Scanning Tunneling Microscope

1.) Probability of electron tunneling over $\sim e^{-d}$

Why tunneling? Because the electron cannot escape into air.

i. Too high energy is needed;

ii. If it could go in the air, then the electrons would have left the surface already;

iii. But: inside the metal tip, the energy is low again. The electron has to tunnel through the high energy region of the air.
They put voltage between the metal surface and the tip to generate a current. With no voltage equal number of electrons would jump in both directions.

They knew that they observed tunneling when they moved the tip by a distance of the diameter of an atom and the current changed 1000 fold. Only the exponential function can generate such huge changes.

How to keep the tip so precisely so close?

**Piezoelectricity**
There are materials which contract or expand when you put voltage across them.
Each rod has a voltage applied between its ends.
The z rod contracts if the current increases: this moves the tip up and down.

i. Apply voltage between surface and tip;
ii. Measure the tunneling current of the tunneling electrons;
iii. This current created an induced voltage, which is used to control the location of the tip;
iv. Systematically increase the x-rod voltage—this moves the tip over the surface: “scanning”;
v. If the tip gets close to a bump (atom/structure)—the tunneling current and hence the induced voltage increases;
vi. Apply increased voltage to z-rod. This causes z rod to contract;
vii. Shorter z-rod pulls up tip to avoid bumping into bump.
Today: many variations

1. STM:
   Scanning Tunneling Microscope
   i. metal—metal
   ii. controlled by current

2. AFM:
   Atomic Force Microscope
   i. insulator—insulator
   ii. controlled by force, generated by surface, very soft cantilever
   iii. How do they measure position?
       [no current in insulator]: put tiny mirror on tip, shine laser on it and analyze reflected laser beam

3. MFM:
   Magnetic Force Microscope
   i. magnet—magnet
   ii. the tip is magnetic, controlled by magnetic force between tip and surface

4. Atomic crane:
   i. pick up atoms one by one
   ii. move wherever they want to (wrote “IBM”)

Surface of silicon—very important for semiconductor/computer industry

Develops tiny regular mountain structure: “7 atom by 7 atom”

Structure and shape of organic molecules (our department head does this)
Nuclear Physics and $\alpha$-decay

Tunneling in the atomic nucleus: alpha particles in/out of nucleus

i. To get into nucleus, alpha particles need energy 9 MeV or more
ii. So the energy barrier is probably 9 MeV high.
iii. So if an alpha particle climbs UP the mountain form the inside and then “slides down the other side” its energy is conserved. Thus it should have 9 MeV at least.
iv. Instead, Rutherford found lots of alpha particles with E=4 MeV in the alpha radioactive decay.

--Strange--
Gamow’s theory of $\alpha$-decay

$\alpha$ particle (two protons, two neutrons) trapped in the nucleus

Note: nucleus is just a collection of protons and neutrons. Gamow pictured some protons and neutrons binding more strongly into an $\alpha$ particle. The other protons and neutrons “trap” the $\alpha$ particle.
Gamow’s theory of $\alpha$-decay

Energy – Classical picture

$E_\alpha < E_{peak}$: Classically the $\alpha$ particle is trapped. For the particle to get out it would need an energy input $\Delta E$.

$1 \text{ fm} = 10^{-15} \text{ m}$

Radial distance

Size of nucleus
Gamow’s theory of $\alpha$-decay

Energy – quantum picture

Quantum mechanically: Particle can tunnel out with an energy less than $\Delta E$!
We measure the energy of the alpha particle, and find they really are tunneling!

The height and width of the barrier control the rate at which tunneling occurs. Different barriers means different decay rates -- or halflives!
Gamow’s theory of $\alpha$-decay

i. 2 proton + 2 neutron inside nucleus join into an alpha particle.

ii. This alpha tunnels out from nucleus, instead of climbing over mountain.

Bombardment by particles: sometimes they can tunnel IN, too.

Cockroft + Walton (1932)

They shot not too high energy protons into nuclei and sometimes those converted into other types of nuclei.

\[
p + \text{Li} \rightarrow 2 \text{He} \quad \text{Alpha} + \text{N} \rightarrow \text{O} + \text{p} \quad \ldots
\]

“splitting the atom” (recall: “atom” means “un-splittable”)

First observation of tunneling
The $\alpha$-decay of Uranium:

**Initial:**
Uranium with 238 nucleons
- 92 protons
- 146 neutrons

238 particles in nucleus

**Final:**
Thorium with 234 nucleons
- 90 protons
- 144 neutrons

234 particles in nucleus

& alpha particle (2 p, 2n)

Gamow's theory of $\alpha$-decay
Number of protons controls the attraction of electron, and hence controls chemistry.

