How can the nucleus be lighter than its constituents?

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The nucleus is lighter than its constituents

We all know this.
But it is rather weird is it not?
At least coming from classical physics this seems very counterintuitiv, as if the sum of the parts of a car would weigh more than the car.
It would be nice to have some intuitiv understanding of how this can be.

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The energy in nuclear decays

The reduction in mass is necessary from energy conservation

Since the energy before is just the mass and after is the mass pluss released energy, mass per nucleon must be reduced.

Let us look at chemistry

Energy conservation says the same must happen in chemistry; there must always be a mass difference equal to the reaction energy.
But can this be measured? Yes!

$$M_p + M_e - M_{{}^1_1H} \approx 13.3 \text{ eV}$$

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The mass of the electron

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Let us calculate

The electric field, $E \propto 1/r^2$ and its energy density $u_E \propto E^2 \propto 1/r^4$.
Integrating gives us the total energy, $U_E(r_0)$ outside of r_0 as,

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With all constants

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The mass of a hydrogen atom

Destructive interference

Outside the atom the proton and electron fields cancel, thus reducing the mass of the hydrogen atom.

Let us see how much, set $r_0 = 10^{-10}$ m, the reduction in mass becomes,

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Why two protons repell

Constructive interference increases mass

Since $u_E \propto E^2$, constructive interference gives 4 times the contribution of a single proton.
So the 2 proton state gets heavier than 2 single protons and “decays”.

The mass of a nucleus

Nucleus according to Yukawa

If we trust Yukawa, the nucleus consists of protons and neutrons held together by spin-0 meson fields.

Spin-0 fields

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Why teach this?

- Can give a more intuitiv understanding of the mass of nuclei.
- Shows the reality of electric field energy.
- Shatters the idea of classical particles.
- Paves the way for QFT by showing how the electric field is an integral part of the electron that affects its properties.