃ (bending - a ₁)	26.1	7.7	44
BaCl ₂ (¹ A ₁)	v ₁ (asym stretch - b ₂)	259.7	258.8	265
	v ₂ (sym stretch - a ₁)	270.0	267.2	255
	v ₃ (bending - a ₁)	41.1	39.7	[36]
RaCl ₂ (¹ A ₁)	v ₁ (asym stretch - b ₂)	248.0	247.2	
	v ₂ (sym stretch - a ₁)	247.6	246.9	
	v ₃ (bending - a ₁)	37.7	37.8	

^a CCSD(T)/awCVTZ with anharmonic corrections from MP2/awCVTZ/wCVTZ-PP(Sr,Ba,Ra).

^b The frequencies for SrCl₂ were evaluated at 160°.

The values for ω_e are within about 5 cm^{-1} of experiment for diatomic M-F, and the M-F values are in better agreement with experiment^{77,84} than for diatomic M-O. Again, the M-F values are lower than experiment consistent with the predicted bond lengths being too long. For the diatomic chlorides, all of the results are within 5 cm^{-1} of experiment^{80,83,84,85} except for the awCVQZ-DK result for SrCl where the difference is about 10 cm^{-1} . The estimated values in the JANAF Tables⁶⁷ are consistent with our calculated values including anharmonic corrections for the difluorides and dichlorides (Table 5). SrCl₂ is discussed in more detail above.

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3 For the monohydroxides, the calculated Sr-O stretch for SrOH is essentially the same as
4 the reported experimental value and the SrOH bend is $\sim 12 \text{ cm}^{-1}$ above the experimental
5 value.^{98,99} For BaOH, the calculated Ba-O stretch is in within 10 cm^{-1} of experiment and the
6 calculated bend is too high by about 20 cm^{-1} .¹⁰⁰ For Ba(OH)₂, the two calculated OH stretches
7 are within better than 10 cm^{-1} of experiment.¹⁰² In this case, the agreement with experiment for
8 the two Ba-O stretches is not as good suggesting a possible role for matrix effects.
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17 **Heats of Formation** As the TAEs are the prime component of the heats of formation predictions,
18 these are discussed first. The CBS-DTQ TAEs (Supporting Information) obtained with Eq. 2 are
19 mostly within 0.5 kcal/mol of the CBS-Q5 values calculated with Eq. 1. The components for the
20 total CBS-Q5 atomization energies are given in Table 7 and the heats of formation are given in
21 Table 8. The comparison to experiment for the diatomic dissociation energies is given below in
22 the discussion of the bond energies. The T₁ diagnostic values¹⁰³ (Supporting Information) show
23 that the wavefunctions are dominated by a single configuration. The largest T₁ values are for the
24 monoxides. We found that there are no doubles amplitude values above 0.05 for any of these
25 monoxides, so they are truly dominated by a single configuration. In our previous work on BeO
26 and MgO,¹⁸ we found that there was one doubles amplitude above 0.05 for BeO and MgO with
27 that for MgO being the largest. For these two molecules, calculations were performed up to
28 CCSDTQ and the correction was found to be 0.98 kcal/mol to the total atomization energy. Thus
29 the corrections for higher order excitations will be smaller than this value for SrO, BaO, and RaO
30 as they have even less multi-reference character.
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49 The only additional contribution to the total atomization energy to be discussed is that of
50 ΔE_{rel} which includes a pseudopotential correction and scalar relativistic corrections for O, F, and
51 Cl. The values of this correction range from -1.9 to +2.3 kcal/mol. The largest ΔE_{rel} corrections
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Table 6. Calculated and Experimental Vibrational Frequencies in cm^{-1} for the Alkaline Earth Hydroxides.

Molecule	Symmetry	Calculated ^a	Anharm corrected ^b	Expt.
SrOH($^2\Sigma^+$)	ν_1 (O-H stretch - σ)	3935.7	3766.9	3766 ± 10^{98}
	ν_2 (Sr-O stretch - σ)	536.6	523.6	526.99^{99}
	ν_3 (Sr-O-H bend - π)	400.6	375.3	363.69^{99}
BaOH($^2\Sigma^+$)	ν_1 (O-H stretch - σ)	3904.0	3734.9	
	ν_2 (Ba-O stretch - σ)	493.6	483.1	494.4 ± 0.8^{100}
	ν_3 (Ba-O-H bend - π)	379.9	363.7	341.6 ± 0.6^{100}
RaOH($^2\Sigma^+$)	ν_1 (O-H stretch - σ)	3903.7	3733.7	
	ν_2 (Ba-O stretch - σ)	461.5	451.6	
	ν_3 (Ba-O-H bend - π)	378.7	366.5	
Sr(OH) ₂ (1A_1)	ν_1 (O-H sym stretch - b_2)	3931.8	3763.7	
	ν_2 (O-H asym stretch - a_1)	3930.7	3762.7	
	ν_3 (O-Sr-O sym stretch - b_2)	508.7	496.4	
	ν_4 (O-Sr-O asym stretch - a_1)	500.3	489.0	
	ν_5 (H-O out-of-plane-wag - a_2)	454.6	419.2	
	ν_6 (H-O out-of-plane-twist - b_1)	449.7	418.6	
	ν_7 (H-O in-plane-wag - a_1)	444.8	415.3	
	ν_8 (H-O in-plane-twist - b_2)	440.2	405.2	
	ν_9 (O-Sr-O bend - a_1)	44.8	43.0	
Ba(OH) ₂ (1A_1)	ν_1 (O-H sym stretch - b_2)	3897.4	3725.8	3723^{102}
	ν_2 (O-H asym stretch - a_1)	3897.0	3725.3	3718^{102}
	ν_3 (O-Ba-O sym stretch - a_1)	469.7	387.4	410^{102}
	ν_4 (O-Ba-O asym stretch - b_2)	442.2	374.7	422.8^{102}
	ν_5 (H-O out-of-plane-wag - a_2)	425.0	389.8	
	ν_6 (H-O out-of-plane-twist - b_1)	422.1	359.2	
	ν_7 (H-O in-plane-wag - a_1)	405.3	317.9	
	ν_8 (H-O in-plane-twist - b_2)	384.9	370.3	
	ν_9 (O-Ba-O bend - a_1)	72.2	76.4	
Ra(OH) ₂ (1A_1)	ν_1 (O-H sym stretch - b_2)	3898.0	3730.7	
	ν_2 (O-H asym stretch - a_1)	3897.8	3730.7	
	ν_3 (O-Ra-O sym stretch - a_1)	451.6	442.0	
	ν_4 (O-Ra-O asym stretch - b_2)	422.4	402.4	
	ν_5 (H-O out-of-plane-wag - a_2)	416.0	397.8	
	ν_6 (H-O out-of-plane-twist - b_1)	415.6	404.7	

	$\nu_7(\text{H-O in-plane-wag} - a_1)$	399.5	375.3	
	$\nu_8(\text{H-O in-plane-twist} - b_2)$	378.6	357.9	
	$\nu_9(\text{O-Ra-O bend} - a_1)$	67.1	67.3	

^a CCSD(T)/awCVTZ. ^b CCSD(T)/awCVTZ with Anharmonic correction from MP2/awCVTZ /wCVTZ-PP(Sr,Ba,Ra) and UMP2/awCVTZ /wCVTZ-PP(Sr,Ba,Ra) for open shells.

are found for compounds containing Ra. For all atoms, the oxides show the largest corrections with that for BaO being -1.9 kcal/mol and that for RaO being +2.2 kcal/mol. The value for SrO is 1.3 kcal/mol. We note that the only other two large corrections are for RaF of 0.8 kcal/mol and for RaF₂ of 1.1 kcal/mol.

The experimental heats of formation and the corresponding bond dissociation energies of SrO and BaO have been previously reviewed.⁸ For SrO, the heat of formation is within the experimental^{8,67} error bars of ± 4 kcal/mol and very similar to the value derived in a review from spectroscopic measurements.⁸ For BaO, the calculated heat of formation is in very good agreement with the experiment; within the ± 1.9 kcal/mol error bar for the more negative experimental value,⁶⁷ and is significantly more negative than the average value given in a review.⁸ Thus, we suggest that the experimental value for the heat of formation from thermodynamic Knudsen cell measurements of BaO be further examined, and we confirm the value for SrO derived from the spectroscopic information. The heats of formation of SrF and BaF are in excellent agreement with experiment⁶⁷ considering the ± 2 kcal/mol error bars from experiment. The same is true for SrCl and BaCl and we note that the BaCl experimental⁶⁷ error bar is larger at ± 3 kcal/mol.

For the difluorides, the calculated heats of formation are significantly more negative than the experimental values⁶⁷ which have small error bars of ± 1 kcal/mol suggesting an issue with

the experimental values. We note that the heats of formation of the dichlorides are closer to experiment, with BaCl₂ just outside of the experimental⁶⁷ ±4 kcal/mol error bars.

