Nuclear Energy

Matthew Williams • Physics • May 20, 2026

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Mass-Energy Equivalence

Einstein showed that mass and energy are equivalent. A small loss of mass (Δm) in a nuclear reaction releases an enormous amount of energy (ΔE):

$$\Delta E = \Delta m c^2$$

where $c = 3 \times 10^8$ m s^{-1} is the speed of light. Even a tiny mass deficit produces a very large amount of energy because c^2 is enormous (9×10^{16} m^2 s^{-2}).

The **mass deficit** is the difference between the total mass of the reactants and the total mass of the products. The products weigh slightly less than the reactants; the missing mass has been converted to energy.

Nuclear Fission

Nuclear fission is the splitting of a heavy nucleus into two lighter nuclei (fission fragments), releasing energy and several neutrons. The classic example is the fission of uranium-235:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3{}^{1}_{0}\mathrm{n} + \gamma$$

Key points:

- A slow (thermal) neutron is absorbed by U-235, making it unstable.
- The nucleus splits into barium-141 and krypton-92 (the fission fragments).
- Three fast neutrons are released, along with gamma radiation.
- Mass and atomic number are conserved on both sides.

- The total mass of products is less than the total mass of reactants, the difference is the mass deficit, released as energy.

The Chain Reaction

Each fission event releases 3 neutrons. If each neutron causes another fission, the number of fissions doubles each generation, a **chain reaction**. An uncontrolled chain reaction releases energy explosively (atomic bomb). In a nuclear reactor, control rods (usually boron or cadmium) absorb excess neutrons to keep exactly one neutron per fission causing the next, maintaining a controlled, self-sustaining chain reaction.

Fission mass deficit and energy released (2023 Paper 02, Q6)
In the fission of U-235:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3^{1}_{0}\mathrm{n} + \gamma$$

Suppose the total mass of reactants (U-235 + 1 neutron) is 3.9188×10^{-25} kg and the total mass of products (Ba-141 + Kr-92 + 3 neutrons) is 3.9171×10^{-25} kg.

Mass deficit:

$$\Delta m = 3.9188 \times 10^{-25} - 3.9171 \times 10^{-25} = 1.7 \times 10^{-28}\mathrm{kg}$$

Energy released:

$$\Delta E = \Delta m c^2 = 1.7 \times 10^{-28} \times (3 \times 10^{8})^2 = 1.7 \times 10^{-28} \times 9 \times 10^{16} \approx 1.5 \times 10^{-11}\mathrm{J}$$

This is the energy released per fission event, an enormous amount per kilogram of fuel compared to chemical reactions.

Nuclear Fusion

Nuclear fusion is the combining of light nuclei to form a heavier nucleus, releasing even more energy per unit mass than fission. The Sun's energy comes from fusion, four hydrogen nuclei combine to form helium:

$$4^{1}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + 2^{0}_{+1}\mathrm{e} + 2\nu$$

A simpler fusion reaction studied for power generation:

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n} + \mathrm{energy}$$

Fusion requires extremely high temperatures (millions of degrees Celsius) to overcome the electrostatic repulsion between positively charged nuclei. At these temperatures, matter exists as a plasma. Achieving and containing fusion reactions long enough to generate net power is an ongoing research challenge.

Arguments For and Against Nuclear Power

For	Against
Very large amounts of energy from a small mass of fuel	High construction and decommissioning costs
Low greenhouse gas emissions during operation	Risk of catastrophic accidents (Chernobyl 1986, Fukushima 2011)
Reliable base-load power generation (unaffected by weather)	Long-lived radioactive waste requires safe storage for thousands of years
Reduces dependence on imported fossil fuels	Uranium mining has environmental and safety impacts
No CO,during operation, helping limit global warming	Nuclear plants are targets for sabotage or terrorism

Nuclear power is not currently used in the Caribbean, but the arguments above are examinable.

> **📝 Exam Tip**
> In mass-energy calculations: the mass deficit (Δm) is always LHS mass minus RHS mass (reactants minus products). If Δm is positive, energy is released. Substitute in kg and use $c = 3 \times 10^8$ m s{ to get energy in joules.
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> For fission equations: check that A and Z balance on each side. The atomic number of Kr is 36, not 56 (which is Ba). A common exam error is confusing the identity of the products.