Four Types of Atomic Experiments Proving the Existence of the Second Flavor of Hydrogen Atoms

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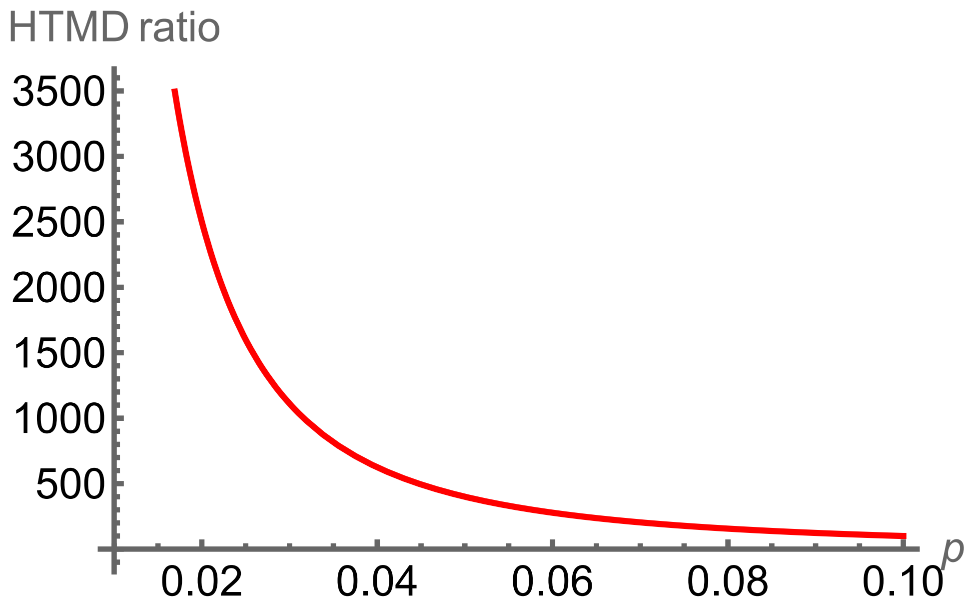
- The Second Flavor of Hydrogen Atoms (SFHA) has been discovered theoretically and proven experimentally to exist for the 1st time – by analyzing atomic experiments related to the distribution of the *linear momentum p* in the ground state of hydrogen atoms (J. Phys. B: At. Mol. Opt. Phys. **34** (2001), 2235).
- It was motivated by the huge discrepancy: the ratio of the experimental and previous theoretical results was up to *tens of thousands*.



- The figure above shows the ratio of the theoretical High-energy Tail of the linear Momentum Distribution (HTMD), calculated by Fock (1935), to the actual 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 $m_e c$, where m_e is the electron mass and c is the speed of light.
- 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: $m_e e^2/\hbar < p << m_e c$.

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

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

- This was the motivation behind my *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.
- The radial part $R_{Nk}(r)$ of the coordinate wave functions has the following behavior at small r :

$$R_{Nk}(r) \propto 1/r^{1+s}, \quad s = \pm(k^2 - \alpha^2)^{1/2}. \qquad (1)$$

- Here N is the radial quantum number, α is the fine structure constant, and k is the eigenvalue of the operator

$$K = \beta(2\mathbf{Ls} + 1) \qquad (2)$$

that commutes with the Hamiltonian (β is the Dirac matrix of the rank 4).

- For the ground state ($k = -1$, $N = 0$) Eq. (1) reduces to

$$R_{0,-1}(r) \propto 1/r^{q}, \qquad q = 1 \pm (1 - \alpha^2)^{1/2}. \qquad (3)$$

- 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 my paper of 2001 in the JPB, I 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.
- In particular, this class of potentials includes those corresponding to the charge 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 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.
- So, in my paper of 2001 in JPB, I 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

