Shedding Light on the Neutron Lifetime Puzzle

via the New Unexpected Result of the Two-Body Decay of Neutrons

Eugene Oks
Auburn University, USA

- The lifetime of free neutrons is *puzzling*: in the **beam** experiments (τ_{beam} = 888.0 ± 2.0 s) it is greater than in the **trap** experiments (τ_{trap} = (877.75 ± 0.28_{stat} + 0.22/-0.16_{syst}) s, e.g., according to Gonzalez et al 2021) well beyond the error margins.
- It would have been explained by the **two-body decay** into a **hydrogen atom** plus antineutrino if the Branching Ratio (BR) – compared to the usual three-body decay – would be ~ 1%: in the **beam** experiments they count only the protons from the three-body decay and **miss the two-body decay.**
- However, the previously known theoretical BR (for such two-body decay) was much smaller: 4×10^{-6}.

Gonzalez et al, Phys. Rev. Lett. 127 (2021) 162501

- Alternatively, Fornal and Grinstein (2018) suggested that neutron might decay into an *unspecified* dark matter (DM) particle.
- The problem still was that the resulting hypothetical DM particle was not identified.
- Moreover, Dubbers et al (2019) showed that the BR for this process is at least several times smaller than required 1%.
- In 2024 experiment by Joubioux, Savajols et al with the hypothetical dark decay $^{6}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + n + \chi$, the corresponding BR for free neutrons was shown to be $\sim 10^{-5}$, while BR $\sim$ 1% is needed for reconciling τ_{trap} and τ_{beam}.

Fornal and Grinstein, Phys. Rev. Lett. 120 (2018) 191801

Dubbers et al, Phys. Lett. B 791 (2019) 6

Joubioux, Savajols et al, Phys. Rev. Lett.

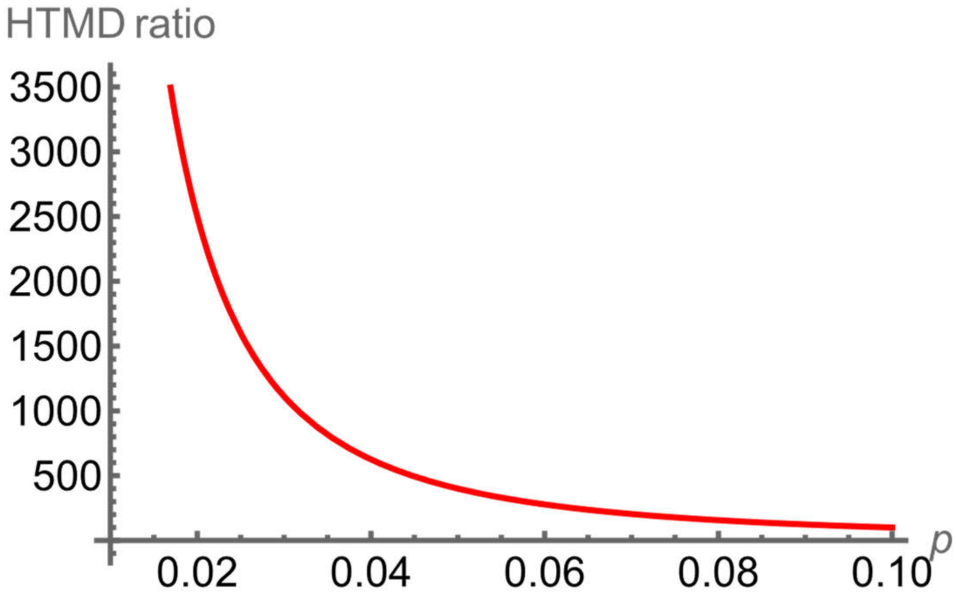
- In our papers [4, 5] of 2024, we brought to the attention of the research community that with the allowance for the second solution of Dirac equation for hydrogen atoms, **the theoretical BR for the decay into a hydrogen atom** (plus antineutrino) **is increased by a factor of 3300, that it to 1.3%.**
- This is in the **excellent agreement with "experimental" BR = (1.15 ± 0.27)%** required for reconciling the above τ_{trap} and τ_{beam}.
- Thus, it seems that the allowance for the above, enhanced two-body decay of free neutrons solves the neutron lifetime puzzle ***completely***.
- Below are some details.

