WHY DID OPPORTUNITY DIE?

Neo Skinner

The United States of America's National Aeronautics and Space Administration's (NASA) major effort to understand the Martian landscape revolves around the launch of sophisticatedly equipped vehicles to Mars. One such Mars 'rover' was Opportunity which launched on the 8th of July 2003, landing on the surface of Mars on the 25th of January 2004. Unfortunately, NASA lost contact with the rover on the 10th of June 2018 and declared the rover's mission over on the 13th of February 2019. The cause of lost contact remains unknown but a leading theory postulates that the rover lost power due to a large dust storm on the surface of Mars which covered the solar panels of the vehicle.

UNDERSTANDING THE PHOTOVOLTAIC EFFECT.

EXCITED? I'M ELECTRIC!

When electromagnetic radiation (a photon) of a visible frequency strikes an atom, an electron is momentarily excited through energy absorption before it is reemitted, and the electron relaxes. Due to the energy gain, the electron 'jumps' or transitions from its ground state to a higher energy level (an excited state) before falling back to the ground state and emitting the incident energy as a photon – it is important to note that the energy reemitted is precisely equal to that of the absorbed energy, thus the theory proves true within energy conservation and mass-energy equivalence.

It is also worth noting here that the incident photon and the emitted photon will have exactly the same frequency through the Planck relation:

$$E = hv \tag{1}$$

Where E is the photon energy, h is the Planck constant, and v is the frequency. As the Planck constant holds the fixed value of $6.626\ 070\ 15 \times 10^{-34}$ J s it follows that:

$$E \propto v \tag{2}$$

Such that the relationship of direct proportionality imparts that if the energy of two photons is equal then so too must be the frequency. This is the basis of spectroscopic studies whereby unknown sample atoms can be identified through the method of light incidence and comparison to a database of known sample atoms. It is also the mechanism that lends homo sapiens eyesight as light incidence upon all materials in a visible state of matter leads to the apparent reflection of light of the frequency related to the incidence material into the eye.

NATURE'S STRONG HAND.

However, when an electron absorbs a greater quantity of energy than its binding energy, it is ejected from the atom. This is because the binding energy is the threshold energy provided by the atomic strong nuclear force such that if the energy achieved by an electron is greater than this limit, the electron 'overcomes' the energy barrier trapping it inside the atom. Furthermore, the negative charge of the ejected electron is correspondent to that of the charge surrounding the atomic nucleus and thus the electron travels outside of the atom's influence entirely. This is the photovoltaic effect and electrons emitted in this fashion are termed photoelectrons.

I CAN'T SEE YOU!

Gases generally have higher binding energies which require much higher frequency radiation such as x-rays in order to liberate electrons by the photovoltaic effect. Moreover, the electrons within atoms of a gas absorb amounts of energy in excitation outside of the visible spectrum, equating to ultraviolet and infrared frequencies instead of visible frequencies. This means that most gases are not visible to the human eye but are still subject to electron excitation and the photovoltaic effect.

THE SCOPE OF EXPERIMENTATION.

The photovoltaic effect can be experimentally proven with a simple apparatus called an electroscope. In an electroscope, two thin sheets of metal are hung vertically within a vacuum chamber with a conductive base. When a current is passed between the two sheets and the conductive base, the sheets appear to be blown apart by a breeze, this is caused by colliding streams of photoelectrons which exert an equal force upon each of the metal sheets.

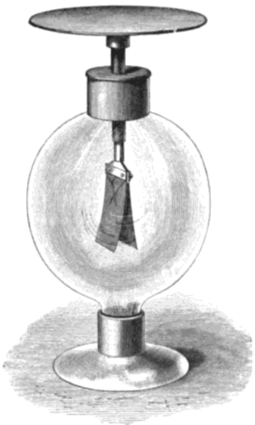

Figure 1: An 1889 Gold-Leaf Electroscope, Drawing by James Edward Henry Gordon for A Physical Treatise on Electricity and Magnetism [2nd Ed., Vol. 1, James Edward Henry Gordon]

EXPLOITING THE PHOTOVOLTAIC EFFECT.