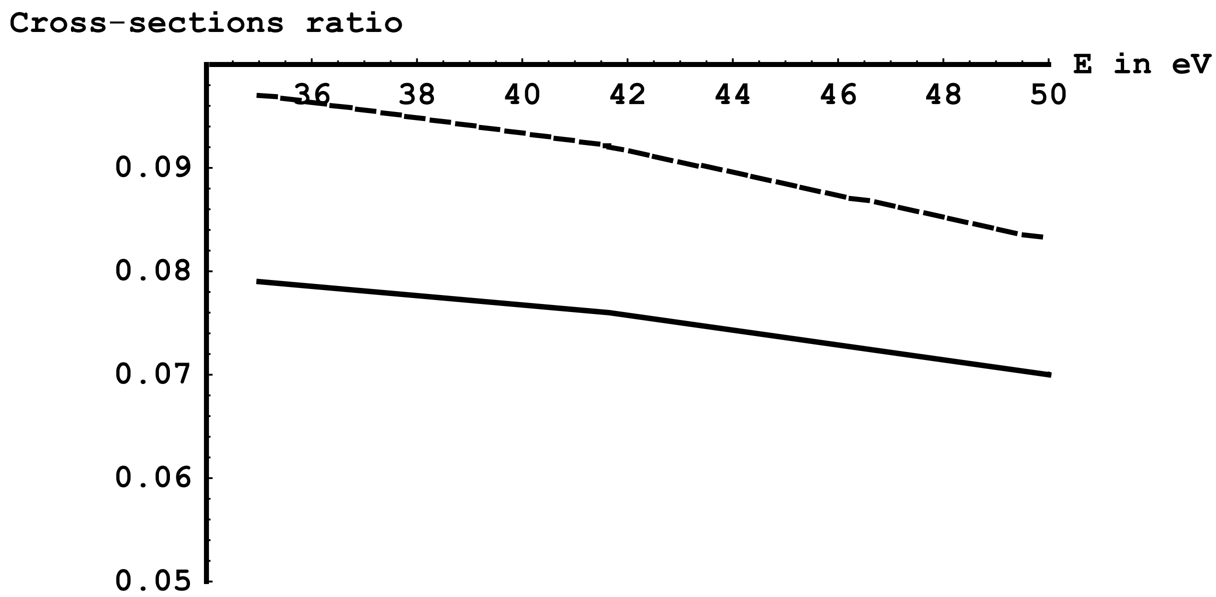
- The corresponding derivation in my paper of 2001in JPB used *only* the fact that in the ground state the eigenvalue of the operator K is

  $k = -1$.

- 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 interior solution and the singular exterior solution are legitimate not only for the ground state $1^2S_{1/2}$, but also for the states $2^2S_{1/2}$, $3^2S_{1/2}$, and so on, i.e., for the states $n^2S_{1/2}$, where $n = N + |k| = N + 1$ is the principal quantum number ($n = 1, 2, 3, \ldots$).
- Both the regular interior solution corresponding to $q = 1 - (1 - \alpha^2)^{1/2}$ and the singular exterior solution corresponding to $q = 1 + (1 - \alpha^2)^{1/2}$ are legitimate also for the $l = 0$ states of the *continuous* spectrum.
- All of these additional results were presented in my paper of 2020 in *Research in Astronomy and Astrophysics* (**2020**, *20(7)*, 109) published by the British IOP Publishing, where I 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 proof of the existence of the SFHA – since no alternative explanation was ever provided.
- Below I briefly present three additional experimental proofs from three *different* kinds of atomic experiments.



<u>Experiments on the electron impact excitation of hydrogen *atoms*</u>

- The figure above presents the comparison of the experimental (Callaway and McDowell (1983)) and theoretical (Whelan et al (1987)) ratio of the cross-section σ_{2s} of the excitation of the state 2s to the cross-section σ_{2p} of the excitation of the state 2p.
- The theoretical ratio (dashed line) is systematically higher than the experimental ratio (solid line) by about 20% - far beyond the experimental error margins of 9%.

Callaway & McDowell, *Comments At. Mol. Phys.* **1983**, *13*, 19

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

- The experimental cross-section σ_{2s} for the excitation to the 2s state was determined by using the quenching technique: by applying **an electric field that mixes the state 2s with the state 2p** and then observing the emission of the Lyman-alpha line from the state 2p to the ground state.
- The central point is the following. In the mixture of the SFHA with the usual hydrogen atoms, both the SFHA and the usual hydrogen atoms can be excited to the 2s state.
- However, after applying the electric field, the mixing of the 2s and 2p states (followed by the emission of the Lyman-alpha line) occurs only for the usual hydrogen atoms.
- This is because the SFHA has only the s-states, so that they do not contribute to the observed Lyman-alpha signal.

