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Communication

Experiments on the Electron Impact Excitation of the 2s and 2p States of Hydrogen Atoms Confirm the Presence of Their Second Flavor as the Candidate for Dark Matter

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Abstract: For the excitation of the $n = 2$ states of hydrogen atoms due to electron impact, we compared the experimental and theoretical ratios of the cross-sections σ_{2s}/σ_{2p}. We found 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 σ_{2s} was determined by using the quenching technique—by applying an electric field that mixed the 2s and 2p states, followed by the emission of the Lyman-alpha line from the 2p state. However, the SFHA only had the s-states, so the quenching technique would not count the excitation of the SFHA in the 2s state and, thus, lead to the underestimation of the cross-section σ_{2s}. We estimates 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 third proof from atomic experiments that the SFHA does exist, the first proof being related to the experimental distribution of the linear momentum in the ground state of hydrogen atoms, and the second proof being related to the experimental cross-section of charge exchange between hydrogen atoms and low-energy protons.

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

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1. Introduction

The theoretical discovery of the Second Flavor of Hydrogen Atoms (SFHA) in [1] was followed by the first experimental proof of their existence. Namely, the high-energy tail of the linear momentum distribution in the ground state of hydrogen atoms (the distribution being derived from the analysis of atomic experiments) was greater than the theoretical prediction for the usual hydrogen atoms by several orders of magnitude. The allowance for the SFHA eliminated this huge discrepancy [1].

The second piece of experimental evidence of the existence of the SFHA was obtained by analyzing 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 into agreement with the experiments within the experimental error margins.

The proven existence of the SFHA has importance for atomic physics in its own right. However, it has also turned out to have significant astrophysical consequences, including for the most fundamental problem of cosmology: finding out what dark matter is, 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 [5], it was demonstrated that, if the additional cooling was caused by collisions with the SFHA, this huge discrepancy would be removed. This outcome suggested 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 [7], it was shown that the allowance for the SFHA explains the puzzling observational results from 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, are favored by the principle of Occam's razor. 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 experiment: experiments on the electron impact excitation of hydrogen atoms to the states of the principal quantum number, $n = 2$. There are many different theoretical approaches to this process—see, e.g., [8–17] (listed in alphabetical order) and the references therein. In our analysis, we limit ourselves to the corresponding experimental and theoretical work where both the cross-section σ_{2s} of the excitation of the 2s state and the cross-section σ_{2p} of the excitation of the 2p state were determined *within the same experiment or within the same theoretical approach*. Then, we compare the experimental and theoretical ratios 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 could be responsible for this discrepancy and estimate the share of the SFHA in the mixture that would be sufficient to eliminate this discrepancy.

2. Comparison of the Experimental Ratios 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 due to electron impact. The experimental measurements of the cross-section σ_{2p} for the excitation to the 2p state are determined by observing the emission of the Lyman-alpha line from the 2p state to the ground state. As for the experimental measurements of the cross-section σ_{2s} for the excitation to the 2s state, they are determined by using the quenching technique: by applying an electric field that mixes the 2s state with the 2p state and then observing the emission of the Lyman-alpha line from the 2p state to the ground state—see, e.g., [18–20] (listed in 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 s-states, so they do not contribute to the observed Lyman-alpha signal. Therefore, measurements of the cross-section σ_{2s} that are conducted 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 states with a higher angular momentum. From the theoretical viewpoint, calculations for $n = 2$ states are simpler than for $n > 2$ states. Therefore, the 2s and 2p states represent the simplest (and, thus, most reliable) test bed from both the experimental and theoretical viewpoints.

Various types of calculations of the absolute cross-section σ_{2s} yield significantly different results—up to a 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 to theoretical papers where both σ_{2s} and σ_{2p} were calculated within the same approach, and we focus on the corresponding σ_{2s}/σ_{2p} ratio within each theoretical approach. In this way, the scatter of the σ_{2s}/σ_{2p} ratios calculated with different theoretical approaches should be noticeably smaller than the scatter of the absolute cross-sections.

