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Laboratory Experiment

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A General Chemistry Laboratory Experiment Relating Electron Configuration and Magnetic Behavior

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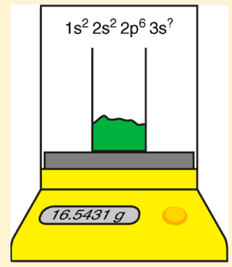
Supporting Information

ABSTRACT: During the time that students spend studying the fundamentals of quantum chemistry and chemical bonding, there are few laboratory experiments that can be performed to reinforce their learning. A simple experiment has been developed to afford students the opportunity to practice writing electron configurations for atoms and ions while relating the configurations to observed diamagnetic and paramagnetic properties of different chemical compounds. Assessment of common exam questions in our fall semester course indicates an improvement in student performance in correctly identifying electron configurations.



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One of the most important abilities for beginning chemistry students to master is the writing of electron configurations for atoms and ions. The Aufbau Principle continues to be an important part of the education of first-year chemistry students and is present in virtually all of the modern general chemistry textbooks.[1−3] Many of the tasks that are presented to students in the area of chemical bonding rely upon the correct assignments of electron configurations to the atoms or ions in a compound. The rules are simple enough. Once students have learned the ordering of atomic orbitals that are available in an atom and understand a few principles of filling in electrons, they can produce ground-state electron configurations. The correct electron configurations can then be used to develop simple models for ionic and covalent bonding.

During the time that students are learning the basics of atomic theory and bonding, a major disconnect can occur between the lecture and laboratory experiences. Other than studying hydrogen line spectra, there are not many complementary experiments for beginning chemistry students to perform in the laboratory. Demonstrations using models are helpful but there is a lack of laboratory work that relates directly to the lecture material. To address this issue, we have developed a new student experiment that connects electron configurations, magnetism, and chemical bonding. This experiment is used in an introductory chemistry course which is similar to those taught for science and technical majors at the college level.

The experiment is conceptually simple. When placed in close proximity, a compound and a magnet will experience attraction to each other, paramagnetism, or be repelled by each other, diamagnetism. The behavior that is exhibited depends upon the presence (paramagnetism) or absence (diamagnetism) of unpaired electrons. Once the magnetic behavior is determined for a particular compound, students can then determine which electron configurations are consistent with the observed magnetism. A unique determination of the electron configuration may not be possible in all cases but electron configurations that are incompatible with the magnetism can be eliminated from consideration.

The concept of relating magnetic properties to chemical bonding is not new.[4] More quantitative laboratory experiments have been described that use the same basic principles and instrumentation.[5−7] The unique features of our laboratory experiment are the simplicity of the measurements, the emphasis on producing a large number of electron configurations, and the inquiry-based approach of correlating the observed magnetic behaviors with the possible electron configurations.

■ INSTRUMENTATION AND COMPOUNDS TESTED

The instrumentation is simple. A strong neodymium magnet, grade N42 or higher, is required. An analytical balance is used to note the magnetic behavior. Samples are contained in small plastic vials that have been preloaded for the students. Preloading the samples saves time for the students and allows for the supplies, magnets, and samples to be stored for future use. The experimental setup is shown in Figure 1.

Students test the magnetic behavior of 16 chemicals. The chemical materials are divided into four classes with four chemicals belonging to each class as shown in Table 1. Classes A, B, and D are composed entirely of diamagnetic compounds and exhibit similar apparent mass gains that average around a few milligrams. Class C contains three paramagnetic compounds as well as the diamagnetic compound, ammonium

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Figure 1. Photo of the experimental setup showing the analytical balance, neodymium magnet, and a sample preloaded in a vial.

Table 1. Compounds for Study

Class	Classification	Substance
A	Simple 1:1 Ionic Compounds	sodium chloride, potassium chloride, calcium oxide, magnesium oxide
B	Ionic Compounds without 1:1 Stoichiometry	magnesium chloride, calcium chloride, aluminum chloride, aluminum oxide
C	Ionic Compounds with Transition Metals	iron(II) chloride, cobalt(II) chloride, copper(II) oxide, ammonium dichromate
D	Molecular Compounds/ Elements	water, iodine, ethanol, sulfur

dichromate. Apparent mass losses in the paramagnetic compounds average about a few tenths of a gram. Complete data for all of the compounds may be found in the Supporting Information.

