ENERGY AND ELECTRONIC CHARGE CONSERVATION DURING ALPHA AND BETA EMISSION

Prasanta Kumar Patra

Centre for Science Education, NEHU
Shillong

Introduction

In 1986, Antoine Henri Becquerel, a French physicist, while working on phosphorescent materials such as uranium salts, found that they emit radiations spontaneously. It was later established that a magnetic or an electric field splits such radiations into three beams. These radiations have been named after the first three letters of the Greek alphabet, i.e., alpha (α), beta (β) and gamma (γ). The first two radiations are corpuscles in nature so they are called particles whereas the third, being electromagnetic radiation, is called a ray. The elements, which spontaneously emit such type of radiations, are called radioactive elements and the phenomenon is known as radioactivity. For discovery of these radiations, Becquerel received Nobel Prize for Physics jointly with Marie Curie and Pierre Curie in 1903.

Before going into detail of the phenomena it is imperative to understand the structure of an atom. An atom consists of a positively charged central core, the nucleus, and negatively charged electrons which revolve round the nucleus in fixed orbits. The nucleus contains positively charged particles protons and neutral particles neutrons. Either a proton or a neutron is called a nucleon. In the normal state of the atom, the number of protons is equal to the number of electrons, so that the atom is electrically neutral. The number of protons is constant and unique to a particular atom and is called the atomic number (Z) whereas the number of protons plus number of neutrons in the nucleus give the mass number (A). Since like charges repel one another, the protons within the nucleus are always trying to push each other apart but they are held together by the attractive nuclear forces resulting from the combined protons and neutrons. When there is imbalance between the attractive nuclear forces and the electrostatic repulsive forces (Coulomb replusion), the nucleus does not have enough binding energy to hold permanently the nucleons together, as a result of which it becomes unstable. In unstable nuclei the binding energy per nucleon is very low. It is found that all nuclei with $Z > 83$ and $A \geq 210$ achieve greater stability by emitting spontaneously one or more α– particles (helium – 4 nuclei), called

$\alpha-$ particles (helium –4 nuclei), called $\alpha-$ emission. Again, it is observed that in stable nuclei the ratio of neutron number to proton number $\left(\frac{n}{p}\right)$ is usually between 1 and 1.5 (excluding the hydrogen nucleus which consists of only one proton) (Marmier, 1969). So the nucleus becomes unstable when it possesses either a higher $\frac{n}{p}$ value than that for stable nuclei by containing excess neutrons or a lower $\frac{n}{p}$ value by containing excess protons. In the former case it emits an electron, called β^-– emission, and in the latter case it emits a positron called β^+– emission, to dissipate excess energy.

(A) Alpha Emission

After $\alpha-$ emission the original atom transforms into a new atom of some other element whose proton and neutron numbers each decreases by by 4 and 2 units respectively. In general this is represented as

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He^{++} + Q \qquad (1)$$

where X and Y are symbols for the parent and the residual atoms respectively and Q, the decay energy, is shared by the kinetic energy of the $\alpha-$ particle and the recoil energy of the resulting atom. From equation (1), it is clear that $\alpha-$ emission is only possible if Q value is positive.

For example,

$$^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He^{++} + 4.19\ MeV, \qquad (2)$$

where mega electronvolt (MeV) is the unit of energy ($1\ eV = 1.6 \times 10^{-19}$ joule).

(i) Conservation of Energy during α–Emission

In equation (2), sum of masses of the products (a thorium-234 and an α-particle) is less than mass of the parent atom. The decrease in mass is converted to energy according to Einstein's mass energy equivalence relation $E = mc^2$, where E is the total energy, m the effective mass and c the velocity of light in free space ($c = 3 \times 10^8$ m/s). This energy is shared by the residual thorium atom and the emitted α–particle. Since α–particle is quite lighter than thorium atom, most of the energy released is carried by the α-particle.

(ii) Conservation of Electronic Charge during α–Emission

It appears from equation (2) that the electronic charge is unbalanced although proton number is conserved in the equation. If we count the number of protons, neutrons and electrons present in the parent and the residual atoms of equation (2), we find that the parent atom has 92 protons,
146 neutrons and 92 electrons whereas the residual atom will have 90 protons, 144 neutrons and 92 electrons as an α–particle contains two protons and two nuetrons only. This reveals that the residual atom has excess of two electrons compared to its total number of protons. Thus it is an ion. It is observed that at the time of decay the residual atom as well as the α–particle is in ionic form but subsequently they acquire neutrality. The question arises what happens to these extra electrons in the residual thorium atom? It appears that a continuous range of values, ranging, from zero up to some maximum

value rather than a discrete value (Beiser, 2006; Evans, 1978). This is in apparent contradiction to the law of conservation of energy. It has been a great puzzle. A second problem is that the emitted electron does not usually travel in a direction opposite to that of the residual atom as in a two-body decay, which shows an apparent violation of conservation of linear momentum. A third problem is that spins of the neutron, proton and electron (in units of *h/2p*) are all ½, so the spins (and hence also angular momentum) is not conserved in equation (3).

All these apparent discrepencies were accounted for Wolfgang Pauli in 1931 (Beiser, 2006; Evans, 1978). He suggested that in addition to electron, another extremely light particle is also emitted and these particles share the energy available in ${}^{14}_{7}N$. This suggestion explains the observed continuous energy spectrum of the emitted electrons. This new particle has to be electrically neutral to conserve charge and has spin of (1/2) (h/2π) to conserve angular momentum. Enrico Fermi has named this particle as 'neutrino' ("little neutral one" in Italian). Later it was recognised as electron-antineutrino ($\overline{\nu}_e$) to conserve lepton number which must be conserved in weak interaction that causes beta emission. The lepton number is experimentally determinable just like electric charge and its value is +1 for leptons such as electron, muon (μ), tau (τ) and their associated neutrinos (ν_e , ν_μ and ν_τ) and –1 for antileptons. The decay equation (3) can thus be modified as

$$ {}^{1}_{0}n \longrightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \overline{\nu}_e + Q \qquad (5) $$

The existence of neutrinos has been experimentally observed by Cowan and Reines (Cowan *et al.*, 1956). The general transformation equation describing β^- emission becomes

$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + \overline{\nu}_e + Q \qquad (6) $$

The continuous energy carried by the electron can be explained in the following way. In β^--emission, electron and electron-antineutrino are ejected out of the nucleus and share the maximum energy of the emission in all proportions with each other, as they are much lighter than the residual atom. When $\overline{\nu}_e$ does not get any energy, the electron carries all the energy and in case $\overline{\nu}_e$ grabs whole of the energy, the electron is left without any energy. Further, the conservation of linear and angular momenta is also satisfied because $\overline{\nu}_e$'s linear and angular momenta exactly balance those of the emitted electron and the residual atom as in three-body decay.

A fundamental level, each neutron consists of one 'up' (u) quark and two 'down' (d) quarks whereas each proton cunts of two u-quarks and one d-quark. The u-quark carries an amount of +2/3 electronic charge and the d-quark carries an amount of –1/3 electronic charge. So, equation (5) is due to the conversion of a d-quark into a u-quark by emission of a W$^-$ boson (Fig.1) due to the weak interaction (Griffiths, 1987). The *W*$^-$ boson subsequently decays into an electron and an electron-antineutrino. So the transformation of a neutron into a proton takes place with the emission of an electron for charge conservation and an electron-antineutrino for energy and momentum conservation.