- **Therefore, measurements of the cross-section $\boldsymbol{\sigma_{2s}}$ in this way, should underestimate this cross-section** compared to its actual value, while the cross-section σ_{2p} should not be affected by the presence of the SFHA, as I wrote in the paper in the Swiss journal *Foundations* (**2022**, *2*, 541).
- In that paper, I showed that the discrepancy between the experiments and the theory **can be eliminated if in the experimental hydrogen gas, SFHA were present in *the share ~ 40%*.**
- No alternative explanation was ever provided.

- The third proof relates to **<u>experiments on the electron impact excitation of hydrogen *molecules*</u>**
- I studied works on the excitation of the <u>first two stable excited electronic *triplet* states</u> of H_2: the state c $^3\Pi_u$ and the state a $^3\Sigma_g^+$.
- The reason for the choice: the singlet states can get populated both by the direct excitation and by exchange between the incident electron and one of the molecular electrons. The triplet states can get populated only by the exchange, so that the *corresponding theory is simpler for the triplet states*.
- I found that even the most advanced calculations - by the convergent close-coupling (CCC) method with the total number of states equal to 491 (Zammit et al, *Phys. Rev. A* **2017**, *95*, 022708) **underestimate** the experimental cross-sections (by Wrkich et al, *J. Phys. B* **2002**, *35*, 4695 and by Mason-Newell, *J. Phys. B* **1986**, *19*, L587) by **at least a factor of two (!)**.

- In my other paper in *Foundations* (**2022**, *2*, 697) I showed that if in some hydrogen molecules one or both atoms would be the SFHA, then the above very significant discrepancy could be eliminated.
- This is because for such "unusual" H_2 molecules, the corresponding theoretical cross-section is by a factor of three greater than for the usual H_2 molecules.
- I estimated that for eliminating that factor of two discrepancy, the unusual hydrogen molecules should be present in the experimental gas in the share of ~ 30%.
- No alternative explanation was ever provided.

- For the lack of time, I only briefly mention the fourth experimental proof of the existence of the SFHA: from **experiments on the charge exchange between hydrogen atoms and low energy protons**
- The experimental cross-sections (Fite et al, *Proc. Royal Soc.* **1962**, *A268,* 527) are noticeably greater than the theoretical ones by Dalgarno-Yadaf, *Proc. Phys. Soc. (London)* **1953**, *A66*, 173).
- Again, this discrepancy can be eliminated if the SFHA was present in the experimental gas (Oks, *Foundations* **2021**, *1,* 265).
- No alternative explanation was ever provided.

- **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** (with the exception of the 21 cm line) – **they remain DARK**.

- **More details**: due to the selection rules, all matrix elements (both diagonal and non-diagonal) of the operator **d** of the electric dipole moment are zeros.
- For this reason, the SFHA do not couple not only to the dipole radiation, but also to the quadrupole, octupole, and all higher multipole terms – because multipoles contain linear combinations of various powers of the radius-vector operator **r** of the atomic electron, which yield zeros in all orders of the perturbation theory.
- For the same reason, the SFHA cannot exhibit multi-photon transitions.
- This is because multi-photon transitions consist of several one-photon virtual transitions, each step being controlled by a matrix element of **r**, but all these matrix elements are zeros.

- There are also **two kinds of the astrophysical evidence** of the existence of the SFHA.
- **The first one** is related to the puzzling observation of the redshifted 21 cm spectral line from the early Universe where it was found that the absorption in this spectral line was about **two times stronger** than predicted by the standard cosmology (Bowman et al, *Nature* **555** (2018) 67).
- 21 cm line is emitted due to the spin-flip transition between the two hyperfine sublevels of the hydrogen ground state.
- The consequence of this striking discrepancy was that **the gas temperature** of the hydrogen clouds **was in reality significantly smaller** than predicted by the standard cosmology.

- Barkana (*Nature* **2018**, *555*, 71) suggested that some unspecified dark matter collided with the hydrogen gas and made it cooler compared to the standard cosmology.
- He estimated that for fitting the observations by Bowman et al (2018), the mass of these dark matter particles should be of the same order as protons, or neutrons, or hydrogen atoms.
- What if Barkana's unspecified dark matter particles are the SFHA?

- The SFHA do not couple to the electromagnetic radiation **except for the radiative transitions between the two hyperfine sublevels of the ground state corresponding to the same 21 cm wavelength** as for usual hydrogen atoms.
- In my paper in Research in Astronomy and Astrophysics (**2020**, *20*, 109) it was explained that in the course of the Universe expansion, the SFHA (due to having only s-states) decouple from the Cosmic Microwave Background radiation (CMB) earlier than the usual hydrogen atoms.
- Therefore, the SFHA **cool down faster** than the usual hydrogen atoms (that decouple from the CMB much later).
- For this reason, **their spin temperature (that controls the intensity of the absorption signal in the 21 cm line) is lower**.
- In that paper I showed that this explains the observed anomalous absorption in the 21 cm line both **qualitatively and quantitatively**.

