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Communication

Analysis of Experimental Cross-Sections of Charge Exchange between Hydrogen Atoms and Protons Yields More Evidence of the Existence of the Second Flavor of Hydrogen Atoms

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Abstract: Measurements of cross-sections of charge exchange between hydrogen atoms and low energy protons (down to the energy ~10 eV) revealed a noticeable discrepancy with previous theories. The experimental cross-sections were systematically slightly higher—beyond the error margins—than the theoretical predictions. In the present paper, we study whether this discrepancy can be eliminated or at least reduced by using the Second Flavor of Hydrogen Atoms (SFHA) in calculations. We show that for the SFHA, the corresponding cross-section is noticeably larger than for the usual hydrogen atoms. We demonstrate that the allowance for the SFHA does bring the theoretical cross-sections in a noticeably better agreement with the corresponding experiments within the experimental error margins. This seems to constitute yet another evidence from atomic experiments that the SFHA is present within the mixture of hydrogen atoms. In combination with the first corresponding piece of evidence from the analysis of atomic experiments (concerning the distribution of the linear momentum in the ground state of hydrogen atoms), as well as with the astrophysical evidence from two different kinds of observations (the anomalous absorption of the redshifted 21 cm radio line from the early universe and the smoother distribution of dark matter than that predicted by the standard cosmology), the results of the present paper reinforce the status of the SFHA as the candidate for dark matter, or at least for a part of it.

Keywords: charge exchange; second flavor of hydrogen atoms; dark matter; stark effect

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1. Introduction

Measurements of cross-sections of charge exchanges between hydrogen atoms and low energy protons (down to the energy ~10 eV), such as, e.g., experiments by Fite et al. [1], Fite et al. [2], and Belyaev et al. [3], revealed a noticeable discrepancy with previous theories. The experimental cross-sections were systematically slightly higher—beyond the error margins—than the theoretical predictions. The source of this discrepancy was stated as unknown [3]. Up to now, there has been no attention paid to this discrepancy, to the best of our knowledge.

In paper [4], we showed analytically that there is a slight difference in cross-sections of charge exchange between the usual hydrogen atoms and protons in comparison to charge exchange between the Second Flavor of Hydrogen Atoms (SFHA) and protons. The SFHA was discovered theoretically, as well as by the analysis of atomic experiments in paper [5], on which subsequent studies of the SFHA are based.

The basis of the theoretical discovery in paper [5] was a fresh analysis of the Dirac equation for hydrogen atoms. There are two solutions of the Dirac equation at a relatively small distance from the proton: the regular solution and the singular solution, with the latter usually being rejected. In paper [5], it was shown that at the proton boundary, the singular solution outside the proton can be tailored with the regular solution inside the proton for the ground state, so that the singular solution outside the proton is legitimate for the ground state. Using this fact, the author of paper [5] eliminated a huge discrepancy—by many orders of magnitude—between the experimental and theoretical distributions of the linear momentum in the ground state of hydrogen atoms. This constituted the first experimental evidence of the existence of the SFHA.

In a later paper [6], it was shown that the singular solution of the Dirac equation outside the proton is legitimate not only for the ground state, but for all discrete and continuous states of the zero angular momentum: for all S-states. This kind of hydrogen atom, having only S-states and described by the singular solution of the Dirac equation outside the proton, was called the "second flavor" in paper [7]—by an analogy with the flavors of quarks, so that there is an additional conserved physical quantity not commuting with some of the other ones and thus leading to an additional degeneracy.

By now, there are also two kinds of astrophysical evidence of the existence of the SFHA. First, the SFHA eliminated by a factor of two discrepancy between the absorption signal at the redshifted 21 cm radio line, recently observed by Bowman et al. [8] and the predictions of the standard cosmology—this was shown in paper [6]. Second, the SFHA explained the recent observations by Jeffrey et al. [9], where they found that the distribution of dark matter in the universe is noticeably smoother than predictions based on Einstein's relativity—this explanation was provided in paper [10].

