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The Third Proof from Atomic Experiments of the Existence of the Second Flavor of Hydrogen Atoms – by Experiments on the Electron Impact Excitation of the 2s and 2p States of Hydrogen Atoms

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ABSTRACT: The theoretical discovery of the Second Flavor of Hydrogen Atoms (SFHA) followed by the 1st experimental proof of their existence: by analyzing the experimental distribution of the linear momentum distribution in the ground state of hydrogen atoms. The 2nd experimental proof of the existence of the SFHA was obtained by analyzing the experiments on charge exchange during collisions of low-energy protons with hydrogen atoms. In the present paper we provide the 3rd experimental proof of the existence of the SFHA, as follows. For the excitation of the n=2 states of hydrogen atoms by the electron impact, we compare the experimental and theoretical ratio of the cross-sections σ2s/σ2p. We find this theoretical ratio to be systematically higher than the corresponding experimental ratio by about 20% – far beyond the experimental error margins. We suggest that this discrepancy can be explained by the presence of the Second Flavor of Hydrogen Atoms (SFHA) in the experimental hydrogen gas. The explanation is based on the fact that in the experiments, the cross-section σ2s was determined by using the quenching technique – by applying an electric field that mixed the states 2s and 2p followed by the emission of the Lyman-alpha line from the state 2p. However, the SFHA has only the s-states, so that the quenching technique would not count the excitation of the SFHA in the state 2s and thus lead to the underestimation of the cross-section σ2s. We estimate the share of the SFHA in the experimental hydrogen gas, required for eliminating the above discrepancy, and find this share to be about the same as the share of the usual hydrogen atoms. Thus, our results constitute the 3rd proof from atomic experiments that the SFHA does exist.

Keywords: electron impact excitation of hydrogen atoms; discrepancy between theories and experiments; second flavor of hydrogen atoms

1. INTRODUCTION

For 36 years there existed an unresolved mystery concerning the high-energy tail of the linear momentum distribution in the ground state of hydrogen atoms: the distribution derived from the analysis of atomic experiments) was by several orders of magnitude greater than theoretically predicted. This huge discrepancy motivated the theoretical discovery of the Second Flavor of Hydrogen Atoms (SFHA) in paper [1]. The allowance for the SFHA eliminated this huge discrepancy [1].

The second experimental evidence of the existence of the SFHA was obtained by analyzing the experiments on charge exchange during collisions of low-energy protons with hydrogen atoms [2]. Namely, the allowance for the SFHA brought the corresponding theoretical cross-sections in agreement with the experiments within the experimental error margins.

The proven existence of the SFHA has the importance in its own right for atomic physics. Yet it turned out to have also significant astrophysical consequences, including the most fundamental problem of the cosmology: to find out what is dark matter, as explained below.

Bowman et al [3] reported a perplexing observation of the redshifted 21 cm spectral line from the early Universe. The absorption signal turned out to be about two times more intense than expected from the standard cosmology, thus indicating an additional cooling of the primordial hydrogen gas. Barkana [4] suggested that the additional cooling was due to collisions with some unspecified dark matter particles. In paper [5] it was demonstrated if the additional cooling was caused by collisions with the SFHA, the above huge discrepancy would be removed. This outcome put forward the SFHA as a candidate for dark matter.

Jeffrey et al [6] reported that the observed distribution of dark matter in the Universe was found to be smoother than the predictions based on Einstein's gravitation. This puzzle induced suggestions that new physical laws are needed: a non-Einsteinian gravity. However, in paper [7] it was shown that the allowance for the SFHA explains the puzzling observational result by Jeffrey et al [6] not only qualitatively, but also quantitatively.

It should be emphasized that the theory behind the SFHA is the standard quantum-mechanical Dirac equation. So, the qualitative and quantitative explanations of the perplexing observations by Bowman et al [3] and by Jeffrey et al [6] obtained by using the SFHA did not introduce any new physical laws (in distinction to the overwhelming majority of other hypotheses on the nature of dark matter) and therefore is favored by the Occam razor principle. All of this solidified the status of the SFHA as a leading candidate for dark matter (or at least for a part of it).

In the present paper we provide yet another experimental proof of the existence of the SFHA – from the third type of atomic experiments: the experiments on the electron impact excitation of hydrogen atoms to the states of the principal quantum number n=2. There are lots of various theoretical approaches on this process – see, e.g., papers [8-17] (listed in the alphabetical order) and references therein. In our analysis we limit ourselves by the corresponding experimental and theoretical works where there were determined – *within the same experiment or within the same theoretical approach* – both the cross-section σ_{2s} of the excitation of the state 2s and the cross-section σ_{2p} of the excitation of the state 2p. Then we compare the experimental and theoretical ratio of the cross-sections σ_{2s}/σ_{2p}. We show that this theoretical ratio is systematically higher than the experimental ratio by about 20% (far beyond the experimental error margins). We explain that the presence of the SFHA in the experimental hydrogen gas can be responsible for this discrepancy and estimate the share of the SFHA in the mixture sufficient for eliminating this discrepancy.