[4] Oks 2024 *New Astronomy* **113** 102275

[5] Oks 2024 *Intern. Review Atom. Molec. Phys.* **15** 49

But first: how the second solution of Dirac equation for hydrogen atoms became legitimate?

- Analysis of atomic experiments related to the distribution of the linear momentum in the ground state of hydrogen atoms revealed a huge discrepancy.
- Namely, the ratio of the experimental and previous theoretical results was up to *tens of thousands* (J. Phys. B: At. Mol. Opt. Phys. **2001**, *34*, 2235).



- This figure shows the **ratio** of the theoretical High-energy Tail of the linear Momentum Distribution (HTMD), calculated by Fock (1935), to the experimental HTMD (deduced from the analysis of atomic experiments for a great variety of collisional processes between hydrogen atoms and electrons or protons, Gryzinski, 1965).
  (The linear momentum p is in units of $m_e c$,)
- It is seen that the relative discrepancy between the theory and experiments can reach many orders of magnitude: **3 or 4 orders of magnitude (!)** – in the relevant range of p: $m_e e^2/\hbar < p << m_e c$.
- Namely, the **experimental HTMD falls off much-much slower** than the theoretical one.

Fock, *Z. Physik* **1935**, *98*, 145

Gryzinski, *Phys. Rev.* **1965**, 138, A336

- This was the motivation behind our *theoretical* results from that paper of 2001 in the JPB.
- The standard Dirac equation of quantum mechanics for hydrogen atoms has two analytical solutions: 1) a *weakly singular* at small r; 2) a *more strongly singular* at small r.
- For the ground state, the radial part of the coordinate wave functions is

$$R_{0,-1}(r) \propto 1/r^{q}, \qquad q = 1 \pm (1 - \alpha^2)^{1/2}.$$

- Here α is the fine structure constant; – 1 in the subscript of the wave function $R_{0,-1}$ is the eigenvalue of the operator $K = \beta(2\mathbf{Ls} + 1)$ that commutes with the Hamiltonian (β is the Dirac matrix of the rank 4).
- So, the 1st solution has only weak singularity: $q \approx \alpha^2/2 \approx 0.000027$ (the "regular" solution, for brevity).
- The 2nd solution is really singular ($q \approx 2$) and is usually rejected (the normalization integral diverges at $r = 0$).

- The situation changes after allowing for the finite nuclear size.
- For models where the charge distribution inside the nucleus (the proton) is assumed to be either a charged spherical shell or a uniformly charged sphere, the 2nd solution outside the proton is justifiably rejected: it cannot be tailored with the corresponding regular solution inside the nucleus.
- In that paper of 2001 in the JPB, we derived a general class of potentials inside the nucleus, for which the singular solution outside the nucleus can be actually tailored with the corresponding regular solution inside the nucleus at the boundary.
- In particular, this class of potentials includes those corresponding to the charge density distributions that have a **peak at r = 0.**
- From experiments on the elastic scattering of electrons on protons (see, e.g., Simon et al (1980) and Perkins (1987)), it is known that the charge density distribution inside protons does have a **peak at r = 0.**

Simon et al, *Nucl. Phys.* **1980**, *A333*, 381

Perkins, *Introduction to High Energy Physics*; Addison-Wesley: Menlo Park, CA, USA, 1987, Sect. 6.5.

- Thus, the regular solution inside the proton can be tailored with the singular solution outside the proton at the boundary.
- So, in that paper of 2001 in JPB, we derived analytically the corresponding wave function.
- As a result, the huge multi-order **discrepancy** between the experimental and theoretical HTMD got **completely eliminated**.
- The reason: for the singular solution outside the proton, a much stronger rise of the coordinate wave function toward the proton at small r translates into a *much slower fall-off* of the wave function in the p-representation for large p (according to the properties of the Fourier transform) than the scaling $\sim 1/p^6$ predicted by Fock (1935).

Oks, *J. Phys. B: At. Mol. Opt. Phys.*, **2001**, *34*, 2235

- The corresponding derivation in that paper of 2001in JPB used *only* the fact that in the ground state the eigenvalue of the operator K is $k = -1$.
- Therefore, actually the corresponding derivation is valid not just for the ground state, but for any state of hydrogen atoms characterized by the quantum number $k = -1$.
- Those are S-states ($l = 0$), specifically $^2S_{1/2}$ states.
- So, both the regular exterior solution and the singular exterior solution are legitimate for ***all*** S-states.
- Both solutions are legitimate also for the $l = 0$ states of the *continuous* spectrum.
- All of these additional results were presented in our paper of 2020 in *Research in Astronomy and Astrophysics* (**2020**, *20(7)*, 109) published by the British IOP Publishing, where we applied these results to solving one of the dark matter puzzles.

- This second kind of hydrogen atoms having only the S-states was later called the Second Flavor of Hydrogen Atoms (SFHA). Here is why:
- Both the regular and singular solutions of the Dirac equation outside the proton correspond to **the same energy**.
- Since this means **the additional degeneracy**, then according to the fundamental theorem of quantum mechanics, there should be an **additional conserved quantity**.
- In other words: hydrogen atoms have ***two flavors*, differing by the eigenvalue of this additional, new conserved quantity**: hydrogen atoms have *flavor symmetry* (Oks, *Atoms* **2020**, 8, 33).
- It is called so **by analogy with quarks that have flavors** (for example, there are up and down quarks).
- For representing this particular quark flavor symmetry, there was assigned an operator of the additional conserved quantity: the isotopic spin I – the operator having two eigenvalues for its z-projection: $I_z = 1/2$ assigned to the up quark and $I_z = -1/2$ assigned to the down quark.

- Thus, the elimination of the huge multi-order discrepancy between the theoretical and experimental distributions of the linear momentum in the ground state of hydrogen atoms constituted **the first experimental evidence of the existence of the SFHA** – since no alternative explanation for this huge discrepancy was ever provided.
- There are also **three additional experimental evidences** from three *different* kinds of atomic experiments:

- from electron impact excitation of hydrogen atoms
- from electron impact excitation of hydrogen molecules
- from charge exchange between low energy protons and hydrogen atoms.

- For all them, the SFHA-based explanation removed large discrepancies (up to a factor of two or more) between the experimental and previous theoretical results, while alternative explanations were never provided.
- So, **the SFHA does exist**.

- **THE PRIMARY FEATURE of the SFHA**: since the SFHA have only the S-states, then according to the well-known selection rules of quantum mechanics, the **SFHA do not emit or absorb the electromagnetic radiation** – **they remain DARK** (with the exception of the 21 cm line resulting from the transition between the hyperfine sublevels of the ground state)

- There is also an astrophysical evidence that SFHA exists.
- There is perplexing observation by Bowman et al (2018) of the anomalous absorption in the (redshifted) 21 cm line from the early Universe.
- The absorption signal was found to be about ***twice stronger*** than predicted by the standard cosmology.
- This indicated that the hydrogen gas temperature was **significantly smaller** than predicted by the standard cosmology.
- Barkana (2018) suggested that some *unspecified dark matter* particles provided an additional cooling of the hydrogen gas by collisions.
- By his estimates, the quantitative explanation of the above anomalous absorption required the mass of unspecified dark matter particles to be ~ baryons masses: **unspecified baryonic dark matter**.