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

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

Energy (eV)	σ_{2s}/σ_{2p} from Close Coupling with Pseudostates in 13-State Approximation	σ_{2s}/σ_{2p} from 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 can be seen that the average theoretical σ_{2s}/σ_{2p} ratio consistently exceeded the corresponding experimental ratio by about 20% over the entire experimental range of energies. This difference was far beyond the experimental error margin, which was 9% or less. At first glance, this might seem to indicate that about 20% of the hydrogen gas used in the experiments was of the SFHA. 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), but also in terms of 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 of 1s–2s, but also from numerous cascade transitions via the intermediate states with a higher angular momentum. In distinction, for the SFHA, the contribution to the excitation cross-section $\sigma_{2s,SFHA}$ originates only from the direct 1–2s transition because there are no states with a higher angular momentum, so $\sigma_{2s,SFHA}$ should be significantly smaller than $\sigma_{2s,usual}$.

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

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

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

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

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

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

From Equation (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

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

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

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

Now, let us estimate the second factor on the right side of Equation (3).

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

In a paper by Bhatia [9], the author compared his calculations of the excitation cross-section $\sigma_{2s,usual}$, which was obtained with the variational polarized orbital method, with the corresponding results from Poet [14], that is, 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 [18], the $\sigma_{2s,usual}/\sigma_{2s,SFHA}$ ratio was about 4. Consequently, from Equation (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

$$\alpha/(1 - \alpha) \approx 0.8. \quad (6)$$

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

We note that the $\sigma_{2s,usual}/\sigma_{2s,SFHA}$ ratio grows as the incident electron energy increases, as can be seen in Table 1 of Bhatia's paper [9]. Therefore, one can expect that, as the incident electron energy increases, the experimental σ_{2s}/σ_{2p} ratio should become closer to unity when keeping the product on the right side of Equation (4) approximately constant, since it is reasonable to expect that the ratio of the share of the SFHA to the share of the usual hydrogen gas in the experimental mixture is independent of the incoming electron energy. As the experimental σ_{2s}/σ_{2p} ratio would become closer to unity, it would fall within the experimental error margins. Thus, to determine the presence and the share of the SFHA in an experimental gas mixture, one should not use an electron beam with too high of an energy.

The range of energies below the ionization threshold is also not favorable for determining the presence and the share of the SFHA in experimental gas mixtures. This is because, in this range, the excitation cross-sections σ_{2s} and σ_{2p} are strongly dominated by so-called "resonances", which are temporary negative hydrogen ions consisting of a proton and two highly correlated electrons—see, e.g., the paper by Williams [21] and the references therein. However, there is no "second flavor" of a negative hydrogen ion. This is because there is no singular solution (outside the proton) for two highly correlated electrons, in distinction to the singular solution (outside the proton) of the Dirac equation for hydrogen atoms, the solution representing the SFHA. Therefore, in this range of energies, the SFHA practically does not contribute to both σ_{2s} and σ_{2p}.

Thus, the range of incoming electron energies that is most favorable for determining the presence and share of the SFHA in an experimental gas mixture seems to be the range presented in Table 1.

3. Conclusions

For the excitation of the $n = 2$ states of hydrogen atoms due to electron impact, we compared the experimental and theoretical ratios of the cross-sections σ_{2s}/σ_{2p}. We found that 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 by Callaway and McDowell [18].

We suggested that this discrepancy can be explained by the presence of the SFHA in the experimental hydrogen gas. This 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 2s and 2p states, followed by the emission of the Lyman-alpha line from the 2p state. However, the SFHA only has s-states, so the quenching technique would not count the excitation of the SFHA in the 2s state and, thus, lead to the underestimation of the experimental cross-section σ_{2s}.

We estimated the share of the SFHA in an experimental hydrogen gas required to eliminate 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 third proof from atomic experiments that the SFHA does exist—this time, from experiments on the excitation of the $n = 2$ states of atomic hydrogen due to 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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