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UC Berkeley
ETP Type: Create a New Lesson
Physics Grades 10,11,12
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Toward Quantum Physics in the High School Classroom

0. Abstract

As part of a mini-unit on Introduction to Quantum Mechanics, I will first conduct a brief survey of students' attitudes toward the relevance of quantum physics. I will then discuss with the students the usefulness and practical applications of quantum mechanical tunneling. This will be connected to the Law of Conservation of Energy by posing the question: if a ball has insufficient speed to get to the top of a hill, how else could it get to equal height on the opposite side? Students will also be introduced to the relevance of attosecond physics by doing a calculation of the "orbital" period of an electron in the hydrogen atom, which is roughly 150 attoseconds. They will also investigate the motion of an electron (after it has tunneled) in a sinusoidally varying electric field of a laser pulse.

Focal Standard or Skill:

NGSS Standard HS-PS4-5:

Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.

Measurable Objective(s):

Students will construct plots of the velocity and position of an electron in a sinusoidally varying electric field, for specific initial values of the electric field on the cycle of the sine wave.

Assessment:

Students will be given a homework assignment where the amplitude and phase of a sinusoidal electric field are given, and it is assumed that the position and velocity of the electron are both zero at time = 0. Students are then given the equations for the velocity and position of an electron in that field as function of time, and asked to plot the motion of the electron for two full cycles of the electric field. Since the full treatment of this problem requires calculus, students will be guided along with "area under the curve" estimates as necessary. Students will then estimate the velocity of the electron when it recombines with the atom (that is, returns to its original position), which will allow for calculation of the electron's energy.

21st Century Skill(s):

Critical Thinking and Problem Solving → Solve problems -> Solve different kinds of problems in both conventional and innovative ways.

21st Century Skill(s) Application:

Students will first apply standard Conservation of Energy to calculate the speed necessary for a ball to climb a hill of a certain height. They will then apply the same technique to an electron in a potential well created by its attractive force to the nucleus of the atom. They will then be guided through a largely conceptual discussion involving the electron tunneling out of the potential well, when the laser electric field has modified the well to make tunneling possible.

Fellowship Description:

I am working with a group of scientists who are investigating the properties of thin-film semiconductors at attosecond time scales. Specifically I have analyzed the static absorption of
light by Germanium and Silicon Nitride, in preparation for an upcoming measurement of the time-dependent absorption properties of those materials. I am also analyzing the time dependence of the absorption of Neon gas. The experimental technique necessary to obtain

this data, heavily involves using optical techniques to generate and control the interaction of lasers with matter.

I am being exposed to the careers of scientists and engineers working at the forefront of research into the interaction of light with matter. My sponsor, the Extreme Ultraviolet (EUV) research group of Professor Stephen Leone of the Chemistry Department at UC Berkeley, is involved with attosecond laser research which probes the behavior of electrons in a wide range of materials, at attosecond time scales.

Fellowship Connection to School or Classroom:

The calculations described above are all directly relevant to the research of the EUV group. I will also try to impress upon the students the importance of quantum mechanics in general, including the development of such widely-used devices as smartphones and solar cells. This is connected to the focal standard in that the energy of a laser is directly connected to its wavelength. Furthermore, the process necessary to created the laser pulses on the attosecond time scale, is optimized when an electron is ejected from the atom at a specific point on the sine-wave cycle of the laser electric field.

Instructional Plan:

(Assume 55 minutes per period)

Day 1:

Attendance, announcements (if any) (3 minutes)

Informal student survey on Quantum Physics (10 minutes): using classroom clickers or simple pencil-and-paper, students will be surveyed on their preconceptions regarding quantum physics. The questions are listed in quantum_survey.docx, and the answers in quantum_survey_answers.docx.

Discussion of survey results (5 minutes)

Brief review of centripetal acceleration (3 minutes) (see Additional Instructional Context)

Hand out and discuss homework assignment (3 minutes): students will be given assignment to calculate speed and orbital period of electron in hydrogen atom, and
also calculate time for half-cycle of laser electric field. See attosecond_hw.docx and attosecond_hw_answers.docx.

Review of energy conservation, including graphical approach, with emphasis on kinetic energy needed to escape potential well (10 minutes).

Discussion of quantum mechanical tunneling as alternative means of escaping potential well; cite experimental evidence for tunneling, and theoretical controversy (12 minutes).

Review of electric fields and nature of light wave (see Additional Instructional Context - 4 minutes).

Discussion of how laser electric field modifies potential well (5 minutes)

(If the lesson runs more quickly than expected, students may use remaining time to work on the homework assignment; if the lesson runs more slowly than expected, any undone portions will be done at the beginning of day 2).

Day 2:

Attendance, announcements (3 minutes)

Brief synopsis of day 1 (3 minutes)

Qualitative discussion of High Harmonic Generation (HHG), emphasis on electron gaining KE then recombining with atom to emit higher-energy photon. (7 minutes)

Discuss motion of electron in laser electric field after tunneling (which leads to HHG). Remind students of area-under-the-curve approach, and also the importance of phase (see Additional Instructional Context). (7 minutes)

Give students solution to integration of electric field to obtain velocity and position of electron as function of time, and also show graphically (10 minutes). (See HHG_hw_solutions.docx)

Work through example where phase = 0 to show that electron would return to atom with zero velocity. (10 minutes)

Work through example with phase = 90 degrees to show that electron would never return to atom. (10 minutes- if time runs short this example could be omitted)

Give homework assignment, including hints regarding area-under-the-curve estimations, where each student is given a different phase, and asked to estimate graphically at what time does the electron reach zero velocity. (Include graphs of velocity and position as function of time) (5 minutes) (See HHG_hw.docx and HHG_hw_solutions.docx).

Day 3:

Attendance, announcements (3 minutes)

Show-and-tell regarding summer research at UC Berkeley (15 minutes) (see summer.pptx)

Hand out and discuss Laser Maze lab (5 minute) (see Laser Maze Lab)

Students do lab (32 minutes -- finish on day 4 if additional time required)

Additional Instructional Context:

The mini-unit on Quantum Physics, which this ETP is a portion of, will be presented near the end of the school year, as it draws on many concepts that have been studied earlier in the year. These concepts include:

- Change of velocity of an object can be calculated from the area under the curve of an acceleration vs. time plot; likewise, change of position (displacement) can be calculated from the area under the curve of a velocity vs. time plot.
- Total energy is conserved in any closed system. For purely mechanical systems, total energy consists of kinetic energy and potential energy. Graphs of potential energy vs. position are often useful tools for analyzing possible motion of a particle.
- For circular motion, centripetal acceleration is the vector sum of forces pointing toward the center of the circle, divided by mass.
- Vibrating systems such as guitar strings can vibrate at several different frequencies which are integer multiples of the lowest possible (fundamental) frequency.
- The phase of an oscillating system refers to: at which point on the sine-wave cycle is the wave at time t=0?
- An electric field causes a force on a charged particle.
- Light consists of massless bundles of energy called photons, which have wave particles. The energy of a photon is proportional to its frequency, hence inversely proportional to its wavelength.
- When light of wavelength λ passes through a diffraction grating, constructive interference occurs according to the equation $\lambda = d sin\theta$.
- A light wave consists of oscillating electric and magnetic fields, which are perpendicular to each other and are each also perpendicular to the direction of travel of the light wave.

In addition, prior to this lesson, students will be exposed to some introductory quantum physics concepts. Specifically, they will be shown a 10-minute portion of the film "Mindwalk" in which they will learn that, for example, the electron in the hydrogen atom has no definite location, until it is measured. They will also be introduced to the Bohr model of the atom.

Part of the purpose of this (or any) lesson is to try to clear up misconceptions students may have regarding physics. This is particularly true as regards the very abstract science of Quantum Physics. In that spirit, here are a few such misconceptions:

- Newtonian physics can accurately describe all phenomena in nature.

- Quantum physics is an intellectual exercise that has no practical value.
- The precision of any scientific instrument is limited only by the quality of the measuring equipment.
- Atomic processes occur instantaneously.
- The time for an electron orbit cannot be estimated using classical physics, because classical physics has no relevance in the atom.
- Light consists merely of tiny particles called photons, which have no wave properties.
- Light waves have nothing to do with electricity or magnetism.
- Lasers used in modern-day research have similar power to sunlight, since both can damage your eyesight.
- An electron in an electric field will always undergo simple harmonic motion, since the electric field is sinusoidal.
- In order to extract useful information from equations or graphs, it is always necessary to plug in specific numbers.

Supply List:

One set of 32 classroom clickers (optional)
Software to program clickers (needed only if clickers are used)
13 lasers (or one for each lab group)
13 shoeboxes
approximately 50 small mirrors
13 small two-way mirrors
13 small rectangular glass pieces

Bibliography:

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Codling, K., Madden, R.P., and Ederer, D.L. "Resonances in the Photo-Ionization Continuum of Argon I (20-150 eV), *Physical Review* 177.1 (1969): 136. Web.

http://henke.lbl.gov/optical_constants/

Faber, Chuck (private communication) kpfaber@gmail.com - author of the Pump-Probe Laser Lab used herein.

Keywords:

Quantum Mechanics, Tunneling, Electron, Physics

Attachments:

quantum_survey.docx (formative assessment)
quantum_survey_answers.docx
attosecond_hw.docx (summative assessment)
attosecond_hw_answers.docx
HHG_hw.docx (summative assessment)
HHG_hw_solutions.docx
Laser Maze Lab (summative assessment)
Summer.pptx
HHG.xlsx