THE HUMBLE SOLAR PANEL.

The photovoltaic effect is commonly exploited for energy using photovoltaic cells (or 'solar panels') which convert the energy carried by electromagnetic waves into a direct current supply for an electrical circuit. This is because when photons hit electrons in a photovoltaic cell they are liberated through the photovoltaic effect, the photoelectrons then move in one direction only – due to the configuration of the p-n junction within the cell – which forces it through a wire to produce a flowing charge (current) that constitutes the net output voltage of the cell.

WHERE POSITIVE MEETS NEGATIVE.

p-n junctions are boundaries between different types of semiconductive materials, namely p- and n-types. p-type semiconductors contain an excess of 'holes,' where electrons have been liberated to produce a positive charge excess, whilst n-type semiconductors have liberated electrons to produce a negative charge excess. Junctions between such materials are the basis of diodes, ensuring that electrical charge flows in a single direction only. Within photovoltaic cells, p-n junctions repel electrons towards an electrical circuit where their energy excess can be usefully harnessed.

TYPES OF RADIOACTIVE DECAY.

There are all manner of different ways in which an unstable atom can decay; from electromagnetic radiation, lighter nuclei, and even neutrinos, nothing is seemingly safe from the unstable nucleus' rampage against itself.

IT'S ALL GREEK TO ME!

The first three types of radioactive decay to be discovered were named after the first three letters of the Greek alphabet – alpha (α), beta (β), and gamma (γ). Alpha decay occurs within proton-rich nuclei, where a neutron deficiency causes the correspondent charges of the nuclear protons to overcome the strong nuclear force and repel an alpha particle – consisting of two protons and two neutrons (a He-4 nucleus) – out of the atomic nucleus. It is a quantum tunnelling process.

There are two types of beta decay, one that produces positive particles and one with the converse (and rather 'originally' named β^+ and β^- decay respectively). In beta-plus decay, a proton-rich nucleus decays by way of nuclear transmutation; with a proton decaying to form a neutron, positron, and electron neutrino through the weak interaction which transmutes a up quark to a down quark within the hadron, thus changing the electric charge, Q (and mass, negligibly), of the particle from +1 q_e to 0 q_e. In order to conserve additive quantum numbers, a positron and electron neutrino must also be produced to ensure the net Q of the interaction remains at a constant +1 q_e alongside the lepton number, L (in this case L_e), which retains the initial zero value. The production of the leptonic pair is mediated through a W^+ boson of the weak interaction.

Beta-minus decay roughly follows as the inverse of beta-plus decomposition in the beta decay conjugate, with a neutron in a proton-deficient nucleus decaying to form a proton, electron, and electron antineutrino through a W^- boson. Furthermore, extra additive quantum number conservation rules can now be highlighted: in the case of the baryon number, B, there remains three quarks within the nucleon with no antiquarks and so this is matched on both sides of the interaction. Moreover, weak isospin, T_3, is also conserved as the switch in value between the up and down quarks is nulled by the two equal value lepton counterparts. Here I could make mention of X-charge, X, but I feel the current discussion of quantum numbers is sufficient, with the same statement extended to combinations of the numbers.

Finally, gamma decay ensures that daughter nuclides achieve a metastable state. This involves the production of high-frequency (low wavelength, $v = f\lambda \Rightarrow f \propto \frac{1}{\lambda} \because v = c$ where c is the fixed speed of light[1]) electromagnetic radiation to reduce the atom from an excited state to a lower energy level. Gamma decay follows other types of radioactive decay that produce unstable isomers, thus requiring gamma decay to complete the decay chain (or decay scheme).

TURNING ROMAN.