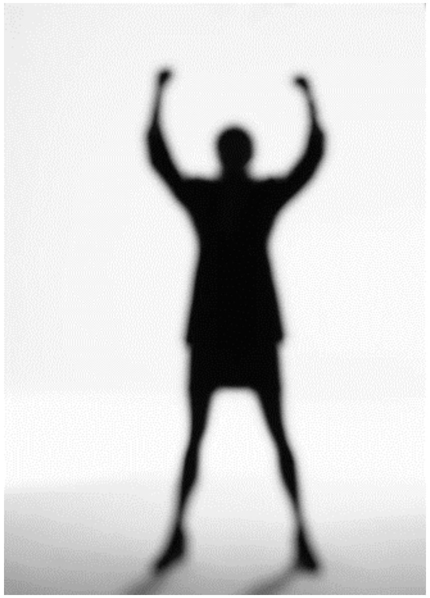
- For the lack of time, I only briefly mention **the second astrophysical evidence** of the existence of the SFHA
- It relates to recent perplexing observations that the distribution of dark matter in the Universe is **smoother, less clumpy** than predicted by Einstein's gravitation (Jeffrey et al, *Monthly Not. Roy. Astron. Soc*. **2021**, *505*, 4626).
- In my other paper in Research in Astronomy and Astrophysics (**2021,** *21*, 241), I showed that this puzzle can be also explained qualitatively and quantitatively by using the SFHA.

Brief Conclusion and Experimental Suggestions

- The theoretical discovery of the SFHA was based on the standard Dirac equation of quantum mechanics without any change of physical laws.
- The existence of the SFHA is proven by 4 different types of atomic/molecular experiments and is also evidenced by 2 different types of astrophysical observations.
- I hope this presentation will motivate further experiments of the above types.
- I encourage experimentalists to perform also another kind of experiments that could yield yet another evidence of the existence of the SFHA.
- Namely: experiments on **the formation of H_2^+ by collision of protons with hydrogen atoms**.
- **Prediction**: if the SFHA is present in the gas (in addition to the usual hydrogen atoms), then the *relative intensity* of the band, corresponding to the radiative transitions between the terms 5fσ and 4dσ of H_2^+, would be enhanced compared to the absence of the SFHA.

Thank you for your attention

Danke für Ihre Aufmerksamkeit



- To be clear: among two dozens theories of dark matter, none of them explains each and every manifestation of dark matter.
- The SFHA is not an exception in this regard: it could be just a part of dark matter.
- In my opinion, **dark matter could be a *multi-faceted phenomenon*** – just as, e.g., electrons, that manifest as particles in some experiments and as waves in other experiments.
- For more details I refer to my recent review in “New Astronomy Reviews” (Elsevier journal) published in **2023**, *96*, 101573).

- We consider an arbitrary spherically-symmetric interaction potential V(r), which takes two different forms in the interior region $r < R$ and in the exterior region $r > R$.
- The singular solution at $r > R$ can be tailored with the regular solution at $r < R$ for the class of potentials satisfying the following condition:

$$\int_0^R V(r')\, r'^{\,2}\, dr' + (1 - E)r^3/3 \approx \left\{ \int_R^\infty [V(r')/ r'^{\,2}]dr' - (1 + E)/r \right\}^{-1},$$

where E is the total energy.

- Those are potentials in the interior region that rise rapidly enough toward the boundary $r = R$.