Table 7. CCSD(T) Calculated and Experimental Total Atomization Energies at 0 K in kcal/mol.

Molecule	ΔE_{CBS}^a	ΔE_{rel}^b	ΔE_{ZPE}^c	ΔE_{SO}^d	$\Sigma D_{0,0\text{K}}$	
					CCSD(T) ^e	Expt.
SrO (¹ Σ ⁺)	98.62	1.30	-0.92	-0.22	98.79	101.9±1.5 (298 K) ¹⁰⁵ 115.53 ⁸⁵
BaO (¹ Σ ⁺)	134.20	-1.89	-0.95	-0.22	131.15	134.3±3.2 (298 K) ¹⁰⁵ 133.52 ⁸⁵
RaO (¹ Σ ⁺)	106.44	2.22	-0.85	-0.22	107.58	
SrF (² Σ ⁺)	128.48	0.02	-0.72	-0.39	127.40	128.67 ⁸⁵
BaF (² Σ ⁺)	138.81	-0.25	-0.66	-0.39	137.50	139.51 ⁸⁵
RaF (² Σ ⁺)	128.01	0.82	-0.62	-0.39	127.82	
SrCl (² Σ ⁺)	99.97	-0.10	-0.43	-0.84	98.60	97.8 (298 K) ¹⁰⁵ 95.92 ⁸⁵
BaCl (² Σ ⁺)	109.24	0.16	-0.40	-0.84	108.16	104.92 ⁸⁵
RaCl (² Σ ⁺)	99.97	0.22	-0.36	-0.84	98.99	82±18 ⁶⁹
SrF ₂ (¹ A ₁)	266.47	-0.25	-1.45	-0.78	264.98	
BaF ₂ (¹ A ₁)	279.59	-0.03	-1.35	-0.78	277.43	
RaF ₂ (¹ A ₁)	261.84	1.08	-1.28	-0.78	260.86	
SrCl ₂ (¹ Σ _g)	214.74	-0.21	-0.80	-1.68	212.05	
BaCl ₂ (¹ A ₁)	226.42	0.13	-0.76	-1.68	224.11	
RaCl ₂ (¹ A ₁)	210.68	0.15	-0.71	-1.68	208.44	
SrOH (² Σ ⁺)	203.75	-0.16	-7.42	-0.22	195.94	
BaOH (² Σ ⁺)	213.66	-0.10	-7.27	-0.22	206.07	
RaOH (² Σ ⁺)	202.28	0.63	-7.23	-0.22	195.47	
Sr(OH) ₂ (¹ A ₁)	417.71	-0.68	-15.02	-0.44	401.57	
Ba(OH) ₂ (¹ A ₁)	428.29	-0.02	-14.48	-0.44	413.34	
Ra(OH) ₂ (¹ A ₁)	410.25	0.61	-14.55	-0.44	395.87	

^a Extrapolated CCSD(T)/awCVnZ energies with $n = Q$ and 5 using Eq. 1. ^b $\Delta E_{\text{rel}} = \Delta E_{\text{awCVTZ-DK}} - \Delta E_{\text{awCVTZ}}$. ^c CCSD(T)/awCVnZ, $n = Q$ for diatomics and $n = T$ for the rest including anharmonic corrections from MP2/awCVTZ/wCVTZ-PP(Sr,Ba,Ra) (see supporting Information). ^d Experimental atomic spin-orbit corrections (-0.22, -0.84 and -0.39 kcal/mol for O, Cl and F and 0 kcal/mol for H, Sr, Ba and Ra); Reference 66. ^e Eq. 3: $\Sigma D_0 = \Delta E_{\text{CBS}} + \Delta E_{\text{rel}} + \Delta E_{\text{ZPE}} + \Delta E_{\text{SO}}$.

Table 8. CCSD(T) Calculated and Experimental Heats of Formation at 0 K and 298 K inkcal/mol.^a

Molecule	$\Delta H_{f,0K}$		$\Delta H_{f,298K}$	
	CCSD(T)	Expt. ⁶⁷	CCSD(T)	Expt. ⁶⁷
SrO ($^1\Sigma^+$)	-0.5	-2.8 ± 4.0	-1.0	-3.2 ± 4.0 0.4 ± 3.6^8
BaO ($^1\Sigma^+$)	-29.2	-29.1 ± 1.9	-29.7	-29.6 ± 1.9 -26.9 ± 1.2^8
RaO ($^1\Sigma^+$)	-12.3/-9.7		-12.8/-10.2	
SrF ($^2\Sigma^+$)	-69.6	-70.0 ± 2.0	-70.0	-70.4 ± 2.0
BaF ($^2\Sigma^+$)	-76.0	-76.5 ± 2.0	-76.5	-77.0 ± 2.0
RaF ($^2\Sigma^+$)	-73.0/-70.4		-73.4/-70.8	
SrCl ($^2\Sigma^+$)	-30.7	-29.3 ± 2.0	-31.0	-29.6 ± 2.0
BaCl ($^2\Sigma^+$)	-36.6	-33.6 ± 3.0	-37.0	-34.0 ± 3.0
RaCl ($^2\Sigma^+$)	-34.0/-31.4		-34.4/-31.8	
SrF ₂ (1A_1)	-187.7	-182.6 ± 1.0	-188.3	-183.1 ± 1.0
BaF ₂ (1A_1)	-197.5	-191.6 ± 1.5	-198.1	-192.1 ± 1.5
RaF ₂ (1A_1)	-187.6/-185.0		-188.1/-185.5	
SrCl ₂ ($^1\Sigma_g$)	-115.6	-112.8 ± 1.5	-116.7	-113.1 ± 1.5
BaCl ₂ (1A_1)	-123.9	-118.9 ± 4.0	-124.3	-119.2 ± 4.0
RaCl ₂ (1A_1)	-114.9/-112.3		-115.2/-112.6	
SrOH ($^2\Sigma^+$)	-46.0	-48.11 ± 5.0	-47.0	-49.1 ± 5.0
BaOH ($^2\Sigma^+$)	-52.5	-53 ± 7	-53.4	-54 ± 7
RaOH ($^2\Sigma^+$)	-48.5/-45.9		-49.5/-46.9	
Sr(OH) ₂ (1A_1)	-141.0	-141 ± 10	-143.6	-142 ± 10
Ba(OH) ₂ (1A_1)	-149.1	-148 ± 9	-151.8	-150 ± 9
Ra(OH) ₂ (1A_1)	-138.3/-135.7		-140.0/-137.4	

^a The Ra values are given in the order of using the heat of formation of Ra, $\Delta H_{f,0K}(\text{Ra}) = 36.35$ kcal/mol from Ref. 68 and after the slash $\Delta H_{f,0K}(\text{Ra}) = 38.95 \pm 2.0$ kcal/mol from Ref 69.

For the monohydroxides, the calculated heats of formation are within the range of the rather large experimental⁶⁷ error bars of up to ± 7 kcal/mol, with the calculated values within 1 to

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3 2 kcal/mol of experiment. For the dihydroxides, the calculated values are in excellent agreement
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5 with experiment⁶⁷ even though there are very large error bars.
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7 Neese and co-workers⁴¹ calculated the energies of reaction 4 where M = Sr, Ba and X =
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9 F, Cl at the CCSD(T) and DLPNO-CCSD(T) levels of theory. We can also calculate these values
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11 from the current heats of formation
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16 using the atomic heats of formation for the atoms and the heats of formation of F₂ and Cl₂ which
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18 are 0.0 kcal/mol at this level of theory in agreement with experiment.¹⁰⁴ The calculated values at
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20 298 K from Neese and co-workers⁴¹ (-229.0, -242.9, -156.9, and -168.8 kcal/mol for SrF₂, BaF₂,
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22 SrCl₂, and BaCl₂, respectively) are within 2.5 kcal/mol of our values (-227.5, -240.9, -155.9, and
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24 -167.1 kcal/mol for SrF₂, BaF₂, SrCl₂, and BaCl₂, respectively). This is reasonable agreement
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26 considering that they used different geometries and frequencies obtained from density functional
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28 theory calculation and we have included additional relativistic corrections. The agreement
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30 between the two sets of calculations confirms the assessment that there are issues with the
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32 experimental heats of formation of SrF₂ and BaF₂.
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37 **Bond Dissociation Energies (BDEs)** The BDEs^{85,105,106} and heats of formation are obviously
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39 linked for the diatomics. Less reliable BDEs for the MO diatomics have been reported in the
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41 literature.¹⁰⁷ The calculated BDEs are reported in Table 9. The calculated values for SrO and
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43 BaO are smaller than either of the experimental measurements.^{85,105} The SrO BDE is closer to
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45 the value¹⁰⁵ of 101.9 kcal/mol; the BaO BDE is within the experimental error bars and closer to
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47 the experimental value of 133.5 kcal/mol. A crossed beam chemiluminescence study of the
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49 reaction of the alkaline earths with ClO₂ gave lower limit BDEs.¹⁰⁸ The calculated BDE for SrO
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51 is significantly below the chemiluminescence value but the calculated BDE for BaO is in good
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Table 9. CCSD(T) Calculated and Experimental Bond Dissociation Energies in kcal/mol at 0 K.