2. COMPARISON OF THE EXPERIMENTAL RATIO OF THE CROSS-SECTIONS WITH THEORIES

Let us first outline the idea. We consider a gas of hydrogen atoms representing a mixture of the SFHA and the usual hydrogen atoms. Further, we consider the excitation of these hydrogen atoms from the ground state to the 2s and 2p states by the electron impact. The experimental measurements of the cross-section σ_{2p} for the excitation to the 2p state is determined by observing the emission of the Lyman-alpha line from the state 2p to the ground state. As for the experimental measurements of the cross-section σ_{2s} for the excitation to the 2s state, it is 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 – see, e.g., papers [18-20] (listed in the alphabetical order).

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 (see papers [1, 5]), so that they do not contribute to the observed Lyman-alpha signal. Therefore, measurements of the cross-section σ_{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. Consequently, by comparing the experimental ratio σ_{2s}/σ_{2p} with the corresponding theoretical ratio, it should be possible to find out whether the SFHA was present in the hydrogen gas used in the experiments and to estimate the percentage of the SFHA in that hydrogen gas.

The 2s and 2p states are chosen for the following reasons. From the experimental viewpoint, for n > 2, the quenching electric field would mix not only s- and p-states, but also the states of the higher angular momentum. From the theoretical viewpoint, calculations for n = 2 states are simpler than for the states of n > 2. Therefore, 2s and 2p states represent the simplest (and thus most reliable) test bed both from the experimental and theoretical viewpoints.

Various types of calculations of the absolute cross-section σ_{2s} yield significantly different results – up to the factor of two [8]. Various types of calculations of the absolute cross-section σ_{2p} also yield significantly different results. Therefore, for the stated purpose of our study we limit ourselves by those theoretical papers where both σ_{2s} and σ_{2p} were calculated within the same approach, and we focus at the corresponding ratio σ_{2s}/σ_{2p} within each theoretical approach. In this way, the scatter of the ratio σ_{2s}/σ_{2p}, calculated within different theoretical approaches, should be noticeably smaller than the scatter of the absolute cross-sections.

Being guided by this principle, we determined the theoretical ratio σ_{2s}/σ_{2p} from the values of σ_{2s} and σ_{2p}, calculated at three different energies of the incoming electrons by Whelan et al [16] by using the close coupling with the pseudostate basis within the 13-state approximation. We also determined the theoretical ratio σ_{2s}/σ_{2p} from the values of σ_{2s} and σ_{2p}, calculated at four different energies of the incoming electrons by Whelan et al [16] by using the 2nd Born approximation. Then we determined the corresponding experimental ratio σ_{2s}/σ_{2p} from the values of σ_{2s} and σ_{2p} presented by Callaway and McDowell [18], which is the latest (to the best of our knowledge) and the most accurate experiment where both σ_{2s} and σ_{2p} were measured. (These values of σ_{2s} and σ_{2p} were cited also by Whelan et al [16]). The results are presented in Table 1.

Table 1. Comparison of the experimental ratio of the cross-sections σ_{2s}/σ_{2p} presented by Callaway and McDowell [18] with the corresponding theoretical ratios from paper by Whelan et al [16].

Energy (eV)	σ_{2s}/σ_{2p} by close coupling with pseudostates in 13-state approximation	σ_{2s}/σ_{2p} by 2nd Born approximation	Average of these two theories	Experimental ratio σ_{2s}/σ_{2p}	Ratio of the average theoretical value to the experimental one
35	N/A	0.097	0.097	0.079	1.23
41.65	0.0933	0.0912	0.092	0.076	1.21
50	0.0802	0.0851	0.083	0.070	1.19
54.4	0.0774	0.0828	0.080	0.067	1.19

It is seen that the average theoretical ratio σ_{2s}/σ_{2p} consistently exceeds the corresponding experimental ratio by about 20% over the entire experimental range of energies. This difference is far beyond the experimental error margin that was 9% or less. At the first glance, this might seem to indicate that there was about 20% of the SFHA in the hydrogen gas used in the experiments. However, the actual percentage of the SFHA was much higher, as explained below.

