Neutron Lifetime Puzzle and Nuclear Stability: A Possible Relation

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Abstract

It is known that a free neutron decays into a proton, an electron, and an anti-neutrino. Interesting, recent attempts to measure the neutron's lifetime has led to two slightly different estimates: namely, the number of decaying neutrons is somewhat larger than the number of newly created protons. This difference is known as the neutron lifetime puzzle. A natural explanation for this difference is that in some cases, a neutron decays not into a proton, but into some other particle. If this explanation is true, this implies that nuclei with a sufficiently large number of neutrons will be unstable. Based on the observed difference between the two estimates of the neutron lifetime, we can estimate the largest number of neutrons in a stable nucleus to be between 80 and 128. The fact that the number of neutrons (125) in the actual largest stable nucleus (lead) lies within this interval can serve as an additional argument is favor of the current explanation of the neutron lifetime puzzle.

1 Formulation of a Problem

Neutrons are unstable: reminder. Neutrons are one of the three main non-zero-mass particles, the other two being protons and electrons. It is known neutrons are unstable: if left on its own, a neutron n decomposes into a proton p^+, a positron e^-, and an anti-neutrino of electron type $\overline{\nu}_e$:

$$n \to p^+ + e^- + \overline{\nu}_e. \tag{1}$$

Neutron lifetime puzzle. It is known that the neutron's lifetime (to be more precise, half-time) is about 900 seconds. Recently, several experiments that tried to measure this lifetime led to differing results. To be more precise, two different types of experiments produce two somewhat different results (see, e.g., [3, 5, 6, 8, 10] and references therein):

- so-called *bottle* experiments count how the number of neutrons in a closed trap ("bottle") changes with time; these experiments consistently show a lifetime of 879.0 ± 0.6 seconds [1, 7, 9, 11, 12, 14];
- other experiments – known as *beam* experiments – measure the number of protons generated by trapped neutrons; these experiments consistently show a different lifetime, of 888.0 ± 2.0 seconds [2, 17].

The resulting 9-second discrepancy between these two estimates is known as the *neutron lifetime puzzle.*

Comment. Interestingly, a theoretical estimate for the neutron lifetime is 883.25 seconds (see, e.g., [5]) – which is almost exactly the arithmetic between the bottle and the beam measurement results.

How accurately do we know this discrepancy. Each of the two experiments has an accuracy of about 1 second. Since these measurements are independent, this means that the variance of the difference is equal to $2.0^2 + 0.6^2 = 4.36$ and thus, the standard deviation is $\sqrt{4.36} \approx 2.1$ seconds; see, e.g., [13]. Crudely speaking, this means that with high probability, the actual discrepancy is in the "one sigma" interval between $9 - 2.1 = 6.9$ and $9 + 2.1 = 11.1$ seconds.

How neutron lifetime puzzle is explained now. The experiments show, in effect, that during the same period of time, we lose a certain number of neutrons, and gain a slightly smaller number of new protons. The difference between the number of decayed neutrons and the number of new protons shows that in some cases (to be more precise, in about 1% of the cases), the neutron decays not following the equation (1), but in some other way, without generating a proton.

To be more precise, this percentage is approximately equal to

$$\frac{9}{883.5} \approx \frac{1}{98}$$

and is most probably in between the values

$$\frac{6.9}{883.5} \approx \frac{1}{128}$$

and

$$\frac{11.5}{883.5} \approx \frac{1}{80}.$$

Since no other massive products of the neutron decay have ever been observed, a natural conclusion is that this product interacts very weakly with the usual matter. In other words, a natural conclusion is that this rare decay product constitutes what physicists call a *dark matter* – a matter whose interaction with normal matter is very weak, so that we can only detect its presence either directly by the mass difference or indirectly, by the difference between the gravitational fields in galaxies and the gravitation fields caused by the usual visible matter; see, e.g., [5].

What we do in this paper. In this paper, we indicate a possible connection between the neutron lifetime puzzle and the nuclear stability.

2 Relation to Nuclear Stability

Brainstorming: neutron lifetime puzzle leads to nucleus instability. Neutron lifetime describes free neutrons, neutrons that exist on their own, without a strong interaction with others. Most neutrons in the Universe, however, are not free, they are part of nuclei. Such neutrons can (and do) decay according to the equation (1), but in a nucleus, there is also an inverse process, when a proton transforms backs into a neutron. With these two opposite reactions, the nucleus remains in some equilibrium state, with the same number of neutrons.

The situation changes if we take into account that some neutrons decay not into protons but into dark matter particles. Such particles practically do not interact with the usual matter, as a result of which they rarely get transformed back into neutrons. As a result, a nucleus becomes unstable – its number of neutrons decreases.

Resulting estimate of the largest number of neutrons in a stable nucleus. Let $p \approx 1\%$ be the proportion of cases in which a neutron decays into a dark matter particle. This means, crudely speaking, that if we start with a nucleus containing N neutrons, then $p \cdot N$ of them "disappear" – i.e., get transformed into difficult-to-directly-observe dark matter.

To provide a more precise understanding of this process, we need to take into account that the number of neutrons in a system is an integer. We cannot lose 0.1 neutrons. Thus, the above instability effect only occurs when the above effects causes at least one neutron to be lost, i.e., when $p \cdot N \geq 1$. So, instability occurs when

$$N \geq \frac{1}{p} \approx 100.$$

Hence, the largest possible number of neutrons N_{st} in a stable atom is equal to the largest integer which is still smaller than $\frac{1}{p}$. In other words, we have

$$N_{st} \approx \frac{1}{p}.$$

Based on the above estimate for p, we conclude that:

- the largest number of neutrons in a stable nucleus is approximately equal to $N_{st} \approx 98$, and
- most probably, thus number is in between 80 and 128: $N_{st} \in [80, 128]$.