Bowman et al, *Nature* **2018**, *555*, 67

Barkana, *Nature* **2018**, *555*, 71

- In that paper of 2020 in Research in Astronomy and Astrophysics (British Publisher IOP) we considered the following: what if these unspecified dark matter particles were the SFHA?
- It should be noted that the SFHA would also contribute to the 21 cm line, while remaining dark otherwise.
- In that paper it was explained that in the course of the expansion of the Universe, the SFHA decouple from the cosmic microwave background radiation (due to having only the S-states) **earlier** than the usual hydrogen atoms.
- For this reason, their spin temperature (controlling the absorption signal in the 21 cm line) was smaller than for the usual hydrogen atoms.
- This explained the observed anomalous absorption both qualitatively and quantitatively, and made the **SFHA a compelling candidate for the baryonic dark matter** – especially because it's based on the standard Dirac equation, it does not go beyond the Standard Model of particle physics and does not change the physical laws – in distinction to the overwhelming majority of theories of dark matter.

- **Back to the neutron two-body decay**.
- Its probability P_{ns} is proportional to the square modulus of the electron wave function at the nuclear surface R (see, e.g., Bahcall 1961 Phys. Rev. 124, 495):

$$P_{ns} = \text{const}\,|\Psi_{ns}(R)|^2,$$

where $\Psi_{ns}(R)$ is the value of the atomic electron wave function at r = R; "const" is the normalization constant whose specific value is immaterial for obtaining the ratio of probabilities below.

- We focus on the formation of hydrogen atoms in the ground state 1S since this has the overwhelming probability:

$$P_{1s} = \text{const}\,|\Psi_{1s}(R)|^2.$$

- In the mixture of the SFHA with usual hydrogen atoms in the ratio ε to 1, outside the proton, the radial part of the Dirac bispinor (based on Eq. (17) from paper of 2001 in the JPB), can be written in the following form for f- and g-components (where all quantities are in the natural units $\hbar = m_e = c = 1$):

$$f(r, \varepsilon) \approx -\beta^{5/4}\ \{1 + \varepsilon\Delta/(2\beta^2 r^2)]\}/(1 + \varepsilon^2)^{1/2},$$

$$g(r, \varepsilon) \approx 2\beta^{3/4}\ \{1 + \varepsilon\Delta/(4\beta^2 r\ )]\}/(1 + \varepsilon^2)^{1/2},$$

$$\Delta = E_0 - E = -4\beta^{3/2}\int_0^R [V_{inter}(r) + 1/r]r^2 dr.$$

Here $\beta = \alpha^2$, α being the fine structure constant; E_0 and E are the unperturbed ($R = 0$) and the perturbed ($R > 0$) energies, respectively; $V_{inter}(r)$ is the potential inside the proton, corresponding to the **experimental charge distribution inside the proton** from work [15].

- This equation is valid for $R \leq r \ll 1/\alpha$.

[15] *The Frontiers of Nuclear Science, A Long Range Plan,* DOE/NSF, Nuclear Science Advisory Committee (2008) and arXiv:0809.3137 (2008)

- Then the probability of the neutron two-body decay becomes:

$$P(R, \varepsilon) = \text{const}\,[f(R, \varepsilon)^2 + g(R, \varepsilon)^2].$$

- Now we calculate the ratio of the probability $P(R, \infty)$, corresponding to the SFHA without any usual hydrogen atoms, to $P(R, 0)$, corresponding to the usual hydrogen atoms without the SFHA:

$$\rho = P(R, \infty)/P(R, 0).$$

- On substituting the numerical value of $\beta \approx 0.0000533$ and $R \approx 0.00218$ (the latter being translated in the natural units from $R = 0.84$ fm), we obtain:

$$\boldsymbol{\rho \approx 3300}.$$

- Thus, **the outcome of the two-body decay of the neutron is – with the overwhelming probability – the SFHA**, rather than the usual hydrogen atom.

- **I can propose the design of the experiment** that will constitute both **the first experimental detection of the 2-body decay of neutrons** and the **experimental confirmation that the 2-body decay of neutrons produces overwhelmingly the SFHA** – ***if you ask me such question***.

