

Question: I have read that the energy of the strong nuclear force is said to be about 100 times stronger than the energy of the electromagnetic force. How was that number determined?

Answer:

There is some confusion about what exactly the “strong nuclear force” is. Prior to the 1970’s or so, the strong nuclear force was defined as the force which holds the nucleons together in a nucleus. Then, after the discovery of quarks and the emergence of the quantum chromodynamic theory, another force was needed, a force that was defined as the force holding the quarks together in a nucleon. For a brief time this force was called the “chromodynamic force”. However, for some reason, scientists decided to combine these two forces--the chromodynamic force and the strong nuclear force--under the same name, and call everything the strong nuclear force. Thus that name, the “strong nuclear force” was redefined as that force which hold the quarks together in a nucleon, causing much confusion. The force holding the nucleons together in a nucleus was then renamed the “nucleon-nucleon” force, or sometimes it is called the “nuclear force”. It is assumed that the nucleon-nucleon force and the chromodynamic force are both sub-sets of the strong nuclear force. This became especially after the introduction of one model for the nucleon-nucleon force, called the residual chromodynamic force, claiming that the nucleon-nucleon force is a residual component of the chromodynamic force. With all this naming confusion, it is no wonder that people are confused.

Thus when you are talking about relative strengths of energies or forces, it must be clear exactly which force you are talking about—the force which holds together the nucleons in a nucleus, or the force which holds the quarks together in a nucleon?

This electromagnetic model of the nucleon-nucleon force is strictly about the force that holds together the nucleons in a nucleus; it does not concern the force holding the quarks together in a nucleus. When looking at relative sizes of forces, what you might have read in other text books or elsewhere on the internet may be about the chromodynamic force, especially if gluons are mentioned. To clarify which sub-force of the strong nuclear force we are talking about, let us call the force which holds together the quarks inside a nucleon the “chromodynamic force”. Let us call the force which holds together the nucleons inside a nucleus the “nucleon-nucleon force”. It is too confusing otherwise.

Energy of the nucleon-nucleon force:

Regarding the nuclear energy associated with the nucleon-nucleon force, the value of the energy required to remove a nucleon from a nucleus is measured experimentally for each of the over 3000 known nuclides. If we look at the binding energy per nucleon for all the nuclides in the nuclear table, we see that the strongest binding energy per nucleon occurs near iron Fe-58, and it is approximately 8.8 MeV per nucleon. If we compensate for the Coulomb energy with an estimate of about 60 MeV for Fe-58, or slightly more than 1 MeV per nucleon, then the nucleon-nucleon energy per nucleon is roughly about 9.8 MeV per nucleon, or 1.57×10^{-12} joules.

The energy of the electric force:

To calculate the maximum repulsive energy of the electric force between two protons, we will look at two protons next to each other. We will assume the protons have a homogeneous charge

of one elementary charge, (1.602×10^{-19} coulombs), distributed evenly and radially throughout the proton. The electric energy is given in Equation 1:

$$\text{Energy} = \frac{1}{4\pi\epsilon_0} \times \frac{Q_1 Q_2}{\text{distance}_{12}} \quad \text{Eq.}$$

where Q_1 and Q_2 are the charges of the two protons, distance_{12} is the distance between the centers of the two protons, and $(1/4\pi\epsilon_0)$ is a constant of nature, equal to 8.987×10^9 in MKS units.

If the two protons are touching each other, and their radius is 0.842×10^{-15} meters (which is what is measured experimentally), then distance between the centers of charge is twice that, or 1.684×10^{-15} meters. The maximum energy between these two homogeneously charged protons can then be calculated, as shown in calculation 1:

$$\text{Energy} = 8.987 \times 10^9 \times (1.602 \times 10^{-19})^2 / 1.684 \times 10^{-15} = 1.37 \times 10^{-13} \text{ Joules} \quad \text{Calc.}$$

The ratio of the two energies is shown in Calculation 2:

$$\frac{\text{Energy}_{\text{electric}}}{\text{Energy}_{\text{nuclear}}} = \frac{1.37 \times 10^{-13}}{11.57 \times 10^{-12}} = 0.0873 = 1/11.46 \quad \text{Calc.}$$

As can be seen, this is not really a factor of 100, but more like a factor of 12. Which brings into question this factor of 100 that you refer to—it is simply not evident in the mathematics or the experimental data. (Perhaps it has something to do with the estimated strength of the chromodynamic forces.) But for the ratio of the electromagnetic force compared to the nucleon-nucleon force, that factor of 100 is simply not correct.