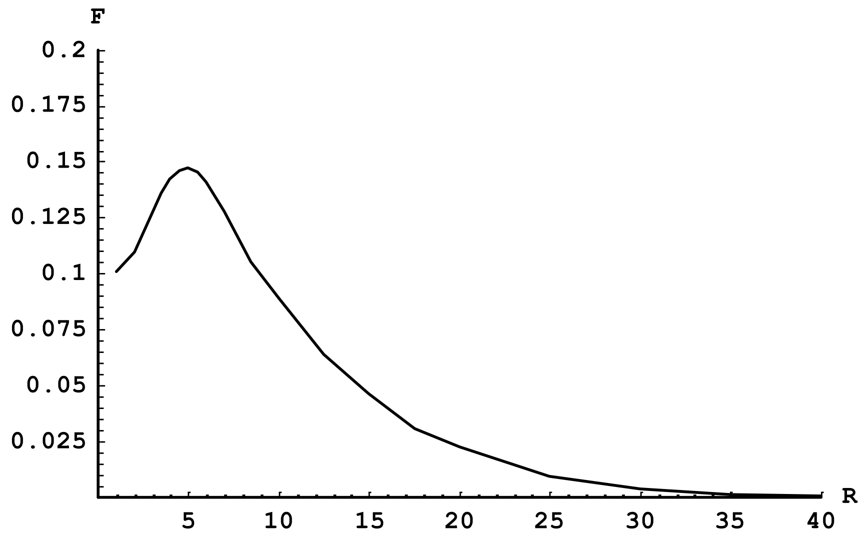
- Here is why for such "unusual" H_2 molecules, the corresponding theoretical cross-section is significantly greater than for the usual H_2 molecules.
- Zammit et al (*Phys. Rev. A* **2017**, *95*, 022708) provided theoretical results not only for the convergent close-coupling method involving 491 states, but also for the CCC involving lesser number of states.
- It showed that the decrease of the number of states involved in their calculations yields significantly greater excitation cross-sections than CCC(491).
- This is the case for the "unusual" (SFHA containing) H_2 molecules: they have significantly lesser number of states (only the s-states) compared to the usual H_2 molecules.

- Here is why the cross-section of the charge exchange with low energy protons is larger for the SFHA than for the usual hydrogen atoms.
- The cross-section for the resonant charge exchange is (roughly) inversely proportional to the square of the ionization potential U_{ioniz} from the particular atomic state.
- For the usual hydrogen atoms, U_{ioniz} increases due to the Stark shift by the field of the incoming proton.
- However, **the energy levels of the SFHA do not shift in the electric field.**

- Here is **why the SFHA does not exhibit any Stark effect in any order of the perturbation theory**.
- In a uniform electric field **F**, the interaction term in the Hamiltonian of an atom is V = –**dF**, where **d** is the operator of the electric dipole moment of the atomic electron.
- The SFHA has only the S-states. Therefore, due to the selection rules, all matrix elements (both diagonal and non-diagonal) of the operator **d** are zeros.
- Thus, the SFHA does not exhibit Stark effect in a uniform electric field *in any order* of the perturbation theory.