- The above results lead to viewing neutron stars in a new light: as the generators of the baryonic DM in the Universe, as presented in our paper of 2024 in New Astronomy (v. 113, 102275).
- There are 3 relevant situations.
- First, at the surface of **old neutron stars** (of ages ~ 10^7 years or older, the surface temperature being ~ 1 eV or smaller [16]), neutrons decay and release the decay products into the star atmospheres.
- Through the secondary decay channel (of the branching ratio ~ 1%) neutrons release the SFHA (plus antineutrinos).
- Since the temperature is ~ 1 eV or smaller, the resulting SFHA can survive and slowly accumulate in the atmospheres of old neutron stars.
- Second, **in the neutron stars, whose mass becomes slightly less than ~ 0.1 of the solar mass**, there occurs the explosive process of the hydrodynamic destruction of these neutron stars [17].
- As a result, these neutron stars throw neutrons into the interstellar medium, where they decay through the two channels discussed above.
- In the warm interstellar medium (neutral or ionized) and in H II regions, where the temperature is ~ 1 eV or smaller, the resulting SFHA survive and slowly accumulate.

[16] Gonzalez and Reisenegger, Astron. Astrophys. 522 (2010) A16

[17] Blinnikov et al, Sov. Astron. 34 (1990) 595

- Third, mergers of a neutron star with another neutron star or with a black hole are accompanied by the ejection of neutron-rich material ([18-20].
- This mechanism potentially can also lead to the formation of SFHA as the ejecta cools down.
- Thus, in all 3 situations, **neutron stars could slowly generate new *specific, described in detail* baryonic DM in the form of the SFHA.**
- There is an **observational evidence** of this: I can explain if you ask the question.

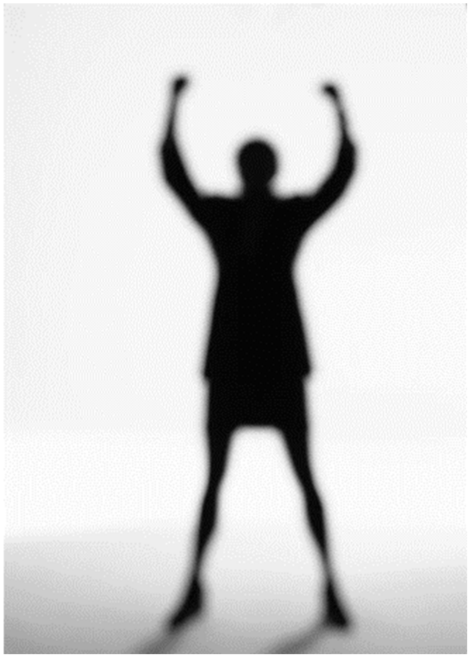
[18] Shibata and Hotokezaka, Annu. Rev. Nucl. Part. Sci. 69 (2019) 1
[19] Radice et al, Annu. Rev. Nucl. Part. Sci. 70 (2020) 95
[20] Fernandez et al, Class. Quantum Grav. 34 (2017) 154001

CONCLUSIONS

- With the allowance for the second solution of Dirac equation for hydrogen atoms (whose existence is evidenced by four different types of atomic/molecular experiments and by astrophysical observations), the **theoretical BR for the two-body decay of neutrons increased by a factor of 3300 to (1.3 ± 0.3)%.**
- **This is in the excellent agreement with “experimental” BR = (1.15 ± 0.27)%** required for reconciling the above τ_{trap} and τ_{beam}.
- Thus, it seems that the above enhanced two-body decay of neutrons **solves the neutron lifetime puzzle *completely*.**
- **I can propose the design of the experiment** that will constitute both **the first experimental detection of the 2-body decay of neutrons** and the **experimental confirmation that the 2-body decay of neutrons produces overwhelmingly the SFHA**.
- Such decay is also the mechanism by which **neutron stars are slowly producing baryonic dark matter** in the form of the SFHA.
- There is an **astrophysical evidence of the existence of this mechanism**.

