We discuss the influence of gravitational forces on bulk molecular properties and intermolecular interactions. We show that the Earth's gravitational field influences molecules to a much greater extent than the traditional intermolecular forces (ionic, ion-dipole, dipole-dipole and dipole-induced dipole). Nonetheless, the influence of gravitation on bulk properties e.g. boiling point elevation is negligible due to the cancellation effect which is due to the Earth's size and flatness of gravitational potential in the vicinity of Earth surface.
Abstract:

We discuss the influence of gravitational forces on bulk molecular properties and intermolecular interactions. We show that the Earth’s gravitational field influences molecules to a much greater extent than the traditional intermolecular forces (ionic, ion-dipole, dipole-dipole and dipole-induced dipole). Nonetheless, the influence of gravitation on bulk properties e.g. boiling point elevation is negligible due to the cancellation effect which is due to the Earth’s size and flatness of gravitational potential in the vicinity of Earth surface.

Keywords:

Intermolecular interactions, bulk properties, gravity
Introduction

Some bulk properties of chemical compounds like the boiling point or vapor pressure of a pure substance are usually related to molecular masses and to polarizability of electron densities of outermost electrons [1,2]. It was established that the total intermolecular interactions which govern these bulk properties do not include gravitational forces between molecules. Such forces have been found to be too small to lead either to the association of atoms into molecules or to the association between molecules generating bulk matter [3]. However, few quantitative explanations in the chemical educational literature exist. The purpose of this article is twofold. Students readily accept the misconception that molecules with larger masses (being “heavier”) are less able to evaporate because of their everyday experience regarding the motions of heavy objects. The counterexample which is usually mentioned in order to help unlearn this misconception is the case of isomers which have different vapor pressures and boiling points even though their molecular (and molar) masses are identical. We provide additional insight into the reason why gravitational force is so ineffective. Furthermore, the method which we employ analyzes the problem with order-of-magnitude estimates of energies and forces. The development of skill of estimating the range of possible values within which the true solution to the problem lies is not often stimulated by existing tutorial problems in textbooks and exams. This skill is essential for problem solving because it provides a simple feedback regarding plausibility of the proffered solution. Students often lean towards generating false accuracy in their numerical answers to the problems by ignoring the correct number of significant digits and
copying down the answers given by calculators. They often embrace the misconception that only accurate numerical results, with large number of significant digits can provide answers to scientific questions.

**Discussion**

We begin by noting that the order of magnitude of intermolecular interaction energies (for ionic, ion-dipole, dipole-dipole and dipole-induced dipole interactions) is within the 0.05-276.0 kJ/mol range [4]. We proceed next to calculate the magnitudes of two types of possible gravitational interactions: between Earth and individual molecule on its surface and between two individual molecules themselves. In order to calculate the magnitudes of these interaction energies we use the well known expression which describes the attractive gravitational potential between two masses M and m separated by the distance r

\[ V = \frac{(G M m)}{r} \]  \hspace{1cm} (1)

We also note that gravitational interactions are temperature independent.

We use the values of Earth’s mass and radius which are: \( r_E = 6.378 \times 10^6 \) m and \( M = 5.976 \times 10^{24} \) kg, respectively [5]. \( G = 6.672 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-1} \) is the gravitational constant [5] and m corresponds to the mass of molecule of a particular chemical compound. When calculating the gravitational potential energy due Earth’s field the value in the equation (1) can be set equal to \( r_E \). This is because practical chemical operations involving our molecules take place very close to the Earth’s surface. The Earth and its gravitational field can be assumed to be approximately spherically
symmetric. Therefore, the magnitude of gravitational potential exerted by Earth on its surface can be calculated by assuming that all of the Earth’s mass is concentrated at its core (center-of-mass) [3]. The separation between the Earth core and our molecules then approximately equals $r_E$. We shall use as an example a hypothetical compound A with molar mass of 200 g/mol which is equivalent to the molecular mass of $m = 3.3 \times 10^{-25}$ kg. Plugging the values into the equation (1) gives the attractive gravitational potential energy at Earth surface for one molecule of A as $2.063 \times 10^{-17}$ J. Multiplying by Avogadro’s constant we obtain total attractive gravitational energy (between Earth and 1 mole of A) as 12503 kJ/mol. This value is much larger than the range of intermolecular interaction energies originating from electromagnetic forces mentioned above! On the other hand, assuming that our molecules of A approach each other to within $1 \text{Å} = 10^{-10}$ m we can also calculate the upper limit of the attractive gravitational energy between the two molecules of compound A. After entering suitable values in (1) we obtain the gravitational potential energy of $7.36 \times 10^{-50}$ J for the interaction between two identical molecules of A. This corresponds to a very small attractive gravitational potential of $\frac{1}{2}(4.43 \times 10^{-26})$ J/mol. The factor $\frac{1}{2}$ ensures that we do not count gravitational interactions twice. We can conclude that intermolecular gravitational interactions are negligible due to the smallness of molecular masses [3]. On the other hand the gravitational interaction energies between Earth and bulk matter are far from negligible when compared to intermolecular interactions within the bulk matter itself.
Why should gravitational attractive forces then be neglected when considering bulk physical properties? The explanation for neglecting interactions between Earth and the molecules on its surface can be outlined as follows. Manipulations involving molecules in the chemical laboratory (e.g. distillation) take place within the range of a few tens of meters away from the Earth’s surface and the Earth’s gravitational field varies very slowly at large distances from the core. To verify this assertion one can substitute the value of $r_{E}+10$ (which corresponds to the molecules of A being carried up to the height of 10 m) into the equation (1) and show that the gravitational potential energy remains unchanged. Therefore the gravitational potential energy remains unchanged during laboratory operations; the free energies of final and initial states of matter in our processes (e.g. vaporization of compound A) contain equal contributions from the Earth’s gravitational field and thus cancel out in $\Delta G$ for the process.

The cancellation of gravitational effects ensures that intermolecular interactions based on electromagnetic forces wield the controlling influence since they are different in the initial and final states of A.

Does the attractive gravitational energy change if molar mass of substance is different? To illustrate the effect let us assume that we now have another compound B with molar mass of 210 g/mol. Using equation (1) as before gives the attractive gravitational potential energy for B as 13128 kJ/mol. The two gravitational potential energies for substances A and B differ by almost 800 kJ/mol! Does this imply (in accordance with the student misconception) that heavier molecules should indeed have higher boiling points and lower vapor pressures? Not at all, as
the examples quoted in textbooks show. One such example is the comparison between measured vapor pressures at 300K of H$_2$S (2181 kPa) and ammonia (1062 kPa). The vapor pressure of the former is larger even though H$_2$S molecules are heavier than the ammonia molecules. This example disproves the misconception linking mass and vapor pressure. Why is that so? For the same reason as was already discussed; the flatness of gravitational potential in the immediate vicinity of Earth’s surface leads to the cancellation of gravitational contribution to free energy change in A as well as in B. If gravitational contributions in both cases are nil it is obvious that difference in bulk properties e.g. in vapor pressures between A and B must be attributed to intermolecular interaction energies of electromagnetic nature. These energies do not cancel when A and B undergo changes because intermolecular interaction potentials vary significantly with distance within the span of intermolecular separations applicable to solid, liquid and gas phases.

We have presented the example of a problem where students have to compare different forces which act on molecules. Out of the four fundamental forces in Nature: weak/strong nuclear, gravitational and electromagnetic only the last one influences the behavior of matter commonly encountered in chemistry which we practice. This single type of force gives rise to the immense richness and diversity of Life. Whether other forces do the same in distant galaxies by generating other types of objects is an open question which can be profitably discussed in the class in order to stimulate students’ interest in Science and to establish conceptual links with Physics. Another usefulness of the example discussed in this note is that student has to apply critical thinking carefully in order to deduce the existence of
cancellation effect. The problem discussed is suitable for undergraduates taking
general chemistry subject and does not require sophisticated mathematical skills. It
is best incorporated into the discussion of different states of matter and forces
which are involved in determining their properties.
References and Notes:


