Nuclear Physics

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Nuclear Physics 1 [Structure]

1. **Atomic Structure** can be investigated by *Rutherford [Geiger-Marsden] scattering*, which involves a-particles being repelled electrostatically by nuclear protons in a gold foil target.

2. **Most α-particles** (≈ 99.95%) are undeflected, indicating that atoms are predominantly empty space and most of the atomic mass is concentrated in a small fraction of the atomic radius (i.e. the nucleus).

3. **Some α-particles** (≈ 0.05%) are deflected up to 90°, indicating that nuclei are charged.

4. **A few α-particles** (≈ 0.01%) are deflected up to 180°, indicating that nuclei are positively charged (as they repel the positively charged a-particles).

5. **Data fixes only** the *upper limit* of nuclear radius as scattering measures least distance of approach. Scattering pattern is also affected by nuclear recoil and SNF interactions (as alpha particles are hadrons) and cannot be detected at exactly 180°. Evacuated chamber and thin gold foil are used to reduce the chance of absorption and/or multiple scattering.

6. **Nuclear radius** can be investigated more accurately by *high-energy electron diffraction,* as (de Broglie) wavelength approximates to nuclear diameter (10^{-14} m).

7. **Electrons are** unaffected by SNF interactions (as electrons are leptons), but first diffraction minimum is sometimes hard to determine due to superposition with electrostatic scattering between electrons and nuclear protons.

Nuclear Physics 2 [Radiation 1]

1. **Radioactive Decay:** The random, spontaneous process in which an unstable nucleus attains greater stability by shedding mass in the form of energetic particles (a or β) or electromagnetic radiation (**ɣ**). Instability can result from: too many or too few neutrons; too many nucleons; or too much energy.

2. **Isotopes:** Atoms of the same element with the same number of protons but differing numbers of neutrons.

3. **Decay constant:** The probability that an unstable nucleus will decay per unit time.

$$A \propto N \qquad [A = -\lambda N] \qquad \left[A = -\frac{\Delta N}{\Delta t}\right]$$

4. **Half-life:** The average time taken for the number of radioactive nuclei in a source to fall to half its previous value (or the activity of a source to fall to half its previous value).

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

5. **α emission:** [Radon-222] $^{+4}_{+2}\mathrm{He}$ / fixed energy (two body process). Strongly ionising (≈ 10,000 ionisations/mm as slow and large +2e charge) ∴ low penetration (≈1 mm thick sheet of paper). Small *E* and *B* field deflection.

6. **β⁻ emission:** [Carbon-14] $^{0}_{-1}\mathrm{e}$ / varying energies (three body process: anti-neutrino produced). Moderately ionising (≈ 100 ionisations/mm as fast and small -1e charge) ∴ moderate penetration (≈ 5 mm thick sheet of aluminium). Large *E* and *B* field deflection.

7. **ɣ emission:** [Technetium-99m] $^{0}_{0}\gamma$ / varying energies. Weakly ionising (fast and no charge) ∴ high penetration (≈ 20 mm thick sheet of lead). No *E* and *B* field deflection.

Nuclear Physics 3 [Radiation 2]

1. **Number of undecayed nuclei** (*N*) [no units]
2. **Activity** (*A*) becquerels (disintegrations per sec) [Bq (s^{-1})]
3. **Decay constant** (λ) disintegrations per second [s^{-1}]
4. **Half-life** ($T_{½}$) seconds [s]
5. **Nucleon number** (*A*) [no units]
6. **Proton number** (*Z*) [no units]
7. **Decay Equation** $N = N_o e^{-\lambda t}$ $\left[A = A_o e^{-\lambda t}\right]$

Nuclear Physics 4 [Detection & Dangers]

1. **Background Count Rate:** The persistent count rate that is detected even in the absence of an observable radioactive source. Caused by *background nuclear radiation*.
2. **Background Nuclear Radiation:** Produced by radioactive decay in: astronomical bodies (e.g. Sun); naturally occurring terrestrial isotopes (e.g. radon gas, uranium etc.); waste or leaks from nuclear power stations; nuclear bomb tests; medical procedures (e.g. radiotherapy, waste etc.); industrial processes (e.g. smoke alarms); nearby food sources (e.g. Carbon-14).
3. **Failure to correct** recorded count rates for background count rate will shift the exponential decay curve upwards, parallel to the y-axis, resulting in the calculation of an erroneous, higher-value half-life that increases with time.
4. **Geiger-Müller Tube:** Incident radiation may not register due to: absorption of some α-particles by mica window; failure of γ-rays to ionise the argon gas; ionisation occurring during the tube's recovery ('dead') time.
5. **Cloud chambers:** Supercooled (supersaturated) gas condenses on ion tracks. Alpha tracks are short, thick, and straight. Beta tracks are longer, thin, and feeble. Magnetic fields often applied to show charge of particles (through direction of path curvature).
6. **Nuclear radiation** can damage living cells either by destroying cell membranes or by creating free radical ions which corrupt DNA.
7. **Safety checks for radioactive sources:** Use for shortest possible duration; hold using tongs at distance; keep away from food and drink; wash hands before and after use; wear film dosage badge when possible.

Nuclear Physics 5 [Decay]

1. ***N-Z* graph** is proportional for Z values up to 20, but then increasingly steep for larger nuclei.
2. **Larger nuclei** require a higher neutron:proton ratio in order to remain stable, as the additional neutrons contribute to the attractive SNF while separating the EM repulsive protons.
3. **α emitters** are positioned just below the stability belt beyond the $Z \approx 60$ region, where the attractive SNF is unable to counteract the EM repulsion of the protons.
4. **β^- [β^+] emitters** are found just above [below] the stability belt where isotopes are neutron [proton] rich compared to stable atoms (i.e. fission fragments [which can also be pure neutron emitters in extreme cases]).
5. **ɣ emitters** produced by an excited nucleus stabilising its remaining nucleons (for example following alpha or beta emission, electron capture, or collision with neutron in nuclear reactor)
6. **Nuclear Radius Equation:** $R = r_o A^{\frac{1}{3}}$
7. **Einstein's Special Principle of Relativity** states that energy and mass are interchangeable ($E = mc^2$). This relationship is bi-directional, and hence energy can derive from reductions in mass (e.g. nuclear reactions) and mass from reductions in energy (e.g. particle collisions).

Nuclear Physics 6 [Energy]

1. **Binding energy (BE):** The work that must be done against the strong nuclear force to separate a formed nucleus into its individual nucleons. This work increases the mass of the nucleons ∴ $BE = \Delta mc^2$, where Δm is the mass defect.
2. **Mass defect (Δm):** The difference between the mass of a formed nucleus (smaller) and the sum of the masses of its separated, individual nucleons (larger). $\Sigma BE = \Delta mc^2$, where Δm is the mass defect.
3. **Binding energy per nucleon (BEPN):** The stability of a nucleus increases with binding energy *per nucleon* value (BEPN), the most stable being iron (${}^{56}_{26}Fe$). $\Sigma BE = (\Delta BEPN)$(number of nucleons)
4. **Fusion:** Small nuclei (nucleon number less than iron) with a low BEPN increase their stability by undergoing fusion (joining together) to form one large nucleus with a higher BEPN, releasing energy in the process.
5. **Fission:** Large nuclei (nucleon number greater than iron) with a low BEPN increase their stability by undergoing fission (splitting) to form two smaller nuclei, each with a higher BEPN, releasing energy in the process.
6. **Fusion Example:** ${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He$ + Energy
7. **Fission Example:** ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba + (3)({}^{1}_{0}n)$ + Energy

Nuclear Physics 7 [Fission Reactors]

1. **A heavy nucleus** is split into *fission fragments* (two lighter nuclei and several free neutrons) by absorbing a slow-moving *thermal* neutron (< 1 eV).
2. **This reaction** releases energy (principally as kinetic (and photon) energy in the fission fragments), much of which is transformed into internal energy through collisions with atoms in the fuel rods and moderator.
3. **The free neutrons either:** (1) escape the fuel rod; (2) get absorbed by more stable atoms (such as Uranium-238) without initiating further fissions; (3) collide with Uranium-235 atoms, producing a *chain reaction*.
4. **The probability** of the chain reaction becoming self-sustaining is increased significantly for fuel rods of *critical mass* (and dramatically the *supercritical mass* generally used in nuclear reactors) and if the freed neutrons are moving relatively slowly ($\approx 2200\ ms^{-1}$ ∴ large *probability-cross-section*).
5. **The efficiency** of a reactor is therefore increased by slowing (*'thermalising')* the fast free neutrons through numerous (≈ 50) elastic collisions with *moderator* atoms (ideally of similar mass to the neutrons, such as carbon atoms in graphite or deuterium atoms in heavy water) which transfer kinetic energy from the neutron to the moderator.
6. **The rate of** reaction is modified by (boron or cadmium) *control rods*, which absorb excess neutrons and therefore prevent them from initiating further fissions (pushing control rods deeper into the reactor reduces the rate of reaction).
7. **Coolant:** The internal energy of both the fuel rods and moderator is extracted by a coolant (such as pressurised water or helium/carbon dioxide gas) which passes through the reactor before transferring this energy to a conventional pressure-turbine system via a heat exchanger.

Nuclear Physics 8 [Waste Management]

1. **Fission reactions** produce many radioactive emissions (from fuel rods/bombarded nuclei becoming unstable through absorption of neutrons [or merely relaxing following excitation through collision with neutrons]).
2. **The reactor** is therefore sealed in a large container (usually made of dense, reinforced concrete), which shields workers from this effect. Waste also need safe disposal in secure sites.
3. **Low Level Waste (LLW):** Generated principally by nuclear fuel cycle (and also medical and industrial processes), comprising paper, rags, tools, clothing and so on. Small amounts of short-lived radioactive sources. Buried in shallow land-fill (often following compacting and/or incineration).
4. **Intermediate Level Waste (ILW):** Generated principally by nuclear reactors, comprising resins, chemical sludges and metal fuel cladding. Significant amounts of radioactive sources. Buried in shallow repositories (for short half-life sources) or geological repositories (for long half-life sources), often following solidification in (shielding) bitumen or concrete.
5. **High Level Waste (HLW):** Generated principally by spent fuel rods or nuclear warheads (and their reprocessing), comprising fission products and transuranic elements with various emissions, activities and half-lives.
6. **Rods are removed remotely** and kept cool for several years in (shielding) water pools (and sometimes thereafter air-cooled casks) until initial activity has dropped significantly prior to reprocessing.
7. **Unrecovered radioactive material** is generally vitrified (or sometimes encased in synroc) to stabilise it in a non-reactive, non-degrading form and then either secured onsite or, ideally, buried in deep geological repositories (such as salt-mines or granite boreholes) that prevent leakage into the water table.