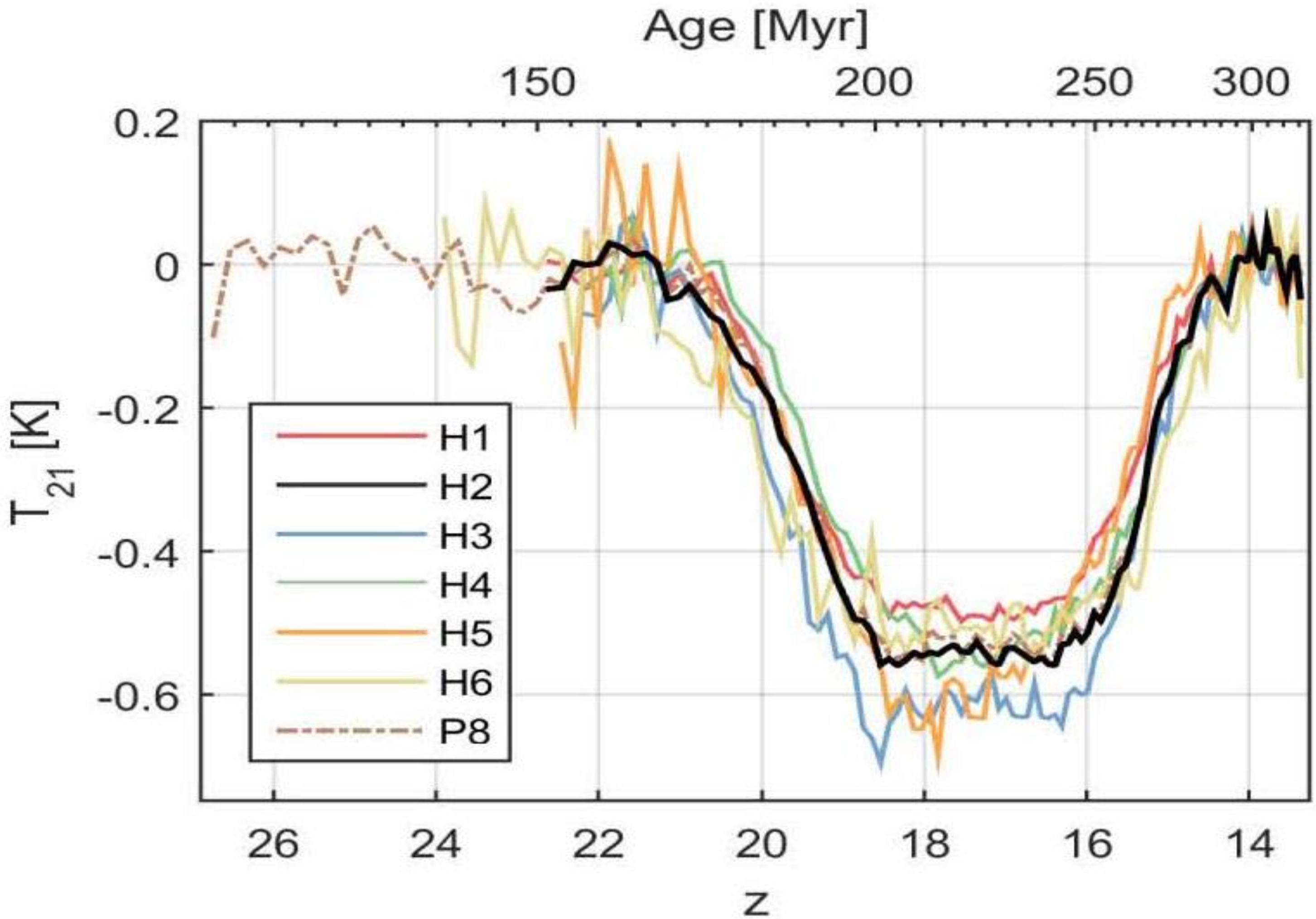
- In the non-uniform electric field of an ion of the charge Z separated from the SFHA by the distance R, the dipole interaction term (~ $1/R^2$) yields zero in all orders of the perturbation theory – for the same reason as in the case of the uniform electric field.
- In the usual hydrogen atom, the next contribution (~$1/R^3$) originates from the quadrupole interaction calculated in the first order and the higher contribution (~$1/R^4$) is due to the following three sources: dipole interaction calculated in the second order, the quadrupole interaction calculated in the second order, and the octupole interaction calculated in the first order – as shown by Sholin (*Optics Spectrosc*. **1970**, *26*, 275).
- However, **for the SFHA, the quadrupole, octupole, and all higher multipole terms**, containing linear combinations of various powers of the radius-vector operator **r** of the atomic electron, **yield zeros in all orders of the perturbation theory** – both diagonal and non-diagonal matrix elements of the operator **r** are zeros.

- The largest and most detailed map of the **distribution of dark matter** in the Universe has been recently created **by the DES team**.
- The distribution was found to be slightly (be few percent) smoother, less clumpy than predicted by the general relativity. This prompted calls for new physical laws.
- **Our model does not involve new physics**. It deals with the dynamics of a system consisting of a large number of gravitating neutral particles, whose mass is equal to the mass of hydrogen atoms.
- The central point of the model is a **partial inhibition of the gravitation for a relatively small subsystem** of the entire system.
- Our estimate of the percentage of the pairs of particles, exhibiting the inhibition of the gravitational interaction and thus the inhibition of the unlimited "clumping", is $\gtrsim 2.5\%$.
- This agrees with the percentage observed by the DES team: the few percent more smooth, less clumpy distribution of dark matter compared to the prediction of the general relativity.
- The **most viable candidate for the dark matter particles in this model is the SFHA** that has only S-states and therefore does not couple to the electric dipole radiation or even to higher multipole radiation, so that the SFHA is practically dark.



Above: The frequency F (in units of 10^5 cm^{-1}) of the radiative transitions between the terms 5fσ and 4dσ of H_2^+ versus the internuclear distance R (in atomic units).

- The figure shows that this spectral band has an edge, in the vicinity of which **the intensity per unit frequency range should be heightened**.
- Moreover, the edge of this spectral band is at the wavelength of 680 nm.
- Thus, it should be easier to observe compared to the spectral bands that are completely beyond the visible range.
- If the SFHA is present in the gas (in addition to the usual hydrogen atoms), then **the *relative intensity* of this band would be enhanced compared to the absence of the SFHA.**
- This is because the SFHA would not contribute to the usually observed bands, corresponding to the radiative transitions between the terms of lower quantum numbers.



