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Evaluation of students' understanding of Pauli's exclusion principle

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Abstract

The purpose of this study was to collectively assess and ascertain knowledge about junior and senior year university student's understanding of the monumental Lindus Pauli's Exclusion Principle (PEP). Student's misconceptions were identified and addressed to acquire an better understanding of their misapprehensions. This study was based on the written answers given by our university students to a survey addressing Pauli's Exclusion Principle administered by our faculty. The diagnostic survey was applied to junior and senior year year university students, majoring in Chemistry and Physics. Some interesting results about PEP are presented and their critiques evaluated. An interesting feature of the data obtained was that there were no great difference between junior and senior year students knowledge and understanding of PEP.

Keywords: epistemology; cognitive; structure, periodic table

1. Introduction

The misunderstanding of various concepts in science have been noted in the past for example, force and motion (Gunstone & Watts, 1985), mechanics (Mc.Dermott, 1984), the atomic theory (Schmidt, 1997; Harrison & Treagust, 2000; Toomey et al., 2001) and mass and energy (Stansbury, 2000). Also, Pauli's Exclusion Principle (PEP) has been somewhat vaguely expressed in the past leading to an unclear description of Pauli's principle (Bransden & Joachain, 2003). This study was to ensure that PEP was taught correctly and that the important points about it were understood. There have been no studies about PEP in the past and so we cannot compare other efforts of studies regarding PEP. Therefore this kind of study can shed light on better and more effective teaching and teaching methods.

Epistemological understanding of science is important in creating better science students, science teachers and scientists in general (American Association for the Advancement of Science, 1993; National Research Council,

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1996; National Science Foundation, 1996). Additionally, this study was to examine if students were able to use the history of science together with what they had been taught previously in their own cognitive development. We envisioned students being capable of coalescing various aspects of science into interestingly compelling ideas or phenomena.

Though the Bohr model of the atom was a good start in explaining the structure of the atom, it was still deficient with respect to space geometry. The Bohr model of the atom gives a basic conceptual model of electron orbits and energies (Bohr, 1913). The correct theory of the atom was defined via quantum mechanics by way of the Schrodinger equation (Schrödinger, 1926; Griffiths, 2005). The Schrodinger equation allowed atomic electrons to occupy three-dimensional space. As a result three coordinates, better known as quantum numbers, to site orbitals in which electrons could be found were described. These quantum numbers are familiarly denoted as the principal (n), angular momentum (l), and magnetic (m_l) quantum numbers. As we know these quantum numbers describe the size, shape, and orientation in space of the orbitals on an atom.

A fourth solution to the Schrodinger equation, as we know, arises from the spin of the atomic electron, the spin quantum number m_s. This is explicitly described by PEP (Pauli, 1925). The restrictions imposed by PEP led to the building up of the periodic table of the elements. Is this a true statement? Was PEP an absolute necessity, or would Hund's rule have been suffice? Would chemistry be as we know it with, all the elements of the periodic table, or would it have all been much more different? The goal of this study was to examine if students understood PEP and if they recognized the distinction between the development of a theory like the PEP and the reality which the theory describes. Students were presented with a hypothesis about Pauli's Exclusion Principle in the form of a short survey.

Science textbooks and curricula outline all too well the structure of the atom. Freshmen general chemistry students are presented with the Dalton's Atomic Theory leading onto the work of Thompson (Thomson, 1904), Rutherford (Rutherford, 1914) and Bohr (Bohr, 1913). The hydrogen atom gets introduced as the simplest atom among all atoms, and that it consists of an electron and a proton having $1s^1$ electronic configuration. Electrons are added subsequently, thereafter, to atomic orbitals, and this building up process is called the *aufbau* approach. We know that when two or more degenerate orbitals are available, electrons are distributed in an unpaired fashion, with parallel spins, before they are spin paired with anti-parallel spins, as outlined by Hund's rule. Electrons fill oribitals in accordance to Hund's Rule, where term symbols s, p, d, f, g, h.... ordering follow the requirements of lower energy oribtals filling first. Hund's Rule is based on the results of the measurements of magnetic properties of the atom (Atkins & de Paula, 2002).