PRELAB EXERCISE

To make sense of the magnetic results, students are required to determine electron configurations for the atoms and possible ions that could be present in the compounds in classes A, B, and C. A portion of this assignment is shown in Table 2. Our laboratory periods are 110 min in length so this task is assigned as a prelab. With more time available, it might be possible to have students complete these electron configurations in groups during the laboratory period. Certain reasonable limits are placed upon the magnitudes of charges. In classes A and B, positive or negative charges greater than 3 are not considered. In class C, the charge of each metal ion is either stated in the name or can be determined by using oxidation number balance. Crystal field theory is not taught in the course, so class C compounds are treated by ignoring the crystal field of the anions and only considering the ionic charge of the central metal. Only weak field complexes are used in the experiment, which allows this simple approach to work. A course that contains a discussion of crystal field theory could apply those principles to the weak field compounds that are used and add some strong field complexes as well. The use of both low- and high-spin d^6 complexes in this experiment could serve as a starting point for a discovery of the existence of weak and strong crystal fields.

Table 2. Portion of the Student Prelab Assignment

Atom/Ion[a]	Electron Configuration (short-hand notation)	No. of Unpaired Electrons	Magnetism (P or D)[b]
Na	$[Ne]3s^1$	1	P
Na^+	[Ne]	0	D
Na^{2+}	$[He]2s^22p^5$	1	P
Na^{3+}	$[He]2s^22p^4$	2	P
Cl	$[Ne]3s^23p^5$	1	P
Cl^-	[Ar]	0	D
Cl^{2-}	$[Ar]4s^1$	1	P
Cl^{3-}	$[Ar]4s^2$	0	D

[a]The complete table is available in the Supporting Information. [b]P is paramagnetic and D is diamagnetic.

EXPERIMENTAL PROCEDURE

A strong neodymium magnet, grade N42 or higher, is placed upon an electronic balance and the mass recorded. Magnets may be placed directly upon the balance pan or supported by a plastic block of a height of about 2 in. The issue with the magnet being placed directly onto the balance is that the actual weight of the magnet is affected by the interaction with the balance. We have noted differences as large as 10%. But because the only measurement that is critical in this experiment is the relative difference in apparent mass between the magnet in the presence and absence of the chemical sample, the "true" mass of the magnet is not needed. If desired, the plastic block can be used to minimize the interaction between balance and magnet. A plastic vial that contains a chemical compound is then brought close to the top of the magnet and the apparent mass of the magnet is recorded again. Depending upon the strength of the magnet, a noticeable change in apparent mass may be seen when the sample and magnet are about a centimeter or two apart. The maximum effect will be seen when sample and magnet are as close as possible without touching. If desired, a weighing boat can be inverted completely over the top of the balance pan so that all samples can be placed at the same distance from the magnet. A smaller reading of mass on the balance indicates that the compound is paramagnetic and attracting the magnet. A larger mass reading results from the interaction with a diamagnetic compound. Although students are recording masses during the experiment, it is important that students appreciate the difference between the actual mass of the magnet, which does not change, versus the apparent mass of the magnet that results from the weight changing in the presence of the magnetic field. The magnitude of the apparent loss or gain in the mass is not a concern. Students will observe that the diamagnetic interactions are much weaker than the paramagnetic interactions. All that matters is whether the compound tested exhibits diamagnetic or paramagnetic behavior. It requires very little time to determine the magnetic properties of a single sample. As a result, many compounds can be tested during a laboratory period resulting in a large quantity of data from which to draw conclusions.

To perform the experiment correctly, students need to be aware of a few issues. As they are placing the chemical samples into a magnetic field by holding small plastic vials near the magnet, they should investigate the effects that the human hand and the plastic have on the magnetic behavior. Students are instructed to investigate the effects of just placing a hand near the magnet as well as holding an empty vial. They are usually quite amazed that they themselves are diamagnetic as well as the plastic. One possible issue with the data collection is the possibility of a static charge on the vial interfering with the measurements, particularly for the diamagnetic materials. Students are instructed to ground themselves through a light switch faceplate prior to making a measurement.

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The experiment is designed to be a group project. Our laboratory sessions contain a maximum of twenty students. Groups of five rotate between four tables with each table containing a class of chemical compounds.

■ HAZARDS

A grade N42 magnet generates quite a magnetic pull. When handling these magnets, the possibility of pinched fingers does exit. Care should be taken not to place two magnets together. It will very difficult to pull them apart. Most of the solids cause respiratory tract irritation while $K_2Cr_2O_7$ is also carcinogenic. Take proper precautions while loading the plastic vials and be sure to secure and seal the vials before using.

■ POSTLAB DATA ANALYSIS

After the students have completed the full table of electron configurations and collected the data concerning magnetic behavior, they are asked to answer a series of questions. The analysis requires that students assume that the ions in a compound belonging to classes A, B, or C (ionic compounds) are magnetically independent of each other and do not exhibit magnetic coupling or sharing of electrons. A diamagnetic compound in classes A, B, or C would then require two diamagnetic ions. A paramagnetic compound would need to contain at least one paramagnetic ion. For compounds in classes A and B, students are asked to determine chemical formulas that are consistent with the magnetic data. For class C, they are asked to identify the feature of these compounds (d electrons) that lead to the paramagnetism. Covalent bonding has yet to be introduced at the time when the students perform this lab. They have not been instructed in the mechanics of producing Lewis structures using the octet rule. The class D results are different from those of the other three classes and are only intended to demonstrate that covalent bonding leads to electron pairing even if the component atoms are paramagnetic. A result of this experiment is that students will have some empirical evidence for electron pairing in chemical bonds when they start the topic of covalent bonding. If an instructor believes that the introduction of electron pairing in molecular compounds would be confusing to students, it could be omitted from the experiment. The full set of questions and answers is found in the Supporting Information.

■ ASSESSMENT

The major reason for developing this experiment was to give students an activity that was related to their study of chemical bonding. A question to be addressed was whether the students would become more proficient in writing electron configurations as a result of the experience. This experiment was used for the first time during the fall semester of 2010. The historical average for 10 electron-configuration questions included on the common exams dating back to fall of 2003 was 81% with a standard deviation of 14%. Student populations for those exams average slightly over 1000 students per exam. In 2010, when asked to identify a correct electron configuration for Ge in a multiple-choice question, 1006 of 1042 students (97%) were able to do so. On the 2011 exam, 886 out of 1015 students (87%) were able to correctly identify the electron configuration of Fe. In the latest result during the fall semester of 2012, 950 out of 989 students (96%) were able to correctly identify the electron configuration of the fluoride ion. We also wanted students to be able to identify paramagnetic or diamagnetic atoms and ions. On the fall semester exam in 2010, 84% of students were able to pick a diamagnetic ion out of a list of ions. Unfortunately, we have no historical data for this type of question. Although there are other variables that may affect these outcomes, the positive nature of the results is encouraging.

■ FINAL CONSIDERATION

Although there is a definite correlation between electron configuration and the magnetism of these simple ionic compounds, it is important that students not attribute the stability of these compounds solely to the electron configurations. Stability is a result of a number of factors that are best demonstrated through a Born–Haber cycle. Instructors are provided with Born–Haber cycles for the formation of $Mg^{+}O^{-}$, $Mg^{2+}O^{2-}$, and $Mg^{3+}O^{3-}$ to discuss the various factors that ultimately determine the energetics of the formation of ionic compounds. These cycles are included in the Supporting Information.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Full laboratory instructions; instructor's guide; Quick Time movie demonstrating the magnetic behavior; Born–Haber cycles for MgO. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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