Molecule	Product	CCSD(T)	Expt. ¹⁰⁵
SrO (¹ Σ ⁺)	Sr + O	98.8	101.9 ± 1.5, 115.5, ⁸⁵ ≥ 107.7 ± 3.5 ¹⁰⁸
BaO (¹ Σ ⁺)	Ba + O	131.1	134.3 ± 3.2, 133.5, ⁸⁵ ≥ 133.6 ± 3.5, ¹⁰⁸ 133.5 ± 1.3 ¹⁰⁹
RaO (¹ Σ ⁺)	Ra + O	107.6	
SrF (² Σ ⁺)	Sr + F	127.4	129.5 ± 1.6, 126.8, 128.7 ⁸⁵
BaF (² Σ ⁺)	Ba + F	137.5	140.3 ± 1.6, 136.6, 138.8, 139.5 ⁸⁵
RaF (² Σ ⁺)	Ra + F	127.8	
SrCl (² Σ ⁺)	Sr + Cl	98.6	97.8, 95.6 ± 1.6, ¹⁰⁶ 95.92 ⁸⁵
BaCl (² Σ ⁺)	Ba + Cl	108.2	104.2 ± 2, 105.8, 106.8 ± 2.2, ¹⁰⁶ 104.9 ⁸⁵
RaCl (² Σ ⁺)	Ra + Cl	99.0	82 ± 18 ⁶⁹
SrF ₂ (¹ A ₁)	SrF + F	136.6	131.7
BaF ₂ (¹ A ₁)	BaF + F	139.9	134.1
RaF ₂ (¹ A ₁)	RaF + F	133.0	
SrCl ₂ (¹ Σ _g)	SrCl + Cl	113.5	112.5
BaCl ₂ (¹ A ₁)	BaCl + Cl	116.0	114.2
RaCl ₂ (¹ A ₁)	RaCl + Cl	109.4	
SrOH (² Σ ⁺)	Sr + OH	94.2	97.2, 92 ± 4, 95 ± 3 ¹⁰⁶
	SrO + H	97.2	98.0
BaOH (² Σ ⁺)	Ba + OH	104.4	107, 107 ± 4, 105.8, 111 ± 14 ¹⁰⁶
	BaO + H	74.9	76.6
RaOH (² Σ ⁺)	Ra + OH	93.8	
	RaO + H	87.9	
Sr(OH) ₂ (¹ A ₁)	SrOH + OH	103.9	102.0
Ba(OH) ₂ (¹ A ₁)	BaOH + OH	105.6	99, 104.5
Ra(OH) ₂ (¹ A ₁)	RaOH + OH	98.7	

agreement, within the experimental error bars. Another chemiluminescent reaction study¹⁰⁹ of the reaction Ba + CO₂ gave a BDE value with smaller error bars in excellent agreement with our calculated value. The experimental BDEs from these experiments were not included in the evaluation⁸ of the heat of formation of BaO but they do confirm our calculated value for

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3 $\Delta H_f(\text{BaO})$, suggesting that there is a consistent error in the Knudsen cell measurements.
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5 However, the calculated value for the SrO BDE is in excellent agreement with the average
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7 spectroscopic value from an extensive review,⁸ which suggests an issue with the
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9 chemiluminescence values for SrO. We note that there is a significant increase in the BDE from
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11 SrO to BaO followed by a decrease from BaO to RaO. The BDE for RaO is larger than that for
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13 SrO.
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17 The calculated BDEs for Sr-F and Ba-F are in agreement with the available experimental
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19 values^{85,105} given the error bars of the latter quantities. The M-F BDE increases from Sr-F to Ba-
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21 F and then decreases to Ra-F, just as found for the oxides. The Sr-F and Ra-F BDEs are almost
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23 identical. The M-F BDEs are larger than the M-O BDEs even though we would formally write a
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25 single bond for the M-F and a double bond for the M=O. The BDEs for Sr-F and Ra-F are
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27 substantially larger than those of Sr-O and Ra-O, respectively, and the Ba-F BDE is only slightly
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29 larger than for Ba-O.
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33 The calculated BDEs for Sr-Cl and Ba-Cl are in agreement with experiment^{85,105,106} and
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35 that for Ra-Cl is within the larger error bound of the experimental value.⁶⁹ The M-Cl BDEs
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37 follow the same trend as the M-F BDEs as one goes down the column. The Sr-Cl and Ra-Cl
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39 BDEs are comparable to the corresponding Sr-O and Ra-O BDEs.
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42 The first BDEs for SrF_2 and SrCl_2 are larger than the second value. The values are more
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44 similar to each other than for the monohalides, and the Sr-X and Ba-X dissociation energies are
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46 closer to each other even though the Ba-X values are always the largest. The Ra-X first BDEs are
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48 always the smallest. The first Sr-F BDE is larger than experiment and the first Sr-Cl BDE is in
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50 good agreement with experiment suggesting that the M-F values need to be reevaluated.¹⁰⁵
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3 There are two BDEs to consider for MOH, the M-OH and the MO-H. For SrOH, the O-H
4 BDE is larger than the Sr-OH BDE and this is reversed for BaOH. The change is probably due to
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6 the strength of the BaO BDE. For RaOH, the Ra-OH BDE is larger than the RaO-H BDE. The
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8 M-OH BDEs follow the same trends as the M-F and M-Cl BDEs with the Ba-OH BDE being the
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10 largest and the Sr-OH and Ra-OH BDEs being comparable. The M-OH BDEs are smaller than
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12 the M-F BDEs. For $M(OH)_2$, the first BDE for Sr and Ba are comparable and slightly larger than
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14 that for Ra. In all cases, the first M-OH BDE is larger than the second just as found for the
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16 dihalides. The M-OH and MO-H BDEs for Sr and Ba are in very good agreement with the
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18 experimental values¹⁰⁵ for MOH given the lack of any error bars on the experimental values. In a
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20 similar way, the M-OH BDE for $M(OH)_2$ is also in good agreement with experiment.¹⁰⁵
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26 ***Cohesive energies*** The cohesive energy of a solid^{67,69} is the energy required to convert the solid
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28 into the gas. The cohesive energy is usually applied to metals and is equivalent to the
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30 sublimation energy. All that is required to calculate the cohesive energy are the heat of formation
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32 of the solid and that of the gas phase species. We are interested in vaporizing to the particular
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34 molecular monomer. The cohesive energies for all alkaline earths are reported in Table 10. The
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36 cohesive energy of the oxides decreases from BeO/MgO to BaO and then increases to RaO.
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38 There is a large decrease from SrO to BaO. The difluorides behave in a different manner. There
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40 is a substantial increase from BeF_2 to MgF_2 and the values increase to CaF_2 . The cohesive energy
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42 for SrF_2 is comparable to that for CaF_2 and there is decrease to BaF_2 followed by an increase to
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44 RaF_2 . The decrease for BaF_2 is consistent with the strong bonds in BaF_2 . The chlorides show an
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46 interesting pattern of increasing from a low value of 32 kcal/mol for $BeCl_2$ to a value of ~95
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48 kcal/mol for $RaCl_2$. The dihydroxides show an increase from $Be(OH)_2$ to $Mg(OH)_2$ and the
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Table 10. CCSD(T) Calculated Cohesive Energies in kcal/mol.^a

Molecule	$\Delta H_{f,298K}$ (gas)	$\Delta H_{f,298K}$ (solid)	Cohesive Energy
	CCSD(T)	Expt. ⁶⁷	CCSD(T) - Expt.
BeO	30.1	-145.4	175.5
MgO	32.3	-143.7	176.0
CaO	4.7	-151.8	156.5
SrO	-1.0	-141.5 \pm 0.8	140.5
BaO	-29.7	-131.0 \pm 0.5	101.3
RaO	-12.8/-10.2	-123.0 ⁶⁹	110.2/112.8
BeF ₂	-190.1	-245.4	55.4
MgF ₂	-174.4	-268.7	94.3
CaF ₂	-189.1	-293.0	103.9
SrF ₂	-188.3	-290.9 \pm 0.7	102.6
BaF ₂	-198.1	-288.9 \pm 1.0	90.8
RaF ₂	-188.1/-185.5	-282.4 ⁶⁹	94.3/96.9
BeCl ₂	-86.5	-118.6	32.1
MgCl ₂	-95.1	-153.3	58.2
CaCl ₂	-114.9	-190.2	75.3
SrCl ₂	-116.7	-198.1 \pm 0.6	81.4
BaCl ₂	-124.3	-205.2 \pm 3	80.9
RaCl ₂	-115.2/-112.6	-207.7 ⁶⁹	92.5/95.1
Be(OH) ₂	-150.8	-216.5	65.7
Mg(OH) ₂	-132.8	-221.0	88.2
Ca(OH) ₂	-146.6	-235.7	89.1
Sr(OH) ₂	-143.6	-231.6 \pm 2.2	88.0
Ba(OH) ₂	-151.8	-226.2 \pm 1.5	74.5
Ra(OH) ₂	-140.0/-137.4	-221.2 ⁶⁹	81.2/83.8

^a The Ra values are given in the order using the heat of formation of Ra, $\Delta H_{f,0K}(\text{Ra}) = 36.35$ kcal/mol from Ref. 68 and after the slash $\Delta H_{f,0K}(\text{Ra}) = 38.95 \pm 2.0$ kcal/mol from Ref 69. The gas phase values for Be, Mg, and Ca are from Ref. 18.

values for Mg to Sr are comparable. There is a decrease from Sr to Ba followed by an increase to Ra.