The most striking feature of the SFHA is that since they have only S-states, then due to the well-known selection rules, the SFHA does not interact with the electromagnetic radiation (except for the radiative transition at a 21 cm wavelength between the two hyperfine structure substates of the ground state). Thus, the SFHA remains "dark". In combination with the above two kinds of astrophysical evidence, this makes the SFHA a good candidate for dark matter, or at least for a part of it.

The purpose of the present paper is to find out whether, by using the SFHA, one can eliminate, or at least reduce, the aforementioned discrepancy between the experimental and theoretical cross-sections of charge exchange involving hydrogen atoms and low energy protons. For this purpose, we extend the theory from paper [4] (where it was developed for excited states) specifically for the ground state since the corresponding experiments dealt with hydrogen atoms in the ground state. We demonstrate that for the SFHA, the corresponding cross-section is noticeably larger than for the usual hydrogen atoms. We show that the allowance for the SFHA does bring the theoretical cross-sections in a better agreement with the corresponding experiments within the experimental error margins.

2. Calculations and the Comparison with Experiments

According to paper [11], classically, the cross-section σ for the resonant transition of the electron from being associated with one ion to being associated with another ion is

$$\sigma = (8\pi/I^2)(1 - 0.8z^{2/5}),\ z = v/(2I)^{1/2} \quad (1)$$

Here, v is the relative velocity of the colliding nuclei, and I is the ionization potential from the particular atomic state. In the present paper we use atomic units unless noted otherwise. Formula (1) is valid for relatively small velocities:

$$v << v_{max} = (2I)^{1/2} \quad (2)$$

We study the resonant charge exchange between a hydrogen atom in the ground state and an incoming proton, so that from now on, I is the ionization potential of hydrogen atoms from the ground state. For calculating the quantity I, we take into account the Stark shift (if any) of the ground state due to the electric field the proton separated by the distance R from the atom.

It should be emphasized upfront that only the energy levels of the usual hydrogen atoms experience the Stark shift. In contrast, the energy levels of the SFHA have *no Stark shift* in the field of the proton *in any order of the multipole expansion*, as explained in paper [4]. This fact leads to the difference in the corresponding cross-sections of charge exchange for collisions of protons with the usual hydrogen atom compared to the collision of protons with the SFHA, as calculated below.

For a relatively large R, the ground state energy of *usual* hydrogen atoms can be represented in the form (according to Equation (4.59) from book [12]):

$$E_{large} = -1/2 - 9/(4R^4) - 15/(2R^6) \quad (3)$$

where we omitted higher order terms in this expansion; the subscript "large" signifies that this expansion is valid for relatively large R. So, the ionization potential for the ground state has the form:

$$I_{large} = 1/2 + 9/(4R^4) + 15/(2R^6) \quad (4)$$

In paper [11], it was noted that for the no-barrier transition of the electron from one nucleus to another nucleus, at the midpoint between the two nuclei, the interaction potential for the electron in the field of two nuclei should surpass the corresponding ionization potential. This condition translates in the following relation between the charge-exchange-effective distance R_0 of the proton from the atom and the ionization potential [11]:

$$I = 4/R_0 \quad (5)$$

Upon substituting Equation (5) in Equation (1), we obtain:

$$\sigma = (\pi R_0{}^2/2)\,[1 - 0.8v^{2/5}(R_0/8)^{1/5}] \quad (6)$$

Further, upon substituting Equation (5) into the left side of Equation (4) (and omitting the subscript "0"), we obtain:

$$4/R = 1/2 + 9/(4R^4) + 15/(2R^6) \quad (7)$$

The relevant root of this equation is

$$R_{large} = 7.991 \quad (8)$$

(We reiterate that the subscript "large" here and below simply refers to the fact that the results were obtained from the energy expansion for relatively large R).