There are misleading statements about science in various books. One example includes a statement about PEP saying that if it was not presented then all the atoms as we now know them would not exist, and in effect only the hydrogen atom would have existed (Bransden & Joachain, 2003). Bransden and Joachain report that all the electrons would be distributed into a single orbital, the 1s subshell, and therefore there would not be other types of atoms (Bransden & Joachain, 2003). Thus there would not be other forms of matter. If elaboration proves necessary, then suffice to say that all matter would be formed from hydrogen. When this notion was presented to students, many of them made the same erroneous judgement as descibed above. If the above were actually true, then we can infer that Pauli himself created the atom, and prescribed the resulting different energy states. In addition, Pauli created all other atoms, and infact all other types of matter! However, it is a known fact that Pauli did not do such thing. It is a sure thing that with or without PEP there would still be different types of atoms existing in nature. Pauli just expressed how two electrons occupy the same single orbital of the atom. PEP, established in 1925 (Pauli, 1925), and this earned him the 1945 Nobel Prize in Physics. The aim of this study was to reaffirm this honourable scientist's work and to acquire an understanding of whether students could appreciate the difference between discovery and invention in science.

Consider Newton's Inverse Square Law, known for it's application to the Kepler's Laws, expressing the force of gravitation F existing between any two masses m_1 and m_2 as proportional to each of them, and inversely proportional to the square of their separation distance r, that is, $F = G(m_1.m_2)/r^2$, where G is known as the constant of universal gravitation. If this law was not found, would masses not attract each other? Also, similarly, if Coulomb's law was not discovered, would charges not interact with each other? Certainly all these would have happened, just perhaps these type of interactions would not have been scientifically expressed. These laws have been found ingeniously and expressed quite sufficiently.

2. Survey Structure

Our survey in essence was not whether students understood PEP, but rather whether they recognized the distinction between the development of a theory like the PEP and the reality which the theory describes. The investigation was carried out on 188 junior and senior year university students: 95 students were chemistry major students; and 93 students were physics major students; 108 students were junior year university students and 80 students were senior year university students; 129 students (69%) were male and 59 students (31%) were female.

The notion of PEP not ever existing was addressed after a 45 minute review session of the 'Electronic Structure and the Periodic Table'. The question posed was of the following format: Pauli's Exclusion Principle: No two electrons in the same atom can have all four quantum numbers the same. As a result of Pauli's Exclusion Principle, an atomic orbital can hold only two electrons and that these two electrons must have opposite spin. In your comprehension of Pauli's statement, consider the case of Pauli's Exclusion Principle not existing. In your opinion, which of the following is/ are correct? Briefly explain your answer.

A. Pauli's Exclusion Principle is not important; it does not contribute to science.

B. Pauli's Exclusion Principle describes particles having half integral spin (spin ½) and are known as fermions. These particles can only occupy the same atomic orbital if they have a different set of quantum numbers.

C. If Pauli's Exclusion Principle did not exist, all the electrons of the atom will occupy the same orbital and thus only the hydrogen atom would have existed.

D. If Pauli's Exclusion Principle did not exist, all the atoms of the periodic table would still have existed. Pauli's Exclusion Principle only explains how the electrons are distributed in the atomic orbitals.

E. Pauli's Exclusion Principle is the reason for the diversity of the elements of the periodic table and if Pauli's Exclusion Principle did not exist then there would not be many elements of the periodic table.

F. Pauli's Exclusion Principle is a remarkable principle that justifies the structure of complex atoms, chemical periodicity, and molecular structures.

G. Pauli's Exclusion Principle describes particles having integral spin (spin 1) and are known as *bozons*. Pauli's Exclusion Principle applies to identical *bosons* and are distributed within the same atomic orbital.

H. If Pauli's Exclusion Principle did not exist, the wave/ particle duality would not be correct and there would no relationship between a particle's mass and velocity and its wavelength.

I. An alternate suggestion could have been .... Using your scientific background give an alternate suggestion. Please explain your answer.

3. Discussion

This study was based on the junior and senior year undergraduate students. The total number of students was 188 students. Table 1 reflects students major, year and gender. The number of chemistry students was approximately the same as the number of physics students. The percentage of female students majoring in chemistry (29%) were comparable to the percentage of female students majoring in physics (33%). Similarly, the percentage of male students majoring in chemistry (70%) were comparable to the percentage of male students majoring in physics (67%).