The absorption signal in the red-shifted 21 cm spectral line, observed by Bowman et al (2018), versus the cosmological red shift $z = (\lambda_{obsv} - \lambda_{emit})/\lambda_{emit}$.

- To avoid any confusion, I remind the following.
- For the case of the corresponding Schrödinger equation, the ground state is non-degenerate as the consequence of the so-called "oscillation theorem". This theorem proves that the ground state wave function has no nodes, from where it follows that the ground state is non-degenerate.
- However, in the case of the Dirac equation, there need not be a nodeless eigenfunction for the ground state – because the oscillation theorem for the Dirac equation differs from the oscillation theorem for the Schrödinger equation – see, e.g., Rose-Newton paper.
- Physically this difference is due to the fact that for the Schrödinger equation there is a lower bound for the discrete energy spectrum, while there is no lower bound in the case of the Dirac equation – because it allows infinite number of solutions of the energy $E < -mc^2$.

Rose, M.E.; Newton, R.R. Properties of Dirac wave functions in a central field. *Phys. Rev.* **1951**, *82*, 470.

- For representing the quark flavor symmetry, there was assigned an operator of the isotopic spin (isospin) 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.
- By analogy, in the case of the SFHA it seems reasonable to introduce a new operator: the operator of *isohydrogen spin*, abbreviated as *isohyspin* and denoted as $I^{(h)}$. Similarly to the isospin, the z-projection of the isohyspin operator has two eigenvalues: $I^{(h)}_z = 1/2$ assigned to the regular flavor of hydrogen atoms and $I^{(h)}_z = –1/2$ assigned to the singular flavor of hydrogen atoms.
- The isospin (of quarks) couples to the strong force (strong interaction). This is logical because it is related to intra-nuclear physics, where the strong interaction plays the dominant role. As a result, the strong force can transform the up quark into the down quark and vice versa.

- In distinction, the isohyspin does not relate to intra-nuclear physics: so, it would be logical to state that the isohyspin does not couple to the strong force/interaction – since the isohyspin relates to a hydrogen atom as the whole.
- For the same reason, it would be logical to state that the isohyspin does not couple to the weak force/interaction.
- Also there seems no ground to expect that the isohyspin would couple to the gravitational force/interaction.
- As for the electromagnetic force/interaction, the (ordinary) spin couples to the magnetic field, but the isospin of quarks does not couple to the electromagnetic force/interaction.
- Therefore, there seem to be no reason for the isohyspin to couple to the electromagnetic force/interaction either.
- Consequently, there seem to be no reason for transitions between the two flavors of hydrogen atoms.

- Gryzinski's free-fall model was successfully applied to various inelastic processes not only in hydrogen atoms, but in many other atoms and molecules as well (see, e.g., review [1]and references in the later paper [2]).
- Moreover, attempts by Percival's group [3, 4] to use in classical calculations for the bound electrons the quantal-distribution function from equation (1), having the HTMD of $\sim 1/p^6$, resulted in about 60% discrepancy with the experimental ionization cross-section of atomic hydrogen by electrons at relatively *low-incident energies*, while the employment of the free-fall model (where the HTMD was $\sim 1/p^4$) for calculating the same ionization cross-section [5–7] yielded very good agreement with the experiments at the same range of energies.

[1] Gryzinski M 1989 *Classical Dynamics in Atomic and Molecular Physics* ed T Grozdanov, P Grujic and P Krstic (Singapore: World Scientific) p 50
[2] Gryzinski M and Kunc J A 1999 *J. Phys. B: At. Mol. Opt. Phys.* **32** 5789
[3] Abrines R and Percival I C 1966 *Proc. Phys. Soc.* **88** 861
[4] Abrines R, Percival I C and Valentine N A 1966 *Proc. Phys. Soc.* **89** 515
[5] Gryzinski M, Kunc J and Zgorzelski M 1972 *Phys. Lett.* A **38** 35
[6] Gryzinski M, Kunc J and Zgorzelski M 1973 *J. Phys. B: At. Mol. Phys.* **6** 2292
[7] Gryzinski M and Kunc J A 1986 *J. Phys. B: At. Mol. Phys.* **19** 2479