

Molar Mass and Second Virial Coefficient of Polyethylene Glycol by Vapor Pressure Osmometry

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S Supporting Information

ABSTRACT: In this laboratory experiment, students determine the number-average molar masses and second virial coefficients of polyethylene glycol (PEG) polymers ranging in molar mass from 200 to 1500 g mol⁻¹ using vapor pressure osmometry (VPO). Students assess VPO in relation to accurate molar mass calculations of PEG polymers. Additionally, students use the second virial coefficients to identify any PEG self-interactions and any dependence of the second virial coefficient on PEG molar mass. This laboratory experiment is suitable for a biophysical or physical chemistry laboratory.



KEYWORDS: Upper-Division Undergraduate, Laboratory Instruction, Physical Chemistry, Polymer Chemistry, Hands-On Learning/Manipulatives, Aqueous Solution Chemistry, Physical Properties, Solutions/Solvents, Thermodynamics

The ACS Committee on Professional Training now considers polymer chemistry integral to a curriculum for certified ACS graduates.¹ The inclusion of polymer chemistry in the undergraduate curriculum is important since nearly 50% of all professional chemists work within some area of polymer chemistry.² However, many instructors are unable to dedicate large amounts of time to polymer chemistry in established chemistry courses such as organic or physical chemistry. Therefore, inclusion of simple polymer lab experiences or classroom exercises that illustrate polymer synthesis or the physical chemistry of macromolecules is encouraged to expose students to the higher order interactions of macromolecular systems.^{3–7}

Fundamental to the physical chemistry of polymers is determination of molar mass and the second virial coefficient. Techniques such as freezing point depression,⁸ laser light scattering,⁹ membrane osmometry,¹⁰ and vapor pressure osmometry (VPO)¹¹ can be used to characterize both the molar mass and second virial coefficient of a polymer. VPO offers fast and reliable measurements of the osmolality of an aqueous solution with relatively small instrument cost buy-in (between \$5,000 and \$10,000 USD). Additionally, common physical chemistry laboratory textbooks primarily utilize viscosity measurements to obtain viscosity-average molar masses (as opposed to number-average molar masses from VPO) or membrane osmometry with inconvenient long equilibration times. In this experiment, suitable for an advanced, biophysical, or physical chemistry laboratory, students use VPO to determine the number-average molar

mass and second virial coefficient of polyethylene glycol (PEG). PEG is a water-soluble polymer of ethylene oxide and is commercially available with molar masses that range between 200 and 20 000 g mol⁻¹ (polymers of ethylene oxide larger than this are referred to as poly(ethylene oxide)). PEG has numerous applications that depend on molar mass and is routinely used in medical devices, drug development and delivery, wound healing, cosmetics, surfactants, laxatives, and lubricants.^{12–14}

BACKGROUND

Osmolality of a solution represents the effect of all solutes on colligative properties such as vapor pressure, freezing point or boiling point. Osmolality is equal to the molality of an ideal dilute solute that would have the same chemical potential as the real solute at the solution composition of interest. While ideal, dilute solutes affect colligative properties without regard to solute size or shape. This is not so of nonideal or nondilute solutions for which the nonideality of the solute is dependent on the solute type and properties. For nonelectrolytes, the osmolality (Osm) of a solution is the product of the molal osmotic coefficient and the molality of the solute. As the solute concentration approaches zero, the osmotic coefficient approaches 1 and Osm approaches the solute molality (a characteristic of an ideal solution).¹⁵

The osmolality of a solution can be measured using a vapor pressure osmometer. A vapor pressure osmometer measures



the solvent vapor pressure depression as the solute concentration increases. Some vapor pressure osmometers rely on measuring the temperature difference between pure solvent and solution using thermistors. This temperature difference arises from the exothermic condensation of pure solvent vapor on the solution as the vapor pressures of solvent and solution move toward equilibrium. Other vapor pressure osmometers rely on measurement of the difference in ambient versus dew point temperature in the sample chamber. In both cases, the difference in temperature is proportional to the number of solute particles and solute osmolality.