We note that the cohesive energies for the Be compounds are actually quite low with only 32 kcal/mol required for the enthalpy of sublimation for BeCl₂ and only 55 kcal/mol required for

BeF₂. The energy required to sublime MgCl₂ is also low at 58 kcal/mol. Of further interest is the result that the Ra compounds have reasonably large enthalpies of sublimation from 80 to 110 kcal/mol with the lowest being near 81 kcal/mol for Ra(OH)₂.

Fluoride affinity The gas phase fluoride affinity (FA) provides a measure of the Lewis acidity¹¹⁰ and is defined as the negative of the enthalpy of reaction (5).



Addition of an F⁻ to MF₂ leads to a *D*_{3h} MF₃⁻ anion and the M-F bond distances increase by 0.07 to 0.14 Å (Table 11). The smallest M-F bond distance increase is predicted for Mg which has the

Table 11. CCSD(T) Calculated Fluoride Affinities in kcal/mol at 0 K and M-F Bond Distances in Å for all the alkaline earth MF₂ and MF₃⁻.^a

Molecule	FA	CCSD(T)/awCVTZ M-F (Å) in MF ₂	CCSD(T)/awCVTZ M-F (Å) in MF ₃ ^{-b}	Δr(M-F) ^c
BeF ₂ (¹ Σ _g ⁺)	88.1	1.377	1.472	0.095
MgF ₂ (¹ Σ _g ⁺)	91.1	1.742	1.812	0.070
CaF ₂ (¹ A ₁ , C _{2v})	83.7	2.013	2.090	0.077
SrF ₂ (¹ A ₁ , C _{2v})	80.0	2.139	2.238	0.099
BaF ₂ (¹ A ₁ , C _{2v})	71.5	2.246	2.380	0.134
RaF ₂ (¹ A ₁ , C _{2v})	69.9	2.321	2.458	0.137

^a MF₂ for M = Be, Mg and Ca are from Reference 18. ^b All the MF₃⁻ are ¹A₁, *D*_{3h}. ^c Increase in the M-F bond distance on adding F⁻.

highest FA, and the largest M-F increase in the distance is predicted for Ra which has the lowest calculated FA. The trend in the bond distance changes does follow the increase in atomic size of the central atom as one proceeds down the column, excluding Be which has a larger change in the bond distance. The FAs are also given in Table 11 for the MF₂ molecules The fluoride affinities decrease from MgF₂ to RaF₂ consistent with a larger M-F bond distance and less stabilization of the F⁻ by the M(II). The FA for BeF₂ is slightly smaller than that for MgF₂ due to

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3 steric crowding in the former. The FAs show that the difluorides are modestly strong Lewis
4 acids. The FAs are relevant to which species could be formed in molten salt reactors when
5 fluoride is the dominant anion.
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10 **Natural Population Analysis (NPA)** The Natural Population Analysis based on the Natural Bond
11 Orbitals (NBOs)^{111,112} using NBO6^{113,114} (Supporting Information) with wavefunctions
12 calculated at the B3LYP/awCVTZ/wCVTZ-PP(Sr,Ba,Ra) using optimized CCSD(T) geometries
13 was performed using Gaussian09.⁶¹ For the oxides under consideration, the positive charge on
14 the alkaline earth is about 0.4 e less than the formal oxidation state charge of +2.0 e. Most of this
15 charge difference from the formal charge is due to backbonding from the O²⁻ to the alkaline earth
16 valence *d* orbitals. The mono-substituted (halides and hydroxides) radicals have a charge that is
17 within ~0.1 e of the formal charge of +1.0 e. The excess α spin is mostly localized in the valence
18 *s* orbital of the alkaline earth. There is about 0.1 e of backbonding into the valence *d* orbital of
19 the alkaline earth with the largest amount of backbonding predicted for BaCl, which has the
20 lowest positive charge on the alkaline earth. The larger ionic character in the M-F bonds than the
21 M-O bonds may contribute to the apparent increased strength of the M-F bonds as compared to
22 the M-O bonds.
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40 The NPA calculated charges for the Sr, Ba, and Ra compounds show that the di-
41 substituted compounds (halides and hydroxides) are more ionic than the oxides. The mono-
42 substituted halide compounds are slightly more ionic than the corresponding di-substituted ones.
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44 The di-substituted compounds for Sr, Ba, and Ra all have positive charges of 1.8 to 1.9 e on the
45 alkaline earth.
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51 We compare the NPA charges for all of the alkaline earth dihalides. For the difluorides,
52 the least ionic molecule is BeF₂. The backbonding from the two F⁻ groups is split between the 2*s*
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3 and 2p orbitals almost evenly. For MgF_2 , most of the backbonding is into the 3s with a small
4 contribution into the 3p. Both BeF_2 and MgF_2 are linear. The valence d orbitals become available
5 for CaF_2 and all of the backbonding for the remainder of the alkaline earth difluorides is into the
6 valence d. Beginning with CaF_2 , all of the heavier difluorides are bent. Thus the ability to bend
7 correlates with the availability of the valence d orbital. The role of the d orbitals for CaF_2 has
8 been noted previously by Gole et al.¹¹⁵
9

10 For the dichlorides, BeCl_2 is the least ionic with 0.36 e in the 2s and 0.18 e in the 2p.
11 MgCl_2 is also less ionic than all of the fluorides and has 0.26 e in the valence 3s with only 0.05 e
12 in the valence 3p. Both BeCl_2 and MgCl_2 are linear. Again, the availability of a valence d orbital
13 shifts the backbonding into this orbital at CaCl_2 and increases the ionicity. In contrast to the
14 difluorides, however, there is a small backbonding into the valence s on the order of 0.03 to 0.06
15 e for CaCl_2 to RaCl_2 . CaCl_2 has the most backbonding into the valence d and s orbitals and is
16 still linear. SrCl_2 has less valence s and d backbonding than CaCl_2 and is thus more ionic; SrCl_2
17 is slightly bent, although it may be best described as highly fluxional and quasilinear as
18 discussed above. BaCl_2 has more valence d backbonding and less valence s backbonding than
19 SrCl_2 and is clearly bent even though it is less ionic than SrCl_2 . RaCl_2 has essentially the same
20 orbital backbonding as does SrCl_2 , yet it is clearly bent. Thus, the types of orbitals available for
21 the backbonding and the size of the anion are key factors in determining if the molecules are bent
22 or linear. The bent molecules, of course, show deviations from simple valence shell electron pair
23 repulsion theory.¹¹⁶
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49 **Conclusions**

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51 Reliable geometry parameters and frequencies are reported at the CCSD(T) level of
52 theory for the late alkaline earth metal (Sr, Ba and Ra) oxides, fluorides, chlorides and
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3 hydroxides. Our calculated geometry parameters, frequencies, heats of formation and bond
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5 energies were compared with available experimental data and good agreement is found (within
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7 experimental errors) with reliable experimental results. The effects of anharmonicity on the
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9 quasilinear molecules for the ZPE are expected to be very small, < 0.1 kcal/mol. We suggest that
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11 our values for the thermodynamic heats of formation and the BDEs are the most accurate
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13 available with estimated uncertainties of ± 1 to 2 kcal/mol for all except the compounds
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15 containing Ra. The heats of formation of the Ra compounds have additional uncertainty due to
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17 the uncertainty in the heats of formation of the Ra atom and the lack of additional
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19 thermodynamic information against which to test the values for the heat of formation of gaseous
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21 Ra. The higher order corrections for the oxides which potentially have the most multi-reference
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23 character are expected to be significantly below 1 kcal/mol. This suggests that significant
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25 revisions may be needed for some of the gas phase heats of formation. We report the first reliable
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27 energetics, geometry parameters and frequencies for Ra oxides, fluorides, chlorides and
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29 hydroxides. The cohesive energies (heats of sublimation of the monomer) show that the values
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31 for the Be dihalides are quite low. In addition, the results show that the cohesive energies for the
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33 Ra compounds are substantial. The fluoride affinities show that the difluorides are moderately
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35 strong Lewis acids and that such trifluorides may form under the appropriate experimental
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37 conditions. The calculated charges on the alkaline earth suggest that di-substituted compounds
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39 (dihalides and dihydroxides) are more ionic than the corresponding monoxides. In addition, the
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41 charges for the dihalides and backbonding into the available valence orbitals on the alkaline earth
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43 correlate with whether these molecules are bent or linear. These calculated values provide a
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45 consistent set of thermodynamic data for use in further macroscopic simulations, for example, of
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47 molten salt reactors.
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9
10 **Supporting Information** Complete references for Ref. 61 and 62. Energy contributions to the
11 total atomization energies. T_1 diagnostic values at CCSD(T)/ aug-cc-pwCVQZ Level. Calculated
12 ZPE including anharmonic corrections. Calculated and Experimental Vibrational Frequencies in
13 cm^{-1} including anharmonic corrections. Calculated heats of formation at 0 K and 298K from the
14 total atomization energies in kcal/mol at CCSD(T)/CBS-DTQ and CCSD(T)/CBS-TQ5 Levels.
15 Total CCSD(T) and CBS energies in hartrees. The Natural Population Analysis based on the
16 Natural Bond Orbitals. DFT optimized geometries for all group 2 dihalides. SrCl_2
17 CCSD(T)/awCVTZ Frequencies.

References

- ¹ Hastie, J. W. *High Temperature Vapors-Science and Technology*. Academic, New York, 1975.
- ² Schofield, K. Flame Chemistry of Alkali and Alkaline Earth Metals. in *Gas-Phase Metal Reactions*, Fontijn, A., ed., North-Holland, Amsterdam, 1992, pp. 529-571.
- ³ Fennell, P. S.; Dennis, J. S.; Hayhurst A. N. Production of Nanoparticles of MgO, BaO, and Al₂O₃ in a Premixed Flame and Its Relation to the Flame Structure. *Combustion, Explosion, and Shock Waves*, **2006**, *42*, 642–648.
- ⁴ England, W. B. Theoretical Studies of MHD Plasma Molecules. I. Potential Energy Curves and Dipole moments of Linear KOH. *J. Chem. Phys.* **1978**, *68*, 4896-4900.
- ⁵ R. Dirscherl, K. W. Michel, and C. B. Cosmovici, On the Occurrence of Alkaline Earth and Rare Earth Oxides in Sunspots and Cool Stars. *Astron. Astrophys.* **1978**, *68*, 381-387.
- ⁶ Drapatz, S.; Haser, L.; Michel, K.-W. Atomic and Molecular Properties of Metals from Artificial Cloud Experiments in the Upper Atmosphere. *Z. Naturforschung* **1974**, *29a*, 411-418.
- ⁷ Murad, E. Thermochemical Properties of the Gaseous Alkaline Earth Monohydroxides. *J. Chem. Phys.* **1981**, *75*, 4080-4085.
- ⁸ Huntelaar, M. E.; Codfunke, E. H. P. The Standard Molar Enthalpies of Formation of BaO(g) and SrO(g). *J. Chem. Thermo.* **1997**, *29*, 817-826.
- ⁹ Ball, R. G. J.; Mignanelli, M. A.; Barry, T. I.; Gisby J. A. The Calculation of Phase Equilibria of Oxide Core-Concrete Systems. *J. Nuc. Mater.* **1993**, *201*, 238-249.
- ¹⁰ Haubenre, P. N.; Engel, J. R. Experience with the Molten-Salt Reactor Experiment. *Nucl. Applic. Tech.*, **1970**, *8*, 118-136.
- ¹¹ Rosenthal, M. W.; Kasten, P. R.; Briggs, R. B. Molten-Salt Reactors—History, Status, and Potential. *Nucl. Applic. Tech.*, **1970**, *8*, 107-118.

1
2
3
4 ¹² A Technology Roadmap for the Generation IV Nuclear Energy Systems, GIF-002-00, U.S.
5 DOE Nuclear Energy Research Advisory Committee and the Generation IV International
6 Forum, 2002.
7
8

9
10
11 ¹³ Forsberg, C. W.; Peterson, P. F.; Pickard, P. S. Molten-Salt-Cooled Advanced High-
12 Temperature Reactor for Production of Hydrogen and Electricity *Nucl. Tech.*, **2003**, *144*, 289-
13 302
14
15

16
17
18 ¹⁴ Hargraves, R.; Moir, R. Liquid Fluoride Thorium Reactors. *Am. Scientist*, **2010**, *98*, 304-313
19

20
21 ¹⁵ M. Chen, A. R. Felmy, and D. A. Dixon, Structures and Stabilities of (MgO)_n Nanoclusters. *J.*
22 *Phys. Chem. A*, **2014**, *118*, 3136–3146
23
24

25
26 ¹⁶ M. Chen, V. E. Jackson, A. R. Felmy, and D. A. Dixon, Structures and Energetics of
27 (MgCO₃)_n Clusters, n ≤ 16. *J. Phys. Chem. A*, **2015**, *119*, 3419–3428
28

29
30 ¹⁷ Vasiliu, M.; Li, S.; Peterson, K. A.; Feller, D.; Gole, J. L.; Dixon D. A. Structures and Heats of
31 Formation of Simple Alkali Metal Compounds: Hydrides, Chlorides, Fluorides, Hydroxides and
32 Oxides for Li, Na and K. *J. Phys. Chem. A*, **2010**, *114*, 4272-4281.
33
34
35

36
37 ¹⁸ Vasiliu, M.; Li, S.; Feller, D.; Gole, J. L.; Dixon D. A. Structures and Heats of Formation of
38 Simple Alkaline Earth Metal Compounds: Fluorides, Chlorides, Oxides, and Hydroxides for Be,
39 Mg, and Ca. *J. Phys. Chem. A* **2010**, *114*, 9349–9358.
40
41

42
43 ¹⁹ Dixon, D. A.; Feller, D.; Peterson. K. A. A Practical Guide to Reliable First Principles
44 Computational Thermochemistry Predictions Across the Periodic Table. in *Annual Reports in*
45 *Computational Chemistry*, Vol. 8, ed. R. A. Wheeler, Section Ed. G. S. Tschumper, Elsevier,
46 Amsterdam, 2012, Chapt. 1, pp. 1-28
47
48
49
50
51

- 1
2
3
4 ²⁰ Feller, D.; Peterson, K. A.; Dixon, D. A. Further Benchmarks of a Composite, Convergent,
5 Statistically-Calibrated Coupled Cluster-Based Approach for Thermochemical and Spectroscopic
6 Studies. *Mol. Phys.* **2012**, *110*, 2381–2399.
7
8
9
10
11 ²¹ Peterson, K. A.; Feller, D.; Dixon, D. A. Chemical Accuracy in Ab Initio Thermochemistry
12 and Spectroscopy: Current Strategies and Future Challenges. *Theor. Chem. Acc.* **2012**, *131*,
13 1079-1 – 1079-20.
14
15
16
17
18 ²² Purvis, G. D., III; Bartlett, R. J. A Full Coupled-Cluster Singles and Doubles Model: The
19 Inclusion of Disconnected Triples. *J. Chem. Phys.* **1982**, *76*, 1910-1918.
20
21
22
23 ²³ Raghavachari, K.; Trucks, G. W.; Pople, J. A.; Head-Gordon, M. A Fifth-order Perturbation
24 Comparison of Electron Correlation Theories. *Chem. Phys. Lett.* **1989**, *157*, 479-483.
25
26
27
28 ²⁴ Watts, J. D.; Gauss, J.; Bartlett, R. J. Coupled-Cluster Methods with Non-iterative Triple
29 Excitations for Restricted Open-Shell Hartree-Fock and Other General Single-Determinant
30 Reference Functions. Energies and Analytical Gradients. *J. Chem. Phys.* **1993**, *98*, 8718-8733.
31
32
33
34 ²⁵ Bartlett, R. J.; Musial, M. Coupled-Cluster Theory in Quantum Chemistry. *Rev. Mod. Phys.*
35 **2007**, *79*, 291-352.
36
37
38
39 ²⁶ Dunning, T. H., Jr. Gaussian Basis Sets for Use in Correlated Molecular Calculations. I. The
40 Atoms Boron Through Neon and Hydrogen. *J. Chem. Phys.* **1989**, *90*, 1007-1023.
41
42
43
44 ²⁷ Kendall, R. A.; Dunning, T. H., Jr.; Harrison, R. J. Electron Affinities of the First-Row Atoms
45 Revisited. Systematic Basis Sets and Wave Functions. *J. Chem. Phys.* **1992**, *96*, 6796-6806.
46
47
48
49 ²⁸ Hill, J. G. Gaussian Basis Sets for Molecular Applications. *Int. J. Quantum Chem.* **2013**, *113*,
50 21-34.
51
52
53 ²⁹ Vasiliu, M.; Peterson, K. A.; Dixon, D. A. Benchmark-Quality Atomization Energies for BeH
54 and BeH₂. *J. Chem. Theor. Comp.* **2017**, *13*, 649-653.
55
56
57