What is the actual largest number of neutrons in a stable nucleus. Usually, the number of neutrons grow monotonically with the atomic weight. Thus, to find the stable nucleus with the largest possible number of neutrons, we should look for the stable nucleus with the largest possible atomic weight. Such a nucleus is well known – it is the lead (Pb). Lead's nucleus contains 125 neutrons.

Interestingly, this value is within the interval $[80, 128]$ obtained from the nuclear lifetime puzzle.

Conclusion. It is known that a free neutron decays with time, generating a proton, an electron, and an anti-neutrino. The problem is that different experiments lead to somewhat different estimates of the neutron's lifetime. This difference is usually explained by the fact that a small ($\approx 1\%$) proportion of the neutrons decays not into protons, but into dark matter particles.

In real worlds, most neutrons are not free, they are a part of nuclei. Because of the possibility of the dark-matter decay, nuclei with a large number of neutrons become unstable. Based on the difference between the two estimates of the neutron lifetime, we can conclude that the largest number of neutrons in a stable nucleus is in between 80 and 128. The actual largest number of neutrons in a stable nuclear is 125 (for lead), which is consistent with the neutron-lifetime-based interval.

This fact provides one more confirmation of the current explanation of the neutron lifetime puzzle.

Acknowledgments

This work was supported in part by the National Science Foundation grants 1623190 (A Model of Change for Preparing a New Generation for Professional Practice in Computer Science) and HRD-1242122 (Cyber-ShARE Center of Excellence).

References

[1] S. Arzumanov, L. Bondarenko, S. Chernyavsky, P. Geltenbort, V. Morozov, V. V. Nesvizhevsky, Yu. Panin, and A. Strepetov, "A measurement of the neutron lifetime using the method of storage of ultracold neutrons and detection of inelastically upscattered neutrons", *Physics Letters B*, 2015, Vol. 745, pp. 79–89.

[2] J. Byrne and P. G. Dawber, "A revised value for neutron lifetime measured using a Penning trap", *Europhysics Letters*, 1996, Vol. 33, pp. 187–192.

[3] A. Czarnecki, W. J. Marciano, and A. Sirlin, "Precision measurements and CKM unitarity", *Physical Review D*, 2004, Vol. 70, Paper 093006.

[4] R. Feynman, R. Leighton, and M. Sands, *The Feynman Lectures on Physics*, Addison Wesley, Boston, Massachusetts, 2005.

[5] B. Fornal and B. Grinstein, "Dark matter interpretation of the neutron decay activity", *Physical Review Letters*, 2018, Vol. 120, Paper 191801.

[6] J. C. Hardy and I. S. Towner, "Superallowed $0^+ \to 0^+$ nuclear β decays: 2014 critical survey, with precise results for V_{ud} and CKM unitarity", *Physical Review C*, 2015, Vol. 91, Paper 025501.

[7] W. Mampe, L. N. Bondarenko, V. I. Morozov, Y. P. Panin, and A. I. Fomin, "Measuring neutron lifetime by storing ultracold neutrons and detecting inelastically scattered neutrons", *Journal of Experimental and Theoretical Physics (JETP) Letters*, 1993, Vol. 57, pp. 82–87.

[8] W. J. Marciano and A. Sirlin, "Improved calculation of electroweak radiative corrections and the value of V_{ud}", *Physical Review Letters*, 2006, Vol. 96, Paper 032002.

[9] C. Patrignani et al. (Particle Data Group), "Review of particle physics", *Chinese Physics C*, 2016, Vol. 40, Paper 100001.

[10] R. W. Patti Jr. et al., "Measurement of the neutron lifetime using a mangeto-gravitational trap and in situ detection", *Science*, 2018, Vol. 360, pp. 627–632.

[11] A. Pichlmaier, V. Varlamov, K. Schreckenbach, and P. Geltenbort, "Neutron lifetime measurement with the UCN trap-in-trap MAMBO II", *Physics Letters B*, 2010, pp. 221–226.

[12] A. Serebrov et al., "Measurement of the neutron lifetime using a gravitational trap and a low-temperature Fomblin coating", *Physics Letters B*, 2005, Vol. 605, pp. 72–78.

[13] D. J. Sheskin, *Handbook of Parametric and Nonparametric Statistical Procedures*, Boca Raton, Florida: Chapman and Hall/CRC, 2011.

[14] A. Steyerl, J. L. Pendlebury, C. Kaufman, S. S. Malik, and A. M. Desai, "Quasielastic scattering in the interaction of ultracold neutrons with a liquid wall and application in the reanalysis of the Mambo I neutron lifetime experiment", *Physical review C*, 2012, Vol. 85, Paper 065503.

[15] K. S. Thorne and R. D. Blandford, *Modern Classical Physics: Optics, Fluids, Plasmas, Elasticity, Relativity, and Statistical Physics*, Princeton University Press, Princeton, New Jersey, 2017.

[16] D. H. Wilkinson, "Analysis of neutron beta decay", *Nuclear Physics A*, 1982, Vol. 377, No. 4, pp. 474–504.

[17] A. T. Yue, M. S. Dewey, D. M. Gilliam, G. L. Greene, A. B. Laptev, J. S. Nico, W. M. Snow, and F. E. Wietfeldt, "Improved determination of the neutron lifetime", *Physical Review Letters*, 2013, Vol. 111, Paper 222501.