Table 1. Survey of students

	Major							
	Chemistry				Physics			
Number of Students	95				93			
Year	Junior		Senior		Junior		Senior	
Number of Students	52		43		56		37	
Gender	F	M	F	M	F	M	F	M
Number of Students	14	38	14	29	16	40	15	22

F = Female; M = Male

An interesting feature of the data obtained was that there were no great differences between junior and senior year students knowledge and understanding of PEP, as can be seen in Figure 1. Both junior and senior year students were able to give comparable answers. The majority of the students in junior and senior years were able to give at least one correct answer, but had difficulties in giving a second correct answer. Very few were able to link answer B and F together. Answers B, D and F of the survey were the very foundations of PEP, yet not many students could give these three answers together (18% of the junior year students; 15% of the senior year students). The majority of the students preferred single answers. Answer D was the most preferred choice for both junior and senior year students. This shows that the majority of the students understood that electrons are distributed in atomic orbitals, in accordance to PEP. As junior and senior year students gave similar answers we believe that PEP was not well absorbed, and that the students were unable to appreciate the underlying connections between each answer.

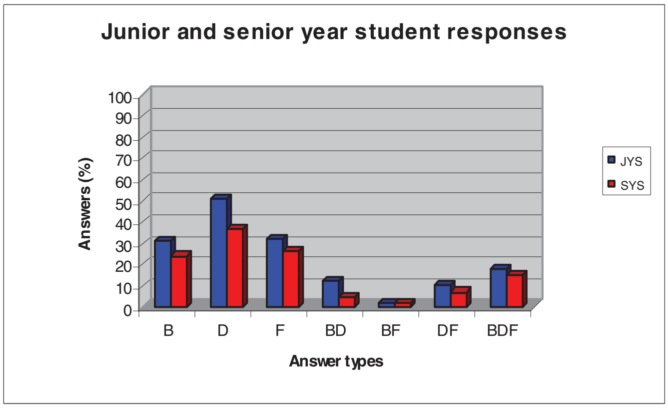

Figure 1. Comparative study of junior and senior year student responses to questions: JYS = Junior Year Students; SYS = Senior Year Students.

Figure 2 outlines the results of the survey. Almost everyone was able to give at least one correct answer; only two percent of the total number of students gave the wrong answer. We believe these students were unable to identify rules and associate them with common sense. Therefore these students predominately chose options that involved incorrect knowledge. They had not acquired any concepts of justification and scientific meaning in terms of the very foundations of PEP and so as a result showed extreme difficulty of realization and recognition.

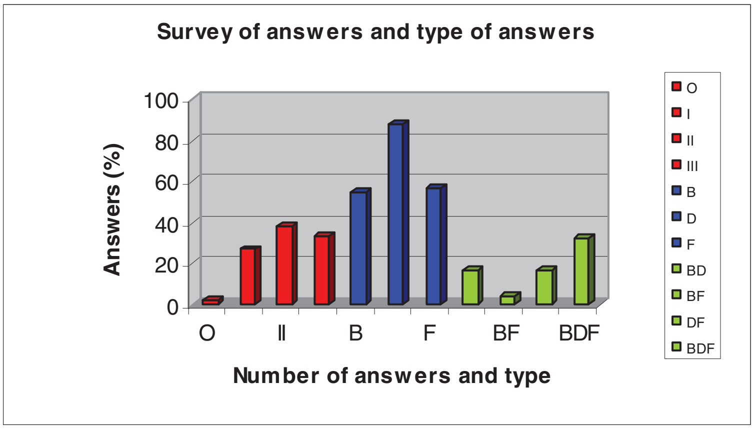

Figure 2. Survey of students answers and type of answers:0 = no correct answers; I = one correct answer; II = two correct answers; III = three correct answers.

The total number of students giving BD and DF two correct answer combinations (64 students) was the same as the total number of students giving BDF three correct answer combination (64 students). Only 8 students (4% of the students) were able to give the BF correct answer combination; this is an insignificant number. Therefore we can say that the number of students giving two correct answers were comparable to the number of students giving three correct answers. The most popular single correct answer was D; almost 90% of students properly answered "D". This is the single most promising result and showed that perhaps students understood the theory in its most basic form. In comparision, fewer students were able to give B; this may show that perhaps there was some difficulty conceptualizing what a fermion was. Likwise, fewer students were able to give F; this revealing that students were not able to see the utility of what they have learned.

Students who were able to give correct answers demonstrated their ability to recognize information that was either familiar or important. Also these students were able to identify rules and associate them with common sense. Thus this is indicative of a high level of learning being achieved. We believe the reason why students who were unable to give correct answers was that they had difficulty recognizing material and had difficulty noticing when it was important. Additionally, we believe that these students may have used incorrect reasoning strategies leading to a distractor that would be attractive to students with prior misunderstandings about PEP.