Another was a neutron-rich nuclide can decay is by neutron emission (n), whereby a neutron is ejected from the nucleus with high energy. This process occurs due to the strong force, which acts repulsively at ranges smaller than 0.7 fm that are achieved with excess neutrons, therefore forcing a neutron out of the nucleus. The energy of the interaction is not dissipated quickly as in the case of alpha and beta decay as neutrons are neutrally charged and thus do not interact further with atomic protons and electrons.

On a similar note, proton emission (p) is a rare form of radioactive decay that can occur in neutron-deficient nuclides whereby a proton is ejected from the nucleus. This can only take place when the proton separation energy, S_p, is negative ($S_p < 0$) – meaning that the energy required to remove the proton from the nucleus is negative (the interaction liberates energy) – and thus the nucleon is unbound and the proton is able to exit the nucleus via quantum tunnelling.

Electron capture (ε) occurs when a proton-rich nucleus absorbs an electron from either one of the atoms two innermost shells (K or L in x-ray notation; 1 or 2 principal quantum numbers, n), transmuting a proton to a neutron – in a similar process to β^+ decay – to produce an electron neutrino (thus conserving L_e) through the weak interaction (W^+ or W^-, the two bosons are interchangeable in this interaction). This facilitates the de-excitation of the daughter nuclide (now an excited isomer) through isomeric transition (discussed later).

Unstable nuclides can also decay by splitting into fragments in similar processes to alpha decay. This sees larger clusters (than α-particles) produced in cluster decay (CD) and nuclei split into two roughly equal parts in spontaneous fission (SF). Cluster decay mirrors the process of alpha decay whilst spontaneous fission can only take place in heavy elements where the nuclear binding energy is past the maximum value achieved by Fe-56.

Finally, isomeric transition (IT, a.k.a. internal transition) occurs to decrease the energy of an excited isomer to a metastable state. This is either through gamma decay or internal conversion – which sees the excited nucleus interacting with an electron, causing it to be ejected from the atom before electrons from higher energy levels descend to fill the newly-created hole in the lower energy level. The rearrangement of electrons in isomeric transition produces x-rays and auger electrons, whereby the energy released from an electron

---

[1] Using the wave speed equation ($v = f\lambda$; where v is the wave speed, f is the frequency, and λ is the wavelength) it is possible to derive the relationship of indirect proportion between the frequency and wavelength components ($f \propto \frac{1}{\lambda}$) as the value of the wave speed is the speed of light, c, which is a fixed constant ($v = c$).

transition is transferred to another electron, resulting in the release of an additional electron from the atom.

Unstable nuclides can decay by any one of the above types of radioactive decay and they may decay more than once, forming a decay chain and often combined decays.

RADIOACTIVITY AS POWER.

Nuclear power generation systems are generally unwieldy and complex, however, if only a small amount of power is required then radioactivity can be harnessed in radioisotope thermoelectric generators (RTGs, a.k.a. RITEGs). RTGs use thermocouples to convert the thermal energy produced by radioactive decay into useful electricity which can power any given electrical system with sufficiently small capacity demands.

LINKING HEAT?

In thermocouples, two electrical conductors made of different materials meet at a junction and the application of heat to one of the conductors creates a temperature gradient which establishes the flow of charge around the circuit. On an atomic level, the thermoelectric effect forces charged particles within one conductor to move towards the other conductor when heat is applied to the circuit via the Peltier–Seebeck effect.

HERE COMES THE HEAT SOURCE…

Thermocouples are placed within the walls of the container of a radioactive source and the thermal energy produced through radioactive decay is harnessed by the thermocouples in order to produce a reliable source of electrical potential. In the first RTG, built in 1957, Pu-210 was used as the radioactive source but Pu-238 soon became the standard in the 1960s with the launch of the United States of America's Department of the Navy's (USN) Transit 4A Spacecraft. Plutonium isotopes are sources of alpha radiation which liberates the large amounts of energy required for RTGs, however, beryllium isotopes and even beta radiation sources have been considered recently due to growing shortages of Pu-238.