The schematic diagram is given below :

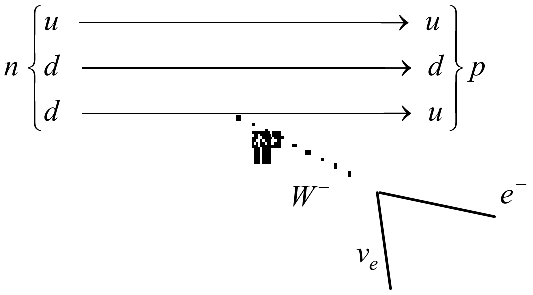

Figure 1: Conversion of a neutron into a proton

(ii) β^+-Emission

A positron is emitted from a nucleus in this case, this is possible only when a proton is converted into a neutron in the nucleus. in order to conserve energy, linear and angular momenta, an electron-neutrino (ν_e) is also emitted. Thus,

$$^1_1p \longrightarrow {}^1_0n + {}^0_{+1}e + \nu_e + Q \qquad (7)$$

The general transformation equation of β^+-emision can be written as

$$^A_ZX \longrightarrow {}_{Z-1}^{A}Y + {}^0_{+1}e + \nu_e + Q \qquad (8)$$

Conservation of Energy during β^+-Emission

Now the pertinent question is, 'how a proton which is smaller in mass than a neutron can convert into a neutron and other particles'. Actually, a free proton, i.e., a proton outside the nucleus, cannot decay into a neutron, as there will be violation of energy conservation. This also explains that why a free proton is stable whereas a free neutron is unstable (half-life =10 min 16 s) (Beiser, 2006). However, this is possible inside a nucleus as proton gets energy from the nucleus and is converted into a neutron by emitting a positron and an electron-neutrino. This can be written as

$$\text{energy} + {}^1_1p \longrightarrow {}^1_0n + {}^0_{+1}e + \nu_e + Q \qquad (9)$$

Since proton number decreases by one and neutron number increases by one, β^+-emission helps to increase $\frac{n}{p}$ value.

Conservation of Electronic Charge during Beta (β^+) Emission

Consider a tritium decay which spontaneously gives helium –3 by emitting an electron and an electron-antineutrino as follows:

$$^3_1H \longrightarrow {}^3_2He + {}^0_{-1}e + \overline{\nu}_e + 18.6 KeV \qquad (10)$$

The number of protons, neutrons and electrons present in a tritium atom is one, two and one respectively whereas the residual helium–3 atom will have two protons, one neutron and one electron. So the residual atom has insufficient number of electrons to balance its number of protons, i.e., it becomes helium ion (He$^+$). Similarly in β^+-emission the residual atom will have one electron more. This implies that the residual atoms in both types of decay processes are ions at the time of decay. It has been observed in early experiments (Linder and Christian, 1952) that a neutral radioactive element gets charged after emitting beta particles and gradually becomes neutral. It appears that the positively charged helium ion subsequently tries to acquire an extra electron from one of the neighbouring atoms to become neutral. And in β^+-emission, the negatively charged residual atom emits an electron to the surrounding to become neutral. Again, in case of β^--emission, the emitted electron encounters numerous collisions and finally stops. Then, it usually attaches to an atom. On the other hand, in β^+-emission, the emitted positron (antiparticle) immediately collides with electron (particle) of the surrounding produces energy which is carried away by two photons of gamma radiation.

References

Beiser, A. 2006. *Concepts of Modern Physics*, 432-441 Tata McGraw-Hill, New Delhi.

Cowan, C. L. *et al.* 1956. *Detection of the Free Neutrino : a Confirmation*. *Science*, 124, 103-104

Evans, R.D. 1978. *The Atomic Nucleus*, 47-48. Tata McGraw-Hill, New Delhi.

Griffiths D.1987. *Introduction to Elementary Particles*, 26-27, 67-68. John Wiley and Sons, New York.

Linder, E.G. and S. M. Christian. 1952. *The use of Radioactive Material for the Generation of High Voltage*, 23, 1213-1216, J. Appl.

Marmier, P.S.E. 1969. *Physics of Nuclei and Particles*, Vol.1, 31-36, Academic Press, New York.