We recognise that the results may be represented in several different ways and in order to identify the suggestions assimilated for part I of the diagnostic survey, keywords were picked from long written descriptions. The written answers led to eight types of descriptions and are represented in Figure 3.

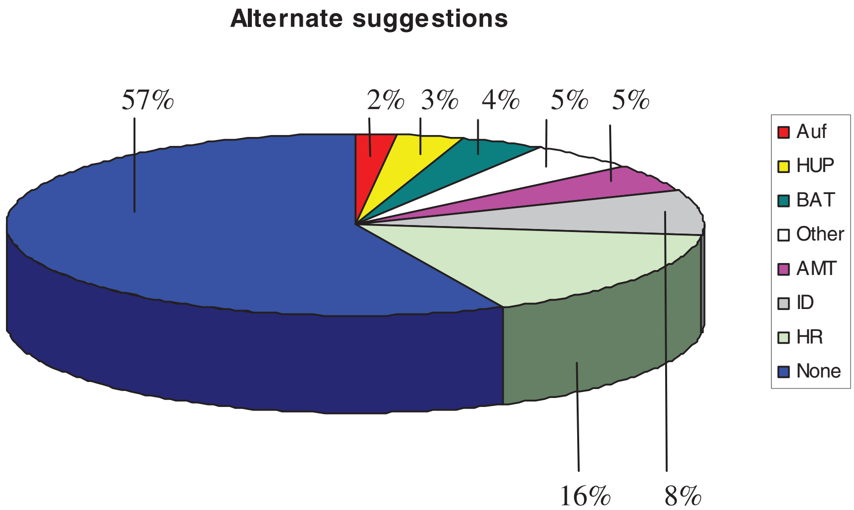

Figure 3. Students alternate suggestions to PEP: HR = Hund's Rule; AMT = Atomic Molecular Theory; BAT = Bohr Atomic Theory; Heisenberg Uncertainty Principle; Auf = Aufbau Principle; Other = Other explanations or theories; ID = Indiscernible comments, explanations or theories.

Part I of the diagnostic survey required the students to think and were invited to express their thoughts and ideas. As the students were not specially prepared for the survey, they had to activate their momentary knowledge. The students were only able to suggest was already known. They were only able to give single one word or one phrase answers and did not expand or discuss them in detail. For example, several students suggested Hund's Rule with no further explanations. One can assume that perhaps the students were afraid of writing down something "improper" or "inaccurate", as there were no time constraints for the survey. Figure 3 shows that most of the students were unable to suggest anything. However 8% of the students were more assertive and were able to suggest something, although examination revealed that they were not of any sound value. These answers were classified as indiscernible. Such indiscernible suggestions include an acid-base theory with no further explanation. Another was a principle of atoms creating other atoms, again with no accompanying discussion. One student suggested something slightly reminiscent of the Schrödinger solutions, suggesting that an electron has its own quantum number, and that it occupies an orbital according to its own specific quantum number.

The aim of Part I of the survey was to see if students were able to demonstrate any epistemological understanding of science in general and whether their former scientific experience and knowledge could contribute to their cognitive development. The data revealed student's difficulties in either expressing their ideas and thoughts, or just actually being unable to conceptualize scientific knowledge.

4. Conclusion

Throughout our daily lives, as human beings we are unable to differentiate between matter and its meaning. We are truly magnificently complex and interesting creations. We do not know the meaning of many things, but still we use them fearlessly. What if PEP did not exist! What would we eat and drink? Would carbon and oxgen not have existed? An alternative concept may be related to Mendel's Theory. The evolution of Mendel's Principle of Inheritance in 1866 (Mendel, 1865; Mendel, 1866) led to the 1916s, X/Y - chromosomal inheritance discovery by Morgan and Bridges (Morgan, Sturtevant, Muller & Bridges, 1916). This discovery in essence is to discriminate one form from another, and thus if PEP not was enunciated in 1925, we believe there would most certainly have been some alternate predicament. Mendel and Morgan and Bridges discoveries could have been suitably extended to perhaps introduce X and Y states, or female and male states, respectively. The quantum numbers n, l and m_l may still be applicable as they are today, and in place of the spin quantum number ms there may have been something called a 'gender quantum number m_g', where when m_g = X, an electron is in the female state, and when m_g = Y, the electron is in the male state. As Mendel's Theory is compatible with the PEP timeline, this may well have been a plausible alternate form of PEP.

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