In contrast, for the SFHA for a relatively large R, the energy of the ground state is

$$E_{large,2} = -1/2 \quad (9)$$

because the SFHA does not experience any Stark shift. (Here, the number 2 in the subscript signifies the "second flavor"). Therefore,

$$I_{large} = 1/2 \quad (10)$$

so that (according to Equation (5))

$$R_{large,2} = 8 \quad (11)$$

Now, let us consider the corresponding situation for relatively small R. In this case, the ground state energy of *usual* hydrogen atoms can be represented in the form (according to Equation (5.13) from book [12]):

$$E_{small} = -2 + 8R^2/3 - 16R^3/3 \quad (12)$$

where we omitted higher order terms in this expansion; the subscript "small" signifies that this expansion is valid for relatively small R. So, the ionization potential for the ground state has the form:

$$I_{small} = 2 - 8R^2/3 + 16R^3/3 \quad (13)$$

Further, on substituting Equation (5) in the left side of Equation (13) (and omitting the subscript "0"), we achieve:

$$4/R = 2 - 8R^2/3 + 16R^3/3 \quad (14)$$

The relevant root of this equation is

$$R_{small} = 0.953 \tag{15}$$

(we reiterate that the subscript "small" here and below simply refers to the fact that the results were obtained from the energy expansion for a relatively small R).

In contrast, for the SFHA for relatively small R, the energy of the ground state is

$$E_{small,2} = -2 \tag{16}$$

because the energy levels of the SFHA do not shift in the electric field (here, the number 2 in the subscript signifies the "second flavor"). Therefore,

$$I_{small,2} = 2 \tag{17}$$

so that (according to Equation (5))

$$R_{small,2} = 2 \tag{18}$$

We note that the ionization potentials, corresponding to the values of R from Equations (8), (11), (15) and (18), can be easily found from Equation (5).

For calculating the cross-sections of the charge exchange by using Equation (6), it is necessary to add the corresponding contributions from both channels, i.e., from both the "large R" case and the "small R" case. For obtaining the ratio of the resonant charge exchange cross-section from the ground state of the SFHA σ_{SFHA} to the corresponding result σ_{usual} for the usual hydrogen atoms in the simplest form—just to get the message across—we will consider the limit of v approaching zero. In this limit, the ratio $\sigma_{SFHA}/\sigma_{usual}$ simplifies to:

$$\sigma_{SFHA}/\sigma_{usual} = (R_{large,2}{}^2 + R_{small,2}{}^2)/(R_{large,}{}^2 + R_{small}{}^2) \tag{19}$$

On substituting into Equation (19) the data from Equations (8), (11), (15) and (18), we finally obtain:

$$\sigma_{SFHA}/\sigma_{usual} = 1.05 \tag{20}$$

so that σ_{SFHA} is by 5% greater than σ_{usual}.

Let us find out whether this result sufficiently improves the comparison with the corresponding experiments. The most precise experiment on the resonant charge exchange between hydrogen atoms in the ground state and relatively low energy protons was performed by Fite et al. [2] (the error margin was 9% or less, while for the later experiment by Belyaev et al. [3], the error margin reached 13%). Figure 1 presents:

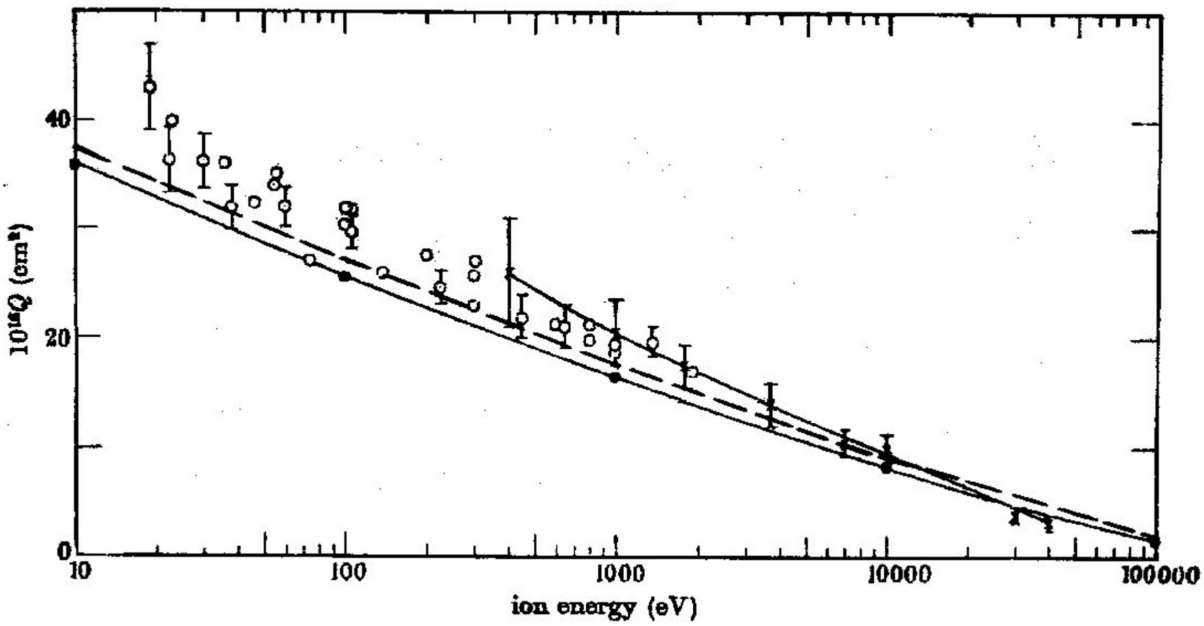

Figure 1. Comparison of the experimental cross-sections of the resonant charge exchange between hydrogen atoms and low energy protons with the corresponding theoretical cross-sections (the cross-sections are in units of 10–16 cm2). Circles (some with error margins)—experiment reported in paper [2]; crosses (with error margins) connected by a solid line—experiment reported in paper [1]; filled circles connected by a solid line—theory from paper [13], allowing only for the usual hydrogen atoms; the dashed line—theory from the present paper, allowing for the SFHA (adapted from [1,2,13]).

(1) the experimental cross-sections—circles, some with error margins—reproduced from Figure 2 of paper [2];
(2) the experimental cross-sections—crosses (with error margins) connected by a solid line—from the earlier measurements by Fite et al. [1], reproduced from Figure 2 of paper [2];
(3) the theoretical cross-sections—filled circles connected by a solid line—calculated by Dalgarno and Yadav [13], reproduced from Figure 2 of paper [2];
(4) the theoretical cross-sections for the case of the SFHA—the dashed line—from the present calculations.

It can be seen that the theoretical cross-sections for the case of the SFHA demonstrate a noticeably better agreement with the corresponding experimental cross-sections.

3. Conclusions

We studied whether the allowance for the SFHA can eliminate, or at least reduce, the noticeable discrepancy between the experimental and theoretical cross-sections of charge exchange involving hydrogen atoms and low energy protons: the discrepancy where the experimental cross-sections are systematically slightly higher than the corresponding theoretical cross-sections. We showed that, for the SFHA, the theoretical cross-sections are noticeably greater than for the usual hydrogen atoms. We demonstrated that the allowance for the SFHA leads to a noticeably better agreement with the experiments: the agreement with experiments within the experimental error margins.

This seems to constitute yet more evidence from atomic experiments that the SFHA is present within the mixture of hydrogen atoms. In combination with the first corresponding piece of evidence from the analysis of atomic experiments (presented in paper [6]), as well as with the astrophysical evidence from two different kinds of observations [9,11], the results of the present paper reinforce the status of the SFHA as the candidate for dark matter, or at least for a part of it.

Compared to other explanations of dark matter effects, the SFHA is favored by the Occam's razor principle. Indeed, it is based on the standard quantum mechanics (the Dirac equation), whereas other hypotheses either resort to mysterious, never-discovered particles beyond the standard model or require significant changes in the existing physical laws.

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