Thank you for your attention

Благодаря за вниманието



- In a beam-type experiment, such as, e.g., from Nico et al (2005) paper, the trapping region intercepts the entire neutron beam and neutrons decay inside this volume in the 3-body and 2-body ways.
- In the trapping mode, the protons resulting from the 3-body decay are confined there.
- Then (as in the counting mode) door electrodes are grounded and a graduated potential is imposed on the central electrodes to flush out protons, while most of the hydrogen atoms, resulting from the 2-body decay, remain in the trapping region.
- **The central point**: then **they should be subjected to an electron beam** to excite both kinds of hydrogen atoms **into the state of the principal quantum number n = 2**. (The laser excitation would not work for the SFHA.)

Nico et al, Phys. Rev. C 71 (2005) 055502

- **The idea is to measure the cross-section σ_{2s} of the excitation to the state 2s by the so-called quenching technique (and then to compare it with the corresponding theoretical cross-section)**.
- Namely, to apply an electric field **for mixing the state 2s with the state 2p** and then to observe the Ly-alpha signal: the radiative transition from 2p to 1s – as this was done in the experiment described in Callaway and McDowell (1983) paper.
- However, in the mixture of the SFHA with the usual hydrogen atoms, **the quenching technique does not work for the SFHA because the SFHA do not have the 2p state**.
- Therefore, **the experimental cross-section σ_{2s}**, obtained via the Ly-alpha signal, **would be significantly lower than the corresponding theoretical cross-section** calculated by Whelan et al (1987).

Callaway and McDowell, Comments At. Mol. Phys. 13 (1983) 19

Whelan et al, J. Phys. B: At. Mol. Phys. 20 (1987) 1587

- For example, in the experiment described in Callaway and McDowell (1983) paper, the measured σ_{2s} was systematically smaller than the theoretical σ_{2s} by about 20% – well beyond the experimental error margins.
- This constituted one of the four experimental evidences of the existence of the SFHA (Oks, 2022).
- In the 2-body decay of neutrons, if the SFHA outnumber the usual hydrogen atoms by orders of magnitude, then in the proposed experiment **the measured σ_{2s} should be smaller than the theoretical σ_{2s} by orders of magnitude**.
- If this would be found to be the case in such experiment, it would constitute both **the first experimental detection of the 2-body decay of neutrons** and **the experimental confirmation that the 2-body decay of neutrons produces overwhelmingly the SFHA**.

Oks, Foundations 2 (2022) 541

- Alternatively, instead of exciting the hydrogen atoms by an electron beam, Mc Andrew et al (2014) suggested using about 10% of hydrogen atoms that should be in the 2S state as the direct result of the two-body decay.
- However, the number of such hydrogen atoms is about 8 times smaller than those in the 1S state, so that the entire apparatus should be much more sensitive compared to our design.
- Most importantly, this design would **not allow to prove that the two-body decay yielded with the overwhelming probability the SFHA** rather than the usual hydrogen atoms: there would **be no corresponding theoretical benchmark**, while in our proposed design the benchmark is the theoretical cross-section of the excitation of hydrogen atoms by the electron impact from the state 1S to the state 2S.

McAndrew et al, *Phys. Procedia* **51** (2014) 37

- As yet another method for detecting the resulting hydrogen atoms, McAndrew et al suggested charge exchange in argon gas ($H + Ar \rightarrow H^- + Ar^+$), the resulting H^- being then energy-selected by an electric counter-field.
- Again, this design would not allow to prove that the two-body decay yielded with the overwhelming probability the SFHA rather than the usual hydrogen atoms: there would be **no corresponding theoretical benchmark** to compare the H^- signal with.
- Besides, Zhang et al (2022) proposed counting the hydrogen atoms in the state 2S by using a microcalorimeter.
- Again, this design would not allow to prove that the two-body decay yielded with the overwhelming probability the SFHA rather than the usual hydrogen atoms: there would be **no corresponding theoretical benchmark**.

Zhang et al, 2022 https://arxiv.org/abs/2210.02314