Solution osmolality can be used to determine the molar mass and second virial coefficient of solute molecules. Since osmolality is a measure of the total number of solute particles in solution, the solute molar mass M_s (PEG in our experiment) is understood to be the number-average molar mass of the polymer solute (molar mass weighted by the number of polymer molecules with a given degree of polymerization).¹⁰ The second osmotic virial coefficient A_2 provides a measure of the strength of solute–solute and solute–solvent interactions ($A_2 > 0$, solvent–solute interactions are favored; $A_2 < 0$, solute–solute interactions are favored, potentially leading to aggregation and precipitation).¹⁰ Both M_s and A_2 can be extracted from a plot of mass concentration-normalized osmolality Osm/ c_s versus mass concentration c_s of solute using eq 1^{8,10,11,15}

$$\frac{\text{Osm}}{c_{\rm s}} = V_{\rm w} m_{\rm w}^* \left(\frac{1}{M_{\rm s}} + A_2 c_{\rm s} + A_3 c_{\rm s}^2 + \dots \right)$$
(1)

where V_w is the molar volume of water (18.07 mL mol⁻¹ at 25 °C), m_w^* is the molality of water (55.51 mol kg⁻¹), and A_3 is the third virial coefficient. A more detailed development of eq 1 is given in the Supporting Information. Equation 1 assumes a dilute solution so that mass concentration c_s (kg of solute per liter of solution) is used instead of solute mass per volume of solvent (necessary for $V_w m_w^*/M_s$ and $V_w m_w^*A_2$ to provide correct values and units for M_s and A_2). The third virial coefficient is significantly harder to interpret than the second virial coefficient, but is a measure of interactions between three solute molecules.^{8,11} As with A_2 , nonzero A_3 values indicate deviation from ideal solution behavior. A plot of Osm/ c_s versus c_s should resemble a quadratic function (as long as A_3 is not zero) with a *y*-intercept of $V_w m_w^*/M_s$.

EXPERIMENTAL OVERVIEW

Students work in pairs to measure the osmolalities of aqueous PEG 200, 600, 1000, and 1500 solutions using a Wescor 5520 vapor pressure osmometer. Additional vapor pressure osmometers are available from companies such as Knauer Wissenschaftliche Geräte GmbH or Gonotec. Student groups use their measured PEG osmolalities along with multiple linear regression of eq 1 to calculate the molar mass and second virial coefficient of their assigned PEG samples.

Instructors may wish to modify this experiment. The polymer molar mass upper limit for most vapor pressure osmometers is 10 000 g mol⁻¹. Thus, PEG samples with larger molar masses than those used in this study could be used if the instructor wishes. Additionally, water-soluble polymers such as dextran with molar masses applicable for VPO could be used for comparison of second virial coefficients.¹⁶

This experiment has been conducted by three groups of two students within our biophysical chemistry course and advanced laboratory. Students were able to complete calibration of the vapor pressure osmometer, data collection, and data analysis within two to three 4 h lab periods. If this amount of time is not available for the instructor, students can be assigned a single PEG to gain appreciation for the technique. This would allow more student throughput on the vapor pressure osmometer within a 4 h period (the typical physical chemistry or advanced laboratory period time). Data collection for a single PEG polymer typically requires 15 min including solution preparation and VPO measurement.

EXPERIMENTAL PROCEDURE

A detailed explanation of the experimental procedure is provided in Supporting Information, but a brief description is provided here. The instructor introduces operation of the vapor pressure osmometer to students. Instructors may wish to calibrate the instrument before lab if the students do not have time in lab to complete both calibration and data collection. If students have time, they can calibrate the instrument with sodium chloride standards provided by the osmometer's manufacturer.

For each dry PEG sample, lab groups should prepare a minimum of six to seven aqueous PEG solutions with osmolalities between approximately 0.09 and 2.0 mol kg⁻¹. Fewer data points will often lead to more error in multiple linear regression coefficients of eq 1. We use 0.09 mol kg⁻¹ as our lowest osmolality reading since our Wescor 5520 vapor pressure osmometer's response is linear from approximately this osmolality to 3.5 mol kg⁻¹. The minimum concentration will vary with the specific manufacturer and model of vapor pressure osmometer.

We ask our students to start by preparing a 0.10 kg L^{-1} PEG solution using a 10 mL volumetric flask and an analytical balance. PEG osmolalities are measured twice and averaged, taking care to have the two osmolality readings within 0.003 mol kg⁻¹. If students have difficulty obtaining this level of precision, they may need to practice their loading technique or the instructor may have to clean a contaminated thermocouple or confirm the micropipettor is delivering a consistent sample volume. Students then prepare a second PEG solution to obtain a reading near 0.09 mol kg⁻¹ (assuming mass concentration is proportional to osmolality). The osmolality of this solution is measured twice and averaged. For the next four to five PEG solutions students prepare, the average osmolality values for all six to seven PEG solutions should be nearly evenly spaced within the range of 0.090 to 2.0 mol kg⁻¹ (again, the lower bound will vary by manufacturer).

Students generate plots of Osm/ c_s versus c_s for each PEG polymer. According to eq 1, a quadratic of Osm/ c_s versus c_s using multiple linear regression yields a *y*-intercept of $V_w m_w^*/M_s$ and the c_s term has a coefficient of $V_w m_w^*A_2$. M_s and A_2 can be solved from these coefficients using values for V_w (18.07 mL mol⁻¹ at 25 °C) and m_w^* (55.51 mol kg⁻¹). Errors from multiple linear regression can be used, along with propagation of error, to determine standard errors in M_s and A_2 . We did not ask students to solve for the third virial coefficient since it often has large error associated with it and a lack of references for comparison.^{8,11}

HAZARDS

PEG is classified as a nonhazardous material, but gloves and eye protection should be worn when handling pure PEG and

aqueous solutions. PEG samples should not be eaten, despite its extensive commercial use. In case of skin contact, wash skin with warm soapy water. Eyes should be flushed with water if exposed to PEG.

RESULTS AND DISCUSSION

Figure 1 shows representative student plots of Osm/c_s versus c_s for PEG 200 and 1500, the smallest and largest PEG polymers



Figure 1. Representative plots of mass concentration-normalized PEG osmolality (Osm/c_s) as a function of PEG mass concentration (c_s) for PEG 200 (A) and PEG 1500 (B). Solid curves from regression analysis assuming a quadratic function using eq 1.

used by our students. Representative values for M_s and A_2 from a pair of students are tabulated in Table 1. M_s values are in excellent agreement with the known molar mass of the PEG samples. In addition, A_2 values are in excellent agreement with PEG second virial coefficients from freezing point depression⁸ and VPO.¹¹

Table 1. PEG 200, 600, 1000, and 1500 Molar Masses and Second Virial Coefficients from VPO

Samples	$M_{\rm s}^{\ a}/{ m g\ mol^{-1}}$	$A_2 \times 10^{3a}$ /mol mL g ⁻²
PEG 200	194 ± 4	6.12 ± 1.85
PEG 600	605 ± 29	6.97 ± 0.96
PEG 1000	1030 ± 140	6.23 ± 2.26
PEG 1500	1580 ± 280	4.58 ± 1.15

 ${}^{\prime\prime}M_{s}$, A_2 and standard errors were derived from multiple linear regression of Osm/ c_s as a quadratic function of c_s using eq 1.

Students were assessed in their ability to achieve accurate M_{e} and A_2 values. Students were also expected to use PEG A_2 values to qualitatively predict the favorability of PEG selfinteractions. Since the A2 values obtained in this experiment were all positive, PEG-solvent interactions were preferred over PEG-PEG interactions, presumably due to hydrogen bonding with water. We stressed to students that A_2 was temperature dependent and that the A_2 values they obtained were specific to ambient temperature using the Wescor 5520 vapor pressure osmometer. Instructors that wish to explore the temperature dependence of A_2 should select more advanced vapor pressure osmometers than the Wescor 5520 vapor pressure osmometer. Students were also asked to identify any dependence of PEG second virial coefficient on PEG molar mass. As seen in Table 1, no obvious dependence of A_2 on M_s exists given standard errors, again in agreement with freezing point depression⁸ and VPO.¹¹ The dependence of A_2 on M_s is expected to be small or negligible due to the balance of polymer–solvent and polymer–polymer interactions.^{8,10}

CONCLUSION

This experiment exposes students to VPO and solution osmolality to determine the number-average molar mass and second virial coefficient of PEG polymers. This experiment could span several lab periods or just a single lab period in an advanced, biophysical, or physical chemistry lab depending on the instructor's goals. Student analysis of the data yielded reliable PEG number-average molar masses and second virial coefficients that compared favorably with literature values. Students were assessed in their ability to obtain accurate PEG molar masses and second virial coefficients, successfully complete a multiple linear regression of the data, and qualitatively predict if PEG-PEG or PEG-solvent interactions were favored based on the PEG second virial coefficient. Modifications to this experiment are suggested to include larger PEG molar masses or different water-soluble polymers for comparison to PEG second virial coefficient values.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00369.

Instructor notes, student prelab and experimental instructions, and representative student data (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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