Also, there is another very significant problem here with the initial assumptions. This ratio suggests that the energy of the nucleon-nucleon energy is about 12 times stronger than the electromagnetic force, *if the assumptions we made at the outset are correct. However, we already know that the assumptions made for this calculation are erroneous.*

Redo Calculations by Considering Quarks:

These assumptions are erroneous because of the existence of quarks. There are three quarks in the nucleon, each quark sharing a bond with one other quark in another nucleon. Thus, the energy required to hold onto one nucleon is 1/3 of the energy of one bond. This means the energy of one bond--be it either electromagnetic or residual chromodynamic--is $(9.8 \text{ MeV} \times 1/3) = 3.27 \text{ MeV}$ per bond. Converting this to MKS units, this is 5.24×10^{-13} joules of energy per bond. This, then, is an good approximation of the energy for one internucleon quark-to-quark bond for the nucleon-nucleon force.

Now let's revisit the electric force between two internucleon quarks. The proton is not homogeneously charged, the neutron is not homogeneously charged, and the quarks are the centers of charge in the nucleons. Quarks have an assumed radius of zero, in other words, they are assumed to be infinitesimally small. If we make a reasonable estimate that the distance between two internucleon quarks is 1/10 the diameter of a nucleon, which is 0.1684 fm, then we

can recalculate an estimate for the electromagnetic force between the internucleon quarks. Starting again with equation 1:

$$Energy = 14\pi\epsilon_0 \times Q_1 Q_2 / distance^2 \quad Eq.$$

The charge of Q_1 , the positive quark is $2/3$ x the elementary charge, and the charge of Q_2 , the positive quark is $1/3$ x the elementary charge, and we estimate the distance separating the quarks to be $1/10$ the diameter of the proton. Then, this is shown in Calculation 3:

$$Energy = 8.987 \times 10^9 (2/3)(1/3) (1.602 \times 10^{-19})^2 / (1.684 \times 10^{-16})^2 = 3.04 \times 10^{-13} J. \quad Calc.$$

Now the electric energy 3.04×10^{-13} joules, and the ratio of the forces for one bond is shown in Calculation 4:

$$Energy_{electric} / Energy_{nucleon} = r = 3.04 \times 10^{-13} / 5.24 \times 10^{-13} = 0.5802 \quad Calc.$$

This ratio is much closer now, less than a factor of 2 different. The electric force is not that much smaller than the experimentally derived nucleon-nucleon force. However, there is a magnetic energy, which we have been ignoring thus far. Adding in the magnetic energy between the two quarks will increase the strength of the electromagnetic energy by quite a bit.

The magnetic energy is more difficult to calculate, especially since the exact magnetic moments of the quarks are unknown and can only be estimated. Also, the energy of the magnetic bond formed between two magnetic moments is vector dependent, and the relative vectors between the two magnetic moments are unknown. For a internucleon up-to-down quark-to-quark bond, where the quark-to-quark distance uses the reasonable estimate of $1/10^{\text{th}}$ the diameter of a proton, and assuming a side-by-side magnetic bond, the magnetic energy is calculated to be 9.62×10^{-13} joules. (This is for one magnetic side-by-side magnetic bond between two up and down quarks, at a distance of $1/10$ the diameter of the proton. See the FAQ about Magnetic Bonds for this calculation on this web site.)

Adding the magnetic energy to the electric energy gives about $(3.04+9.62)=12.66 \times 10^{-13}$ joules for the electromagnetic bond, which includes both the electric and magnetic energies. The new ratio is shown in calculation 5:

$$Energy_{electromagnetic} / Energy_{nuclear} = 12.66 \times 10^{-13} / 5.24 \times 10^{-13} = 2.42 \quad Calc.$$

As can be seen, the electromagnetic energy of one bond is now greater than the experimentally-measured nucleon-nucleon energy of one bond. This means these two internucleon quarks that form the quark-to-quark bond are actually be further away than the assumed reasonable estimate of $1/10^{\text{th}}$ the diameter of a proton. Calculating to solve for this distance, if the electromagnetic force is equal to the nucleon-nucleon force, the distance between the two internucleon up and

down quarks is just more than $1/8^{\text{th}}$ the diameter of the proton. This is a very reasonable value for that distance.

Relating this to your question, that number of the ratio being “100 times” bigger is not realistic when quarks are considered. In fact, even when quarks *are not* considered, it is only a factor of 12 or so, not 100. And when quarks *are* considered, along with the magnetic energy, the theoretical electromagnetic energy between two internucleon quarks is approximately the same as the experimentally measured nucleon-nucleon energy. Keep in mind that as that distance between the internucleon quarks grows smaller, the electromagnetic energy binding them together grows stronger. Furthermore, when taken to the extreme limit, if the distance between the charges becomes infinitesimally small, then the electric force becomes infinite.

In other words, there is NOT an upper limit to the strength of the electromagnetic force, and anyone who tells you this is badly mistaken and still believing in the misconceptions from 70 years ago.

What does this all mean then? First of all, the idea that the nucleon-nucleon force is 100 times stronger than the electromagnetic force is definitely incorrect. The electromagnetic force can be infinitely large if the distance between the charged and magnetic moments is infinitesimally small. Quite clearly, this means that the electromagnetic force between two internucleon quarks is, indeed, strong enough to hold the nucleons together in a nucleus.