The 21 cm absorption line profile as a tool for the search for antimatter in the universe

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A theoretical comparison of the hydrogen (H) and antihydrogen (H̄) atoms in an external magnetic field is made. The 21 cm absorption line is the subject of discussion. It is shown that the difference of radiation polarization in this line in an external magnetic field can be used for the search for antihydrogen atoms in the universe.

Subject Index E10, E23, E28

The absence of antimatter in the universe is one of the most daunting problems of modern physics. In particular, the charge conjugation parity time reversal (CPT) invariance requires the presence of antimatter in the universe. The recent experimental success in the production of antihydrogen atoms [1] makes comparative spectroscopic studies of hydrogen (H) and antihydrogen (H̄) atoms realistic in the near future. The comparison of the spectroscopic properties of H and H̄ atoms may lead to the most accurate limits for possible CPT-violating effects [2].

Up to now, no antimatter atoms have been detected in the universe. It is supposed that in the initial moments of the universe’s evolution the number of baryon particles was larger than that of antibaryons. These numbers were different at the level of $10^{-9}$ for a particle–antiparticle pair. As a result, after annihilation only the baryon particles were present in the universe [3,4]. The idea that the baryon–antibaryon symmetry broken spontaneously in the very early moments after the big bang could lead more naturally to a baryon-symmetric cosmology with a domain structure than to a totally baryon-asymmetric cosmology was suggested in Ref. [5].

The other explanation for the matter prevalence was given by a hypothesis that antimatter is located in remote areas (poorly known) of the universe. A method of testing this hypothesis experimentally has been discussed in, e.g., Refs. [6,7]. One of the methods of antimatter observation is based on the registration of antinuclei, and the antihelium nucleus in particular [8]. Beginning in 1979, the BESS (Balloon-borne Experiment with Superconducting Spectrometer) and PAMELA (payload for antimatter matter exploration and light-nuclei astrophysics) experiments were started with the use of spectrometers on the balloons [9,10]. The BESS-Polar II experiments, with a sensitivity of the
order of $10^{-8}$ [11], have opened new possibilities in the search for antimatter and dark matter in the universe.

In accordance with the CPT invariance, matter and antimatter interact with electromagnetic radiation equally. Thus, stars, planets, galaxies, etc. constructed from matter and antimatter should look completely similar with respect to electromagnetic emission. Nonetheless, recently, a theoretical analysis of the behavior of hydrogen and antihydrogen atoms in external electric and magnetic fields was given in Ref. [12]. In particular, it was pointed out that the polarization properties of the Zeeman sublevels of different levels in an external magnetic field will be different in H