The SFHA differs from the usual hydrogen atoms not only by the fact that the quenching of the 2s state of the SFHA does not work because of the absence of the 2p state (as already noted above). The SFHA differs from the usual hydrogen atoms also by the value of the cross-section of the excitation to the 2s state.

Indeed, for the usual hydrogen atoms the contribution to the excitation cross-section $\sigma_{2s,usual}$ originates not only from the direct transition 1s – 2s, but also from numerous cascade transitions via the intermediate states of the higher angular momentum. In distinction, for the SFHA the contribution to the excitation cross-section $\sigma_{2s,SFHA}$ originates only from the direct transition 1s – 2s because there are no states of the higher angular momentum, so that $\sigma_{2s,SFHA}$ should be significantly smaller than $\sigma_{2s,usual}$.

If α is the share of the SFHA in the hydrogen gas mixture, then the effective theoretical cross-section is

$$\sigma_{2s,eff} = \alpha\, \sigma_{2s,SFHA} + (1 - \alpha)\, \sigma_{2s,usual}. \tag{1}$$

The experimental cross-section observed by using the quenching technique is

$$\sigma_{2s,\,exp} = (1 - \alpha)\, \sigma_{2s,usual}. \tag{2}$$

Consequently, the ratio of the effective theoretical cross-section to the experimental cross section is

$$\sigma_{2s,eff}/\sigma_{2s,exp} = 1 + [\alpha/(1 - \alpha)]\, \sigma_{2s,SFHA}/\sigma_{2s,usual}. \tag{3}$$

From Eq. (3), the ratio of the share of the SFHA to the share of the usual hydrogen gas in the experimental mixture can be represented in the form

$$\alpha/(1-\alpha) = [\sigma_{2s,eff}/\sigma_{2s,exp} - 1]\ \ [\sigma_{2s,usual}/\sigma_{2s,SFHA}]. \tag{4}$$

From the analysis in the preceding part of this paper, we found the first factor in the right side of Eq. (4) to be

$$\sigma_{2s,eff}/\sigma_{2s,exp} - 1 \approx 0.2. \tag{5}$$

Now let us estimate the second factor in the right side of Eq. (4).

In paper by Poet [14], the author provided analytical results for the excitation cross-section σ_{2s} for the model where the wave functions of the hydrogen states are spherically-symmetric. In other words, the target was a hydrogen atom having only the s-states. This means that the results obtained by Poet [14] are applicable to the SFHA.

In paper by Bhatia [9], the author compared his calculations of the excitation cross-section $\sigma_{2s,usual}$, obtained by the variational polarized orbital method with the corresponding result by Poet [14], that is, actually with $\sigma_{2s,SFHA}$. It can be seen that for the values of the energy (of the incoming electrons) closest to the experimental range of the energies from work [18], the ratio $\sigma_{2s,usual}/\sigma_{2s,SFHA}$ is about 4. Consequently, from Eq. (4) the ratio of the share of the SFHA to the share of the usual hydrogen gas in the experimental mixture can be estimated as

$$\alpha/(1-\alpha) \approx 0.8. \tag{6}$$

In other words, in the hydrogen gas used in the experiment analyzed by Callaway and McDowell [18], the SFHA and the usual hydrogen atoms were represented by about equal shares. Thus, our results constitute the 3rd proof from atomic experiments (this time – from the experiments on the excitation of the n=2 states of atomic hydrogen by the electron impact) that the SFHA does exist.

3. CONCLUSIONS

For the excitation of the n=2 states of hydrogen atoms by the electron impact, we compared the experimental and theoretical ratio of the cross-sections σ_{2s}/σ_{2p}. We found this theoretical ratio is systematically higher than the experimental ratio by about 20% (far beyond the experimental error margins) over the entire range of the energies of the incoming electrons used in the experiment analyzed by Callaway and McDowell [18].

We suggested that this discrepancy can be explained by the presence of the SFHA in the experimental hydrogen gas. The explanation is based on the fact that in the experiments, the cross-section σ_{2s} was determined by using the quenching technique – by applying an electric field that mixed the states 2s and 2p followed by the emission of the Lyman-alpha line from the state 2p. However, the SFHA has only the s-states, so that the quenching technique would not count the excitation of the SFHA in the state 2s and thus lead to the underestimation of the experimental cross-section σ_{2s}.

We estimated the share of the SFHA in the experimental hydrogen gas, required for eliminating the above discrepancy, and found this share to be about the same as the share of the usual hydrogen atoms. Thus, our results constitute the 3rd proof from atomic experiments that the SFHA does exist: this time – from the experiments on the excitation of the n=2 states of atomic hydrogen by the electron impact. This is also important because the SFHA is the leading candidate for dark matter (or at least for a part of it).

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