Lesson Plan: The Electron Beam — Discovery, Development, and Modern Uses

Grade Level: High School / Introductory College
Duration: 60–90 minutes (+ optional 45-minute lab)
Subject: Physics / Chemistry / Materials Science

Learning Objectives
By the end of this lesson, students will be able to:
Describe the historical development of the electron beam from the 19th century to today
Explain the basic physics of how an electron beam works
Identify at least four modern industrial applications of electron beam technology
(Optional) Demonstrate how electron beam crosslinking changes the thermal properties of polymers

Part 1: Historical Background

Early Observations (1850s–1870s)
The story of the electron beam begins with the invention of the vacuum tube. German physicists Julius Plücker and Johann Wilhelm Hittorf are credited with first observing that a glowing ray was emitted from the negatively charged electrode (cathode) inside a sealed glass tube. As higher voltages and better vacuums were developed, these "cathode rays" became more defined and controllable. William Crookes then advanced these experiments significantly with his "Crookes tube," a refined vacuum tube that allowed researchers to manipulate the rays and observe their behavior more precisely.

The Discovery of the Electron (1897)
The watershed moment came on April 30, 1897 (now celebrated as International Electron Beam Day), when Cambridge physicist J.J. Thomson announced at the Royal Institution that cathode rays were not waves, but streams of a new kind of negatively charged particle — the electron. Thomson demonstrated this by showing that cathode rays bent toward a positively charged plate (proving the negative charge), and then used the degree of bending in magnetic fields to calculate the particle's mass-to-charge ratio. This single discovery revolutionized both physics and chemistry, providing scientists with the first identified subatomic particle.

"The electron is the fundamental unit of electricity." — J.J. Thomson

Further Development (Early–Mid 20th Century)
Following Thomson's discovery, scientists rapidly developed ways to harness, focus, and accelerate electron beams. Wilhelm Röntgen's related experiments with cathode ray tubes also led to the discovery of X-rays in 1895 — a direct byproduct of high-energy electrons striking glass — for which he received the very first Nobel Prize in Physics in 1901. Through the mid-20th century, electron beam technology evolved from a laboratory curiosity into a precision engineering tool, finding use in electron microscopy, TV cathode ray tube displays, and eventually industrial accelerators.

Part 2: How an Electron Beam Works

An electron beam (or e-beam) is produced by accelerating electrons through a high-voltage electric field in a vacuum. The key components are:

- Cathode — A heated filament that releases free electrons via thermionic emission
- Anode — A positively charged plate that attracts and accelerates the electrons
- Focusing coils — Electromagnetic lenses that shape the stream into a precise beam
- Deflection system — Magnetic or electric fields that steer the beam to a target

The beam can be tuned to deliver enormous amounts of energy with extreme precision. Upon striking a material, electrons transfer energy that can heat, weld, modify, or ionize the target at a molecular level.

Part 3: Modern Applications

Electron beam technology now spans a remarkable range of industries:

- **Electron Beam Welding** — Used in aerospace and automotive manufacturing to create deep, clean welds in metals under vacuum, with minimal thermal distortion
- **Electron Beam Lithography (EBL)** — Writes nanoscale circuit patterns directly onto semiconductor wafers; critical for microelectronics prototyping and research
- **Medical & Food Sterilization** — High-energy electrons destroy bacteria, viruses, and pathogens in medical devices, packaging, and food products without heat or chemicals
- **Polymer Crosslinking** — Modifies plastics and rubber at the molecular level, improving heat resistance, tensile strength, and chemical durability (explored in the lab below)
- **Thin Film Deposition** — Creates precision optical coatings for camera lenses, mirrors, and telescopes using electron beam evaporation
- **Water & Wastewater Treatment** — Destroys organic contaminants and pathogens in water supplies using electron beam irradiation
- **Additive Manufacturing (3D Printing)** — Electron Beam Melting (EBM) builds complex metal parts layer by layer, especially in titanium for aerospace and medical implants

Part 4: Electron Beams and Polymer Science

One of the most commercially important applications of e-beam technology is polymer crosslinking. When a high-energy electron beam strikes a polymer, it ionizes the long molecular chains and generates free radicals — highly reactive, unstable ions. These radicals bond neighboring polymer chains together, creating a three-dimensional network called a crosslinked matrix.
This structural change delivers measurable improvements including:

- Higher melting/softening point (greater heat resistance)
- Improved tensile strength and dimensional stability
- Greater resistance to chemicals and solvents
- Reduced susceptibility to creep under mechanical stress

Common crosslinked products include heat-shrink tubing, automotive wire insulation, and crosslinked polyethylene (PEX) piping.

🔬 Optional Lab Practical 1: Demonstrating Polymer Crosslinking

You can acquire the polymer samples necessary for this lab by contacting Melissa Mayersky at E-BEAM Services at Melissa.Mayersky@ebeamservices.com

Lab Title: Does Crosslinking Change the Heat Resistance of Plastic?
Estimated Time: 40–45 minutes
Safety Level: Low — requires standard lab safety precautions

Background

IIn industrial settings, electron beam crosslinking requires a particle accelerator. For this classroom demonstration, students will work with pre-crosslinked and non-crosslinked polymer samples to observe the real-world difference in thermal behavior. (Crosslinked samples can be sourced from e-beam service providers (see above) or purchased as crosslinked polyethylene [PEX] vs. standard polyethylene [HDPE].)

Materials

Item	Notes
Sample A	Standard polyethylene (HDPE) strip or pellet — not crosslinked
Sample B	Crosslinked polyethylene (PEX) strip — electron beam crosslinked
Hot plate or heat gun	Adjustable temperature preferred
Infrared thermometer or thermocouple	For measuring surface temperature
Metal tongs or heat-resistant gloves	Safety
Lab notebook / observation sheet	For recording data
Ruler	To measure deformation

Procedure

1. Label the two samples clearly: Sample A (HDPE) and Sample B (PEX/crosslinked).
2. Measure and record the dimensions (length, width) of each sample at room temperature.
3. Set the hot plate to approximately 110–120°C. Allow it to reach temperature.
4. Place Sample A on the hot plate surface. Observe and record the time it takes to visibly soften, deform, or melt. Note the temperature at onset of deformation.
5. Remove Sample A with tongs once deformation is clearly visible.
6. Repeat with Sample B at the same temperature. Observe and record behavior.
7. If Sample B shows no deformation at 120°C, gradually increase temperature in 10°C increments until deformation is observed (if possible within safe operating range of equipment).
8. Record and compare onset-of-deformation temperatures for both samples.

Expected Results

Sample A (HDPE) will begin to soften and deform noticeably at around 110–130°C, while Sample B (crosslinked PEX) will remain dimensionally stable at these temperatures due to its crosslinked molecular network. This demonstrates that the covalent bonds formed during e-beam crosslinking significantly raise the polymer's effective heat resistance.

Discussion Questions

1. Why does crosslinking prevent the polymer chains from flowing freely when heated?
2. What happened at the molecular level when the electron beam struck the polymer?
3. Can the crosslinking process be reversed? Why or why not? (Hint: Think about covalent bonds.)
4. What industries would benefit most from a plastic that doesn't melt under high heat?
5. If we didn't have electron beam technology, what other methods exist for crosslinking polymers, and what are their tradeoffs?

Instructor Notes

- PEX pipe sections (available at any hardware store) work excellently as the crosslinked sample; standard HDPE irrigation tubing serves as a direct visual comparison.
- If a hot plate is unavailable, a heat gun on a low setting directed at samples held with tongs also works well.
- For a more quantitative version, students can use a thermocouple to log temperature vs. deformation continuously and graph the results.

Assessment

- Short quiz: Match the historical figure to their contribution to electron beam discovery
- Exit ticket: Name two modern applications of electron beam technology and explain the underlying physics principle each relies on
- Lab report (if practical was completed): Include hypothesis, data table, and answers to all five discussion questions

🔬 Optional Lab Practical 2: Crosslinking Challenge: Polymer Modification Lab

Lab Title: Does Crosslinking Change the Heat Resistance of Plastic?
Course: Chemistry / Materials Science
Grade Level: 8–12
Time Required: 2 class periods (or 1 extended period)
Lab Type: Guided Inquiry / Comparative Testing

Background

Polymers are long chains of repeating molecular units. In their natural state, these chains can slide past one another, making the material flexible but weak under stress. Crosslinking creates chemical bridges between neighboring chains, locking them into a more rigid network. This dramatically improves tensile strength, heat resistance, and durability.

In industry, engineers use electron beam (e-beam) irradiation to crosslink plastics without added chemicals—high-energy electrons break bonds and force chains to link together. This process is used in medical tubing, wire insulation, and heat-shrink packaging.

In this lab, you will model crosslinked vs. uncrosslinked polymer behavior using everyday materials.

Objectives

By the end of this lab, students will be able to:

- Distinguish between crosslinked and uncrosslinked polymer structures
- Collect and analyze quantitative data on tensile strength and flexibility
- Connect physical material properties to molecular-level structure
- Explain why crosslinking is valuable in real-world polymer engineering

Vocabulary

- **Polymer** – a large molecule made of repeating subunits (monomers)
- **Crosslinking** – chemical bonds formed between adjacent polymer chains
- **Tensile strength** – resistance of a material to breaking under tension
- **Elasticity** – ability to stretch and return to original shape
- **E-beam (electron beam) processing** – industrial method of crosslinking using high-energy electrons

Materials

Per lab group (3–4 students):

- 10 strands of cooked spaghetti (cooled, dried slightly on paper towel)
- 1 cup of cooked spaghetti mixed with white school glue (prepared the day before, allowed to set overnight in a flat mold or plastic bag)
- 30 cm of string or thin twine
- Small plastic bags or zip ties to bundle strands
- Ruler
- 500g or 1kg hanging mass (or a bucket filled with measured weights)
- S-hook or tape to hang samples from a desk edge
- Spring scale (optional but recommended)
- Permanent marker for labeling
- Lab notebook or printed data sheet

Safety Notes

- No open flames or hazardous chemicals are used in this lab
- Glue-set spaghetti may crack and produce sharp fragments—wear safety glasses
- Wash hands after handling materials

Procedure

Part 1 — Qualitative Observations

1. Take 3 individual strands of plain cooked spaghetti. Gently bend each one and record your observations: How far does it flex before snapping? Does it return to shape?
2. Take a section of the glue-set spaghetti block. Try to flex it the same way. Record observations.
3. In your lab notebook, sketch a simple diagram of what you think the molecular structure looks like in each sample. Label polymer chains and, where applicable, crosslinks.

Part 2 — Tensile Strength Testing

1. Take 3 individual strands of plain cooked spaghetti. Gently bend each one and record your observations: How far does it flex before snapping? Does it return to shape?
2. Take a section of the glue-set spaghetti block. Try to flex it the same way. Record observations.
3. In your lab notebook, sketch a simple diagram of what you think the molecular structure looks like in each sample. Label polymer chains and, where applicable, crosslinks.
4. Part 2 — Tensile Strength Testing
5. Bundle 5 strands of plain spaghetti together and secure each end with a small zip tie or string loop. Label this sample "Uncrosslinked."
6. Cut a similarly sized piece from the glue-set spaghetti block. Label it "Crosslinked."
7. Hang each sample from the edge of a desk or lab bench using the S-hook and string setup. Apply hanging masses in 100g increments, waiting 15 seconds between additions.
8. Record the mass at which each sample first deforms (bends noticeably) and the mass at which it breaks completely.
9. Repeat each test 3 times and average your results.

Part 3 — Heat Response (Extension / Optional)

1. Briefly warm one plain spaghetti strand and one glue-set piece under warm running water (not boiling) for 30 seconds.
2. Immediately retest flexibility and attempt to apply gentle load.
3. Record whether heat affected each sample differently and hypothesize why.

Data Table

Trial	Sample Type	Mass at First Deformation (g)	Mass at Breaking Point (g)
1	Crosslinked		
2	Crosslinked		
3	Crosslinked		
1	Uncrosslinked		
2	Uncrosslinked		
3v	Uncrosslinked		

Analysis Questions

1. Which sample required more mass to break? By approximately what factor?
2. How did the flexibility of each sample differ during the qualitative test? Is more flexibility always better? Give an example of a product where each property would be desirable.
3. In the molecular diagram you drew, where are the crosslinks? What physical material in your model represented those crosslinks?
4. The glue in this model represents crosslinks formed by chemistry. In industry, e-beam processing achieves the same result without added chemicals. Why might that be preferable for products like food packaging or medical devices?
5. (Critical Thinking) A manufacturer wants a plastic pipe that stays rigid under high heat. Would they prefer a crosslinked or uncrosslinked polymer? Use your data to support your answer.

Conclusion Prompt

Write a 3–5 sentence conclusion that states your hypothesis (if you formed one before testing), summarizes what your data showed, and connects your findings to one real-world application of crosslinked polymers.

Teacher Notes

- Prepare the crosslinked samples the day before by mixing warm cooked spaghetti with white PVA glue (roughly 1:1 ratio), pressing into a flat container, and refrigerating overnight. Elmer's Glue-All works better than school glue for rigidity.
- For a more rigorous version, substitute gelatin vs. gelatin + borax (slime chemistry) to more closely mimic true covalent crosslinking behavior.
- The Part 3 heat test works well as a discussion bridge to polyethylene crosslinking, where e-beam treated plastic resists heat deformation while untreated plastic softens quickly.
- Standards alignment: NGSS HS-PS1-3, HS-PS2-6; Common Core Math for data averaging and ratio analysis.

Media Links

How Electron Beam Crosslinking Works
How Electron Beam Sterilization Works
How Electron Beam Technology Touches Everyday Life