RTGs are reliable sources of energy in remote areas, with terrestrial applications including the Union of Soviet Socialist Republics' (USSR) lighthouses which were transferred to the ownership of the republics after the fall of the USSR. This caused many of the RTGs to be lost as the republics could not afford to pay for their disposal, leading to several incidents including the Lia radiological accident in modern-day Georgia – which killed one civilian and produced acute radiation syndrome in two others. RTGs have also been used in Arctic regions in recent years due to their remote locations.

> *"We may find illustrations of the highest doctrines of science in games and gymnastics, in travelling by land and by water, in storms of the air and of the sea, and wherever there is matter in motion."*[2]

[2] Clerk-Maxwell, J. (1871). *Introductory lecture on experimental physics: Oct. 25, 1871*. Macmillan.

BIBLIOGRAPHY

Alpha decay. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Alpha_decay&oldid=1164680841

Atomic electron transition. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Atomic_electron_transition&oldid=1165748015

Auger effect. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Auger_effect&oldid=1168415741

Bored915. (2016, February 2). *How do electrons jump orbitals?* [Forum post]. Physics Stack Exchange. https://physics.stackexchange.com/q/46801/374971

Conservation of energy. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Conservation_of_energy&oldid=1168172165#Quantum_theory

Diode. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Diode&oldid=1169786515

Electromotive force. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Electromotive_force&oldid=1168670151

Electron capture. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Electron_capture&oldid=1162181538#Reaction_details

Electron excitation. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Electron_excitation&oldid=1168619366

Electron hole. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Electron_hole&oldid=1169361861

Electroscope. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Electroscope&oldid=1147902383

Internal conversion. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Internal_conversion&oldid=1169629295

Ionization energy. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Ionization_energy&oldid=1164463186#Electron_binding_energy

Nuclear force. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Nuclear_force&oldid=1161303562

Opportunity (rover). (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Opportunity_(rover)&oldid=1164147337

Photoelectric effect. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Photoelectric_effect&oldid=1170282901#Uses_and_effects

Photon energy. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Photon_energy&oldid=1169640353

Photovoltaic effect. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Photovoltaic_effect&oldid=1154963604

Planck relation. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Planck_relation&oldid=1146193307

P–n junction. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=P%E2%80%93n_junction&oldid=1166050747

Positron emission. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Positron_emission&oldid=1149459281

Proton emission. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Proton_emission&oldid=1155452804

Quantum jump. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Quantum_jump&oldid=1139901179

Radioisotope thermoelectric generator. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Radioisotope_thermoelectric_generator&oldid=1168245306

Samarth. (2020, December 4). *How do electrons move from one energy level to another?* [Forum post]. Physics Stack Exchange. https://physics.stackexchange.com/q/598130/374971

Separation energy. (2022). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Separation_energy&oldid=1071397152

Skinner, N. (2023). *The D-Series Scientific Datasheet Collection* (1st ed.). https://d-series.neoski.tk

Solar cell. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Solar_cell&oldid=1168685733

[Solved] Photoelectric effect in Gas? (n.d.). Retrieved August 14, 2023, from https://9to5science.com/photoelectric-effect-in-gas

Theory of solar cells. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Theory_of_solar_cells&oldid=1166265068

Thermocouple. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Thermocouple&oldid=1170193317

Thermoelectric effect. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Thermoelectric_effect&oldid=1169464846

Why are gases invisible? (n.d.). Retrieved August 14, 2023, from https://www.sciencefocus.com/science/why-are-gases-invisible

Working principle of thermocouples. (n.d.). Https://Www.Omega.Com/En-Us/. Retrieved August 14, 2023, from https://www.omega.com/en-us/resources/how-thermocouples-work

Articles from Wikipedia fact-checked against footnotes and references to ensure accountability and truth. Direct references are omitted here only for the purpose of brevity.