AP Physics - Kinetic Theory of Matter

She floated into my office like a cloud of French perfume wrapped around sheer black lace. The dame looked at me out of her big baby blues and said, "Are you Mr. Spear?" Her eyes were the kind that a man would dream about in the darkest part of the night – dream of drowning in the deep waters of a whirlpool at the bottom of a tall waterfall.

"That's what the name on the door says, sister." I told her. I ran my eyes over her from the bottom of her stiletto heels to the top of her long, curly hair. She was a blond, her hair was so yellow that it would make a canary look gray. I licked my lips. Everything about her said class. She was wearing a black dress that didn't keep any secrets – she was all woman.

"I need to employ a private detective to look into certain, well, shall we say, delicate matters. Are you up to the job?"

"I'm up for anything, sweetheart. What do you have in mind?"

"Don't get fresh, I loathe hired help taking liberties."

"Who says I'm hired? I may not take the job."

"You'll take the job. You must take the job! I'll pay whatever you want."

"You don't know what I want, lady. You may not be able to pony up my fee." She opened her patent leather purse and pulled out a stack of greenbacks that would choke a sperm whale. She peeled off about two inches of c notes and laid them on my desk.

"Will this serve as a retainer?"

"Lady, you just hired yourself a shamus. What's the caper?"

"My boyfriend, Floyd Gutman, is missing."

"What makes you think he didn't just take off?"

She looked at me out from under one long set of eye lashes that were at halfmast, pursed her lips and said, "Can I call you, Sam?"

I picked up the bills, folded them in half, and slid them into my jacket pocket. "For this much dough you can call me Dapper Dan the Dancing Man."

Her ruby red lips twitched into the semblance of a smile for about two and a half microseconds. I decided she just might be human after all. "Sam, a gentleman acquaintance of mine has suddenly turned up missing. I want you to find him. As for his just 'taking off' as you put it, do you think any man would 'just take off' from a woman like me?"

The dame had a good point.

"So what's this mug mean to you? He your fiancée, boyfriend, something like that?"

"You might call him my traveling companion."

"Okay, sister, I get fifty bucks a day and expenses and I don't do nothing illegal." I ran my thumb over the bills. You got a picture of this galute?

"Why, yes, here in my evening bag let me

Blast: You know, it's happened again. This informative, quality work of physics has been hijacked by some really horrible gumshoe prose. The Physics Teacher thinks that this is probably the fault of his administrative assistant. You may rest assured that the offending bureaucrat will be dealt with harshly.   This must not happen again!

Kinetic Theory of Matter:

We've been using the kinetic theory of matter to explain thermal energy and the transfer of heat from one system to another.

To put this down in a formal way, one can write down the key concepts about the kinetic theory. The kinetic theory can be used for all states of matter, but for some reason, the theory seems to concentrate on gases.

These are the main assumptions for the theory. You should be familiar with them. Again, this is for a gas.

1. The number of particles in a system is enormous and the separation between the particles is huge.

2. All the particles move randomly.

3. The particles have perfectly elastic collisions with each other and other atoms.

4. There are no forces of attraction between the particles of a gas.

5. All the particles are identical.

One of the things you laboriously mastered in chemistry was the good old mole. Remember the mole?

Here is the definition of a mole:

Mole $\equiv$ ***Avogadro's number of a thing.***

Okay, so what is Avogadro's number? Well, that's the number of things in a mole, like 12 is the number of things in a dozen.

$$Avogadro's\ Nr \quad = N_A \quad = \quad 6.02\ x\, 10^{23}\ thingees$$

A mole, like a dozen, is a counting unit and is of very little use for most things. For example, you would not want to go to Burger King and order a mole of french fries. If they actually had enough french fries to make the sale, you would have so many french fries that you could probably cover the surface of the earth with them to a pretty good depth.

This is because a mole is a really big, huge, vast, enormous, gargantuan number.

Moles are very useful, however, when we want to deal with large numbers of very small things. That is why you made use of moles in chemistry for atoms and molecules.

That is what we will do in AP Physics as well.

The number of moles present in a sample is quite easy to calculate:

$$n = \frac{N}{N_A}$$

n is the number of moles, ***N*** is the number of particles in the system, and $\boldsymbol{N_A}$ is Avogadro's number.

The properties of a gas can be described by the ideal gas law. This is one of the real staples of chemistry.

$$PV = nRT$$

P is pressure, ***V*** is volume, ***n*** is the number of moles, ***R*** is the universal gas constant, and ***T*** is the temperature in Kelvins.

You will be provided with this equation on the AP Test.

There are two values for the universal gas constant that we will make use of. We need different values of R for when we use different units. Change the units you use in the equation and you change the value of ***R*** that you need to use.

$$R = 8.31 \frac{J}{mol \cdot K}$$ Use for the SI system

$$R = 0.0821 \frac{L \cdot atm}{mol \cdot K}$$ This is the one you probably used in chemistry.

mol is the abbreviation for a mole.

You probably remember three gas laws from chemistry as well; Boyle's law, Charles' law, and Gay-Lussac's law. These laws described the behavior of a system that was undergoing change. In Boyle's law, the pressure and volume change while the temperature stays constant. Charles' law deals with volume and temperature. Gay-Lussac's law is about pressure and temperature. All three of them can be put together in the combined gas law.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

If the temperature doesn't change, then you get Boyle's law: $P_1V_1 = P_2V_2$

And so on.

You will not be provided with any of these laws, but they are easy to develop from the ideal gas law. We solve the ideal gas law for ***R***, the universal gas constant.

$$PV = nRT \qquad R = \frac{PV}{nT}$$

Now we look a system that is undergoing a change – temperature, pressure, or volume. We have a set of initial conditions and a set of final conditions:

$$R = \frac{P_1V_1}{nT_1} \qquad and \qquad R = \frac{P_2V_2}{nT_2}$$

Both expressions equal ***R***, so we can set them equal to each other.

$$\frac{P_1V_1}{nT_1} = \frac{P_2V_2}{nT_2}$$

The number of moles hasn't changed, so the ***n*** term cancels and we have the combined gas law.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Energy of the Particles: *Temperature is a direct measure of the kinetic energy of the particles. We can find the average kinetic energy of a particle by using the following equation:*

$$K_{avg} = \frac{3}{2}k_BT$$

K_{avg} is the average kinetic energy per particle for the gas, k_B is known as Boltzmann's constant, and ***T*** is the temperature in Kelvins. This would be the amount of kinetic energy for a single particle.

The value of Boltzmann's constant is: $k_B = 1.38\,x\,10^{-23}\,\frac{J}{K}$

You will be provided with this equation (and the value of the different constants) on the AP Test.

- What is the average kinetic energy per molecule of a tank of oxygen gas at 22.0 °C?

$$K_{avg} = \frac{3}{2}k_B T \qquad\qquad T_K = T_C + 273.15$$

$$T_K = 22.0^\circ + 273.15 \quad = 295.15\,K$$

$$K_{avg} = \frac{3}{2}\left(1.38\,x\,10^{-23}\,\frac{J}{\cancel{K}}\right)\left(295.15\,\cancel{K}\right) \quad = 611\,x\,10^{-23}\,J$$

$$K_{avg} = \boxed{6.11\,x\,10^{-21}\,J}$$

Botzmann's constant is given by:

$$k_B = \frac{R}{N_A}$$

Where k_B is Boltzmann's constant, R is the universal gas constant, and N_A is Avogardro's number.

To find the total kinetic energy of the gas, you just need to multiply the average kinetic energy per particle by the number of particles.

$$E = \frac{3}{2}Nk_B T$$

Total kinetic energy of system.

E is the total kinetic energy of the system, N is the number of particles in the system, k_B is Boltzmann's constant, and T is the temperature in Kelvins.

We also know that Boltzmann's constant is given by:

$$k_B = \frac{R}{N_A}$$

Plug this into the total energy equation and we get:

$$E = \frac{3}{2}Nk_B T \quad = \frac{3}{2}N\left(\frac{R}{N_A}\right)T$$

But $\dfrac{N}{N_A}$ is simply the number of moles in the system, so the equation becomes:

$$E = \frac{3}{2}nRT$$ Total kinetic energy of a gas system.

You will not be provided with this equation. Be prepared to derive the thing.

- Find the total energy in a tank that has 2.50 mol of helium at 25.0 °C.

T = 298.15 K $E = \frac{3}{2}nRT$

$$E = \frac{3}{2}\left(2.50\ mol\right)\left(8.31\frac{J}{mol \cdot K}\right)\left(298.15\ K\right) = \boxed{9\,290\ J}$$

Pressure of a Gas: We can explain the behavior of gases and the origin of pressure using the kinetic theorem. You need to understand how the theorem does this.

Within the system there is a huge number of particles smashing into each other and into the walls of the container. These collisions transfer energy and exert forces on the particles. Each time a gas molecule smashes into the container wall, it pushes it outward. It exerts a force on the wall. Add all these forces up and you have an average force that is fairly constant over time. Divide the average force by the area and you get the pressure.
The collisions are responsible for the gases' pressure.

When you blow up a balloon, it gets larger. Why?

Let's look at a partially inflated balloon. Inside the balloon, the air molecules are busy smashing into the interior surface of the balloon, pushing it out. But there are air molecules on the outside of the balloon having collisions with it, pushing it in. An equilibrium develops in which the force pushing in on the balloon is equal to the force pushing out on the balloon. So the balloon stays the same size.

Now you blow additional air into the balloon. More air molecules mean more collisions with the inside surface of the balloon, so the balloon is pushed outward and the balloon get bigger. Eventually the balloon is big enough so that there are more collisions with air molecules on the outside. Eventually the force from the outside collisions becomes equal to the force from the collisions on the inside. A new equilibrium is reached and the balloon has a new size.

What happens when you increase the temperature of the system?

The particles gain kinetic energy, the collisions with the container are more violent, so they push harder. The force increases, therefore the pressure increases. If the system cools, just he opposite happens.

Average Velocity of a Particle: The average velocity of a particle is given by this equation:

$$v_{rms} = \sqrt{\frac{3RT}{M}} = \sqrt{\frac{3k_B T}{m}}$$

$\boldsymbol{v_{rms}}$ is the root mean square velocity (figure average) of the particle, $\boldsymbol{R}$ is the universal gas constant, $\boldsymbol{T}$ is the temperature in Kelvins, $\boldsymbol{M}$ is the molecular mass (mass for one mole of an element or compound), $\boldsymbol{k_B}$ is Boltzmann's constant, and $\boldsymbol{m}$ is the mass of a single particle.

You will be provided this equation on the AP Test.

- ***What is the average velocity of the particles of oxygen at 255 K?***

We'll use this equation:

$$v_{rms} = \sqrt{\frac{3k_B T}{m}}$$

First we need mass of an oxygen molecule.

$$1\, molecule \left(\frac{1\, mol}{6.02\, x\, 10^{23} molecules}\right)\left(\frac{32.0\, g}{1\, mol}\right)\left(\frac{1\, kg}{10^3\, g}\right) = 5.316\, x\, 10^{-26}\, kg$$

$$v_{rms} = \sqrt{\frac{3\left(1.38\, x\, 10^{-23} \frac{kg \cdot m^2}{K \cdot s^2}\right)(255\, K)}{\left(5.316\, x\, 10^{-26}\, kg\right)}} = \sqrt{198.6\, x\, 10^3 \frac{m^2}{s^2}}$$

$$v_{rms} = \sqrt{19.86\, x\, 10^4 \frac{m^2}{s^2}} = \boxed{446 \frac{m}{s}}$$

Dear Cecil:
If cold is simply the absence of heat, i.e., the absence of rapidly moving molecules of water or air, then how come vacuum-packed canned food doesn't come out frozen, or at least very cold? And then if you walked a hundred feet out of your spaceship with a glass of water, would the water freeze because of the vacuum, or would it boil since there's no air pressure or barometric pressure to overcome?

--Barry H., Chicago

Cecil replies:
Christ Almighty, Barry, you're asking for a short course in thermodynamics. Don't you guys want to know about Neil Sedaka anymore?

Let's clear up a couple misconceptions to start with. First, your idea that cold is "the absence of rapidly moving molecules of water or air" is a bit confused. Cold refers to very slow-moving molecules of anything, whether water, air, or Eskimo Pies. If you have no molecules at all, the concept of temperature is meaningless. That's why it's technically incorrect to speak of the "cold of outer space"--strictly speaking, space has no temperature, period. (On the other hand, space will make objects that are floating around in it cold--in some cases, very cold. Space is what's known as a "temperature sink," meaning it sucks heat out of things. But we'll get back to this in a minute.)

Second, a vacuum never causes water to freeze; it causes water to boil. As air pressure decreases, so does boiling point. That's why water boils much faster on a mountaintop than it does at sea level. By the same token, you can make water boil at room temperature in the laboratory by applying a partial vacuum.

Now then. The contents of an earthbound vacuum-packed can do not freeze because they're in contact with the sides thereof--they absorb room heat by conduction. There is no room heat in space, though, so the temperature of a solid object floating in the void consists of the difference between the heat the object absorbs from the sun and the internal heat it radiates away. This temperature is dependent on such things as the reflectance of the object's surface, its shape, mass, orientation toward the sun, and so on.

Polished aluminum will absorb sufficient heat to raise its temperature as high as 850 degrees Fahrenheit; certain types of white paint, on the other hand, absorb so little heat that their temperature may not get much above -40 Fahrenheit, even in full sunlight. Parts of the space shuttle get down to -180 to -250 degrees Fahrenheit.

Theoretically, the temperature of an object in deep space could get down pretty close to absolute zero, -460 degrees Fahrenheit. But even in the middle of nowhere there's enough in the way of stray particles and radiation to heat thing up to 3 degrees Kelvin--that is, the equivalent of 3 degrees Celsius (5 degrees F) above absolute zero.

Finally, we have the question of liquids in space. In a vacuum most liquids have such a low boiling point that they vaporize almost instantly. For that reason, most substances exist in space in either the gaseous or the solid state. When the astronauts take a leak while on a mission and expel the result into space, it boils violently. The vapor then passes immediately into the solid state (a process known as desublimation [or deposition – Physics Teacher]), and you end up with a cloud of very fine crystals of frozen tinkle. It is by such humble demonstrations that great scientific truths are conveyed.