- 1
2
3
4 ³⁰ Fang, Z.; Vasiliu, M.; Peterson, K. A.; Dixon D. A. Prediction of Bond Dissociation
5 Energies/Heat of Formation for Diatomic Transition Metal Compounds: CCSD(T) Works. *J.*
6 *Chem. Theor. Comp.* **2017**, *13*, 1057-1066.
7
8
9
10
11 ³¹ Cheng, L.; Gauss, J.; Ruscic, B.; Armentrout, P. B.; Stanton, J. F. Bond Dissociation Energies
12 for Diatomic Molecules Containing 3d Transition Metals: Benchmark Scalar-Relativistic
13 Coupled-Cluster Calculations for 20 Molecules. *J. Chem. Theor. Comp.* **2017**, *13*, 1044–1056.
14
15
16
17
18 ³² Koput, J.; Roszczak, A. CaF₂ As a Quasilinear Molecule: the Vibrational–Rotational Energy
19 Levels Predicted by Ab Initio Quantum Chemistry Approach *J. Phys. Chem. A* **2004**, *108*, 9267-
20 9273.
21
22
23
24
25 ³³ Haworth, N. L.; Sullivan, M. B.; Wilson, A. K.; Martin, J. M. L.; Radom, L. Structures and
26 Thermochemistry of Calcium-Containing Molecules. *J. Phys. Chem. A* **2005**, *109*, 9156-9168.
27
28
29
30 ³⁴ Yang, C.-H.; Zhang, X.; Han, K.-L. Theoretical study on analytical potential function and
31 spectroscopic parameters for CaF molecule *J. Mol. Struct. (THEOCHEM)* **2004**, *678*, 183-188.
32
33
34
35 ³⁵ Koput, J.; Peterson, K. A. Ab Initio Prediction of the Potential Energy Surface and
36 Vibrational–Rotational Energy Levels of X²A' BeOH *J. Phys. Chem. A* **2003**, *107*, 3981-3986.
37
38
39
40
41 ³⁶ Sullivan, M. B.; Iron, M. A.; Redfern, P. C.; Martin, J. M. L.; Curtiss, L. A.; Radom, L. Heats
42 of Formation of Alkali Metal and Alkaline Earth Metal Oxides and Hydroxides: Surprisingly
43 Demanding Targets for High-Level ab Initio Procedures *J. Phys. Chem. A* **2003**, *107*, 5617-5730.
44
45
46
47
48 ³⁷ Ho, D. S.; DeYonker, N. J.; Wilson, A. K.; Cundari, T. R. Accurate Enthalpies of Formation
49 of Alkali and Alkaline Earth Metal Oxides and Hydroxides: Assessment of the Correlation
50 Consistent Composite Approach (ccCA). *J. Phys. Chem. A* **2006**, *110*, 9767-9770.
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4 ³⁸ DeYonker, N. J.; Ho, D. S.; Wilson, A. K.; Cundari, T. R. Computational *s*-Block
5 Thermochemistry with the Correlation Consistent Composite Approach *J. Phys. Chem. A* **2007**,
6 *111*, 10776-10780.
7
8
9
10
11 ³⁹ Iron, M.A.; Oren, M.; Martin, J.M.L. Alkali and alkaline earth metal compounds: core-valence
12 basis sets and importance of subvalence correlation *Mol. Phys.* **2003**, *101*, 1345-1361.
13
14
15
16 ⁴⁰ Hassett, D. M.; Marsden, C. J. The Shapes and Bending Potentials of Monomeric MgF₂ and
17 CaF₂. *J. Molec. Struct.*, **1995**, *346*, 249-263.
18
19
20
21 ⁴¹ Minenkov, Y.; Bistoni, G.; Riplinger, C.; Auer, A. A.; Neese, F.; Cavallo, L. Pair Natural
22 Orbital and Canonical Coupled Cluster Reaction Enthalpies Involving Light to Heavy Alkali and
23 Alkaline Earth Metals: The Importance of Sub-valence Correlation. *Phys.Chem.Chem.Phys.*
24 **2017**, *19*, 9374-9391.
25
26
27
28
29
30 ⁴² Peterson, K. A. Systematically Convergent Basis Sets with Relativistic Pseudopotentials. I.
31 Correlation Consistent Basis Sets for the Post-d Group 13 – 15 Elements *J. Chem. Phys.* **2003**,
32 *119*, 11099-11112.
33
34
35
36
37 ⁴³ Peterson, K. A.; Figgen, D.; Goll, E.; Stoll, H.; Dolg, M. Systematically Convergent Basis Sets
38 with Relativistic Pseudopotentials. II. Small-Core Pseudopotentials and Correlation Consistent
39 Basis Sets for the Post-d Group 16–18 Elements. *J. Chem. Phys.* **2003**, *119*, 11113-11123.
40
41
42
43
44 ⁴⁴ Peterson, K. A.; Puzarini, C. Systematically Convergent Basis Sets for Transition Metals. II.
45 Pseudopotential-Based Correlation Consistent Basis Sets for the Group 11 (Cu, Ag, Au) and 12
46 (Zn, Cd, Hg) Elements *Theor. Chem. Acc.* **2005**, *114*, 283-296.
47
48
49
50
51 ⁴⁵ Peterson, K. A.; Figgen, D.; Dolg, M.; Stoll, H. Energy-Consistent Relativistic
52 Pseudopotentials and Correlation Consistent Basis Sets for the 4d Elements Y-Pd. *J. Chem.*
53 *Phys.* **2007**, *126*, 124101-1 – 124101-12.
54
55
56
57
58
59
60

⁴⁶ Peterson, K. A. Gaussian Basis Sets Exhibiting Systematic Convergence to the Complete Basis Set Limit. In *Annual Reports in Computational Chemistry*; Spellemmeyer, D. C., Wheeler, R. A., Eds.; Elsevier, B. V.: Amsterdam, The Netherlands, 2007; Vol 3, Chapt. 11, pp. 195-206.

⁴⁷ Li, H.; Feng, H.; Sun, W.; Zhang, Y.; Fan, Q.; Peterson, K. A.; Xie, Y.; Schaefer, H. F., III, The Alkaline Earth Dimer Cations (Be_2^+ , Mg_2^+ , Ca_2^+ , Sr_2^+ , and Ba_2^+). Coupled Cluster and Full Configuration Interaction Studies. *Mol. Phys.* **2013**, *111*, 2292-2298.

⁴⁸ Hill, J. G.; Peterson, K. A. Gaussian Basis Sets for Use in Correlated Molecular Calculations. XI. Pseudopotential-Based and All-Electron Relativistic Basis Sets for Alkali Metal (K–Fr) and Alkaline Earth (Ca–Ra) Elements. *J. Chem. Phys.* Accepted, Dec. 1, 2017.

⁴⁹ Peterson, K. A.; Dunning, T. H., Jr. Accurate Correlation Consistent Basis Sets for Molecular Core-Valence Correlation Effects. The Second Row Atoms Al - Ar, and the First Row Atoms B - Ne Revisited. *J. Chem. Phys.* **2002**, *117*, 10548-10560.

⁵⁰ Lim, I. S.; Stoll, H.; Schwerdtfeger, P. Relativistic Small-Core Energy-Consistent Pseudopotentials for the Alkaline-Earth Elements from Ca to Ra. *J. Chem. Phys.* **2006**, *124*, 034107-1 - 034107-9.

⁵¹ Martin, J. M. L. Ab Initio Total Atomization Energies of Small Molecules - Towards the Basis Set Limit. *Chem. Phys. Lett.* **1996**, *259*, 669-678.

⁵² Feller, D.; Peterson, K.A.; Hill, J. G. On the effectiveness of CCSD(T) complete basis set extrapolations for atomization energies. *J. Chem. Phys.* **2011**, *135*, 044102-1 - 044102-18.

⁵³ Peterson, K. A.; Woon, D. E.; Dunning, T. H., Jr. Benchmark Calculations with Correlated Molecular Wave Functions. IV. The Classical Barrier Height of the $\text{H} + \text{H}_2 \rightarrow \text{H}_2 + \text{H}$ Reaction. *J. Chem. Phys.* **1994**, *100*, 7410-7415.

⁵⁴ Dunham, J. L. The Energy Levels of a Rotating Vibrator. *Phys. Rev.* **1932**, *41*, 721-731.

- 1
2
3
4
5
6
7
8
9
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11
12
13
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16
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43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
-
- ⁵⁵ Dunham, J. L. The Wentzel-Brillouin-Kramers Method of Solving the Wave Equation. *Phys. Rev.* **1932**, *41*, 713-720.
- ⁵⁶ Clabo, D. A.; Allen, W. D.; Remington, R. B.; Yamaguchi, Y.; Schaefer, H. F., III, A Systematic Study of Molecular Vibrational Anharmonicity and Vibration-Rotation Interaction by Self-Consistent-Field Higher-Derivative Methods – Asymmetric-top Molecules. *Chem. Phys.* **1988**, *123*, 187-239.
- ⁵⁷ Barone, V. Vibrational Zero-Point Energies and Thermodynamic Functions Beyond the Harmonic Approximation *J. Chem. Phys.* **2004**, *120*, 3059-3065.
- ⁵⁸ Barone, V. Anharmonic Vibrational Properties by a Fully Automated Second-Order Perturbative Approach. *J. Chem. Phys.* **2005**, *122*, 014108-1 - 014108-10.
- ⁵⁹ Møller, C.; Plesset, M. S. Note on an Approximation Treatment for Many-Electron Systems. *Phys. Rev.* **1934**, *46*, 0618-0622.
- ⁶⁰ Pople, J. A.; Binkley, J. S.; Seeger, R. Variational Configuration Interaction methods and Comparison with Perturbation Theory. *Int. J. Quantum. Chem.* **1976**, *10*, 1-19.
- ⁶¹ Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; et al. *Gaussian 09*, revision B.01; Gaussian, Inc.: Wallingford, CT, 2009.
- ⁶² Werner H.-J.; Knowles, P. J.; Knizia, G.; Manby, F. R.; Schütz, M.; Celani, P.; Korona, T.; Lindh, R.; Mitrushenkov, A.; Rauhut, G.; et al. MOLPRO, Version 2012.1, A Package of *Ab Initio* Programs, See <http://www.molpro.net>. Accessed 10-01-2012.
- ⁶³ Werner H.-J.; Knowles, P. J.; Knizia, G.; Manby, F. R.; Schütz, M. Molpro: A General Purpose Quantum Chemistry Program Package. *WIREs Comput. Mol. Sci.* **2012**, *2*, 242-253.

⁶⁴ Senekowitsch, J. *Spektroskopische Eigenschaften aus Elektronischen Wellenfunktionen*, Ph.D. Thesis, Universität Frankfurt, Frankfurt, Germany, 1988.

⁶⁵ de Jong, W. A.; Harrison, R. J.; Dixon, D. A. Parallel Douglas-Kroll Energy and Gradients in NWChem: Estimating Scalar Relativistic Effects Using Douglas-Kroll Contracted Basis Sets. *J. Chem. Phys.* **2001**, *114*, 48-53.

⁶⁶ Moore, C. E. *Atomic Energy Levels as Derived from the Analysis of Optical Spectra, Volume I, H to V*; U.S. National Bureau of Standards Circular 467; U.S. Department of Commerce, National Technical Information Service, COM-72-50282: Washington, D C, 1949.

⁶⁷ Chase, M. W., Jr. *NIST-JANAF Thermochemical Tables*, 4th ed.; *J. Phys. Chem. Ref. Data, Mono. 9*; American Institute of Physics: Woodbury, NY, 1998; Suppl 1.

⁶⁸ Lias, S. G.; Bartmess, J. E.; Liebman, J. F.; Holmes, J. L.; Levin, R. D.; Mallard, W. G. *J. Phys. Chem. Ref. Data* **1988**, *17* (Suppl. 1).

⁶⁹ Yungman, V. S.; Glushko, V. P.; Medvedev, V. A.; Gurvich, L. V., Eds., *Thermal Constants of Substances*, 8 Vols., Wiley: New York, 1999.

⁷⁰ Curtiss, L. A.; Raghavachari, K.; Redfern, P. C.; Pople, J. A. Assessment of Gaussian-2 and Density Functional Theories for the Computation of Enthalpies of Formation. *J. Chem. Phys.* **1997**, *106*, 1063-1079.

⁷¹ Deegan, M. J. O.; Knowles, P. J.: Perturbative Corrections to Account for Triple Excitations in Closed and Open Shell Coupled Cluster Theories. *Chem. Phys. Lett.* **1994**, *227*, 321-326.

⁷² Rittby, M.; Bartlett, R. J.: An Open-Shell Spin-Restricted Coupled Cluster Method: Application to Ionization Potentials in N₂. *J. Phys. Chem.* **1988**, *92*, 3033-3036.

⁷³ Knowles, P. J.; Hampel, C.; Werner, H.-J.: Coupled Cluster Theory for High Spin, Open Shell Reference Wave Functions *J. Chem. Phys.* **1993**, *99*, 5219-5228.

- 1
2
3
4 ⁷⁴ Hoeft, J.; Lovas, F. J.; Tiemann, E.; Törring, T. Microwave Spectrum of BaO, *Z. Naturforsch.*
5 *A* **1970**, *25*, 1750-1751.
6
7
8
9 ⁷⁵ Wharton, L.; Klemperer, W. Microwave spectrum of BaO. *J. Chem. Phys.*, **1963**, *38*, 2705
10
11 ⁷⁶ Ruzlewicz, Ch.; Schütze-Pahlmann, H. U.; Hoeft, J.; Törring, T. Rotational Spectrum and
12 Hyperfine Structure of the $^2\Sigma$ Radicals BaF and BaCl. *Chem. Phys.* **1982**, *71*, 389-399.
13
14
15 ⁷⁷ Blom, C. E.; Hedderich, H. G.; Lovas, F. J.; Suenram, R. D. Infrared and Microwave Spectra
16 of SrO and BaO. *J. Mol. Spectrosc.* **1992**, *152*, 109-118.
17
18
19
20 ⁷⁸ Hocking, W. H.; Pearson, E. F.; Creswell, F. A.; Winnewisser, G. Millimeter Wave Spectra of
21 the Alkaline Earth Metal Oxides: BaO, SrO, and CaO. *J. Chem. Phys.* **1978**, *68*, 1128-1134.
22
23
24
25 ⁷⁹ Rytlewicz, Ch.; Tijrning, T. Formation and Microwave Spectrum of the $^2\Sigma$ -radical Barium-
26 Monofluoride. *Chem. Phys.* **1980**, *51*, 329-334.
27
28
29
30 ⁸⁰ Ault, B.S.; Andrews, L., Nitrogen Matrix Reactions of Alkaline Earth Metal Atoms with
31 Ozone: Infrared Spectra of the Alkaline Earth Metal Oxide Molecules. *J. Chem. Phys.* **1975**, *62*,
32 2320-2327.
33
34
35
36 ⁸¹ E. Tiemann, M. Bojaschewsky, Ch. Sauter-Servaes, T. Törring, Rotationsspektrum von BaO.
37 *Z. Naturforsch.* **1974**, *29a*, 1692-1694.
38
39
40
41 ⁸² Ernst, W. E.; Schröder, J. O.; Törring, T. Hyperfine Structure of SrCl $X^2\Sigma^+$ by Microwave—
42 Optical Polarization Spectroscopy. *Chem. Phys. Lett.* **1984**, *109*, 175-178.
43
44
45
46 ⁸³ Mestdagh, J. M.; Visticot, J. P. Semiempirical Electrostatic Polarization Model of the Ionic
47 Bonding in Alkali and Alkaline Earth Hydroxides and Halides. *Chem. Phys.* **1991**, *155*, 79-89.
48
49
50
51 ⁸⁴ Schütze-Pahlmann, H. U.; Ryzlewicz, Ch.; Hoeft, J.; Törring, T. Millimeter Wave Spectra of
52 the $^2\Sigma$ Radicals SrF and SrCl. *Chem. Phys. Lett.* **1982**, *93*, 74-77.
53
54
55
56
57
58
59
60

- 1
2
3
4
5
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8
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55
56
57
58
59
60
-
- ⁸⁵ Huber, K.P.; Herzberg, G. *Molecular Spectra and Molecular Structure. IV. Constants of Diatomic Molecules*, Van Nostrand Reinhold Co., New York, 1979.
- ⁸⁶ Calder, V.; Mann, D. E.; Seshardi, K. S.; Allavena, M.; White, D. Geometry and Vibrational Spectra of Alkaline-Earth Dihalides. II. CaF₂, SrF₂, and BaF₂. *J. Chem. Phys.* **1969**, *51*, 2093-2099.
- ⁸⁷ Snelson, A. Infrared Spectra of Some Alkaline Earth Halides by Matrix Isolation Techniques. *J. Phys. Chem.* **1966**, *70*, 3208-3217.
- ⁸⁸ Wharton, L.; Berg, R. A.; Klemperer, W. Geometry of Alkaline-Earth Dihalides *J. Chem. Phys.* **1963**, *39*, 2023-2031.
- ⁸⁹ Mann, D. E.; Calder, V.; Seshadri, S.; M.; White, D.; Linevsky, M. J. Geometry and Vibrational Spectra of the Alkaline-Earth Dihalides. I. MgF₂. *J. Chem. Phys.* **1967**, *46*, 1138-1143.
- ⁹⁰ Akishin, P. A.; Spiridonov, V. P. Electron Diffraction Investigation of the Structure of Halides of the Elements in Group II of the Periodic Table. *Kristallografiya* **1957**, *2*, 475.
- ⁹¹ Büchler, A.; Stauffer, J. L.; Klemperer, W. The Determination of the Geometry of High-Temperature Species by Electric Deflection and Mass Spectrometric Detection *J. Am. Chem. Soc.* **1964**, *86*, 4544-4550.
- ⁹² Büchler, A.; Stauffer, J. L.; Klemperer, W. Geometry of the Transition-Metal Dihalides: The Fluorides of Manganese, Cobalt, Nickel, Copper, and Zinc. *J. Chem. Phys.* **1964**, *40*, 3471-3473.
- ⁹³ Hassett, D. M.; Marsden, C. J. The Influence of d Orbitals on the Shape of Monomeric CaF₂. *J. Chem. Soc., Chem. Comm.* **1990**, 667-669.

- 1
2
3
4 ⁹⁴ Kaupp, M.; Schleyer, P. v. R.; Stoll, H.; Preuss, H. The Question of Bending of the Alkaline
5 Earth Dihalides MX₂ (M = Be, Mg, Ca, Sr, Ba; X = F, Cl, Br, I). An Ab Initio Pseudopotential
6 Study. *J. Am. Chem. Soc.*, **1991**, *113*, 6012–6020
7
8
9
10
11 ⁹⁵ White, D.; Calder, G. V.; Hemple, S.; Mann, D. E. Geometry and Vibrational Spectra of the
12 Alkaline Earth Dihalides. III. MgCl₂, CaCl₂, SrCl₂, and BaCl₂. *J. Chem. Phys.* **1973**, *59*, 6645-
13 6651.
14
15
16
17
18 ⁹⁶ Molnár, J. Marsden, C. J.; Hargittai, M. Molecular Structures and Force Fields of Monomeric
19 and Dimeric Magnesium Dichloride from Electron Diffraction and Quantum Chemical
20 Calculations. *J. Phys. Chem.*, **1995**, *99*, 9062–9071
21
22
23
24
25 ⁹⁷ Varga, G.; Ianza, G.; Minichino, C.; Hargittai, M. Quasilinear Molecule par Excellence, SrCl₂:
26 Structure from High-Temperature Gas-Phase Electron Diffraction and Quantum-Chemical
27 Calculations—Computed Structures of SrCl₂·Argon Complexes. *Chem. Eur. J.* **2006**, *12*, 8345-
28 8357.
29
30
31
32
33
34 ⁹⁸ Jarman, C.N.; Bernath, P.F. High Resolution Laser Spectroscopy of the $C^2\Delta-X^2\Sigma^+$ Transition
35 of CaOH and CaOD: Vibronic Coupling and the Renner-Teller Effect, *J. Chem. Phys.* **1992**, *97*,
36 1711-1718.
37
38
39
40
41 ⁹⁹ Beardah, M.S.; Ellis, A.M., Observation of Several New Electronic Transitions of the SrOH
42 Free Radical, *J. Chem. Phys.* **1999**, *110*, 11244-11254.
43
44
45
46 ¹⁰⁰ Pooley, S.J.; Beardah, M.S.; Ellis, A.M., Electronic Spectroscopy of the C-X and D-X
47 Transitions of BaOH, *J. Electron Spectrosc. Relat. Phenom.* **1998**, *97*, 77-88.
48
49
50
51 ¹⁰¹ Wang, X.; Andrews, L., Infrared Spectra and Electronic Structure Calculations for the Group
52 2 Metal M(OH)₂ Dihydroxide Molecules, *J. Phys. Chem. A* **2005**, *109*, 2782-2792.
53
54
55
56
57
58
59
60

- 1
2
3
4 ¹⁰² Andrews, L.; Wang, X. Infrared Spectra of the Group 2 Metal Dihydroxide Molecules. *Inorg.*
5 *Chem.* **2005**, *44*, 11-13.
6
7
8
9 ¹⁰³ Lee, T. J.; Taylor, P. R. A Diagnostic for Determining the Quality of Single-Reference
10 Electron Correlation Methods. *Int. J. Quantum Chem. Symp.* **1989**, *23*, 199-207.
11
12
13 ¹⁰⁴ Feller, D.; Peterson, K. A.; Dixon, D. A. A survey of factors contributing to accurate
14 theoretical predictions of atomization energies and molecular structures *J. Chem. Phys.* **2008**,
15 *129*, 204105-1 – 204105-32.
16
17
18
19
20 ¹⁰⁵ Luo, Y.-R. *Comprehensive Handbook of Chemical Bond Energies*, CRC Press, Taylor and
21 Francis Group, 2007.
22
23
24
25 ¹⁰⁶ Gurvich, L.V.; Ryabova, V.G.; Khitrov, A.N. Determination of Dissociation Energies of
26 Alkaline-Earth Chlorides, Bromides and Hydroxides by Flame Photometry. *Faraday Symp.*
27 *Chem. Soc.* **1973**, *8*, 83-106.
28
29
30
31
32 ¹⁰⁷ Schofield, K. The Bond Dissociation Energies of group IIA Diatomic Oxides. *Chem. Rev.*
33 **1967**, *67*, 707-715.
34
35
36
37 ¹⁰⁸ F. Engelke, R. K. Sander, and R. N. Zare, Crossed-Beam Chemiluminescent Studies of
38 Alkaline Earth Atoms with ClO₂. *J. Chem. Phys.* **1976**, *65*, 1146-1155.
39
40
41 ¹⁰⁹ Dagdigian, P. J.; Cruse, H. W.; Schultz, A.; Zare, R. N. Product State Analysis of BaO from
42 the Reactions Ba + CO₂ and Ba + O₂. *J. Chem. Phys.* **1974**, *61*, 4450-4465.
43
44
45
46 ¹¹⁰ Christe, K. O.; Dixon, D. A.; McLemore, D.; Wilson, W. W.; Sheehy, J. A.; Boatz, J. A. On a
47 Quantitative Scale for Lewis Acidity and Recent Progress in Polynitrogen Chemistry. *J. Fluor.*
48 *Chem.* **2000**, *101*, 151-153.
49
50
51
52 ¹¹¹ Reed, A. E.; Curtiss, L. A.; Weinhold, F. Intermolecular Interactions from a Natural Bond
53 Orbital, Donor-Acceptor Viewpoint. *Chem. Rev.* **1988**, *88*, 899-926.
54
55
56
57
58
59
60

1
2
3
4 ¹¹² Weinhold, F.; Landis, C. R. *Valency and Bonding: A Natural Bond Orbital Donor-Acceptor*
5 *Perspective*, University Press: Cambridge, U.K., 2005
6
7

8
9 ¹¹³ Glendening, E. D. ; Badenhop, J. K.; Reed, A. E.; Carpenter, J. E.; . Bohmann, J. A;
10 Morales, C. M.; Landis, C. R.; Weinhold, F. Natural Bond Order 6.0, Theoretical Chemistry
11 Institute, University of Wisconsin, Madison, WI, 2013. <http://nbo6.chem.wisc.edu/>.
12
13

14
15 ¹¹⁴ Glendening, E. D.; Landis, C. R.; Weinhold, F. NBO 6.0: Natural Bond Orbital Analysis
16 Program. *J. Comp. Chem.* **2013**, *34*, 1429-1437.
17
18

19
20 ¹¹⁵ Gole, J. L.; Siu, A. K. Q.; Hayes, E. F. Non-Empirical LCAO-MO-SCF Studies of the Group
21 IIA Dihalides BeF₂, MgF₂ and CaF₂. *J. Chem. Phys.* **1973**, *58*, 857-868.
22
23

24
25 ¹¹⁶ Gillespie, R. J.; Popelier, P. L. A. *The Chemical Bond and Molecular Geometry: from Lewis*
26 *to Electron Densities*. Oxford University Press, Oxford, 2001.
27
28
29
30
31
32
33
34
35
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