Element related *only* to number of protons

(Does not occur)  (Most common form)

These nuclei are **ALL** Helium, and have the same chemistry. Changing the neutrons does not change elements.

Two nuclei with different number of protons are different **elements**.

The same **element** with different number of neutrons are different **isotopes**.
A bit of chemistry

Number of protons controls the attraction of electron, and hence controls chemistry.

Element related *only* to number of protons

(Does not occur) \( ^2_2 \text{He} \) \( ^3_2 \text{He} \) \( ^4_2 \text{He} \)

(Most common form)

Atomic weight:
- Tells us total number of neutrons + protons.
- Cannot tell element from this number.
- The same element can have different atomic weights: these are the isotopes.

Atomic number:
- Tells us total number of protons.
- Tells us the element.
- Carries the same information as the name “He.”
Red elements have some (known) alpha emitter isotopes. Note they are heavier elements.
Cockroft and Walton knew all terms, except the energy of the outgoing He. They predicted it from this equation to be 8.5 MeV. Energy of the helium was 1 MeV.

Conservation of energy?!?

**Theory or relativity**

Einstein (1905): $E=mc^2$

energy = mass * (light speed)$^2$

kinetic energy of proton + $m_p c^2 + m_{Li} c^2 = (\text{kinetic energy of 2 He}) + 2m_{He} c^2$

We have to include the “energy of the mass,” $E=mc^2$
More on the energy

Which has more mass:

\[
\frac{238}{92} \text{U} \quad \text{or} \quad 92 \times \text{protons} + 146 \times \text{neutrons}
\]

(Seperated)

protons + neutrons
Neutrons + protons inside Uranium are heavier than separately. This mass difference is related to the energy via the famous Einstein formula:

$$E = mc^2$$

Heavy atoms breaking into smaller atoms reduces their energy -- alpha decay.
More on the energy

Break the rules of chemistry: mass is not conserved

\[ m_{\text{initial}} = \text{mass of uranium} \]
\[ m_{\text{final}} = \text{mass of thorium} + \text{mass of } \alpha \]

\[ m_{\text{initial}} > m_{\text{final}} \quad \text{NOT EQUAL} \]

\[ \text{BUT } m_{\text{initial}}c^2 = m_{\text{final}}c^2 + E_{\text{released}} \]

i.e. "Mass is a form of energy"
More on the energy

Energy is released by the atom splitting apart!

NUCLEAR FISSION

Are atoms always more (massive) than “the sum of their parts”? Do they always split to release energy?
Fusion vs. Fission

Sometimes the whole is less than the “sum of its parts”

e.g. alpha is “lighter” (less energy) than 2 protons, 2 neutrons

Joining (fusing) the protons and the neutrons releases energy. Called nuclear fusion.
Fusion vs. Fission

Iron (Fe) stable against either fusion or fission.

This is why most meteorites are made of iron.
i. Charges interact by electric forces. They act long range.
   Neutrons: neutral—do not feel it
   Protons: positive—repel each other [“Coulomb force”]
   So, why does a nucleus remain together if there is so much repulsion? A second type of force explains it.

ii. Strong Force
   All particles inside nucleus—protons and neutrons (nucleons)—attract
   This force is very strong, and only acts at very short distances: essentially neighbors only.

   When # of protons increases, nucleus is held together by strong force—only from neighbors: doesn’t change much from light elements to heavy elements. But # of protons increases: All protons repel each other.
   In heavy nuclei, protons would dissolve nucleus.
   Nature’s solution:
   - put protons farther apart
   - how?
   - by butting more neutrons in between

   Indeed, this happens: success of theory
Nuclear Forces: Summary

• Heavy elements (heavier than Fe) release energy by fission (splitting).
• Light elements (lighter than Fe) release energy by fusing (joining).
• Mass is not conserved in nuclear reactions! The “missing mass” gets transformed into energy: $E = mc^2$.
• Protons and neutrons held together by a strong force, which overcomes the repulsion of the nucleus.
• The same force traps the alpha particle “inside” the nucleus. Alpha decay (fission; releasing an alpha particle) is an example of tunneling!

Alpha decay transforms one element into another:
The ancient dream of ALCHEMY is real!

Lead -> Gold? Stimulus package!

We will see other decays later to explain beta- and gamma-radiation. These cannot be explained by tunneling because particles change identities (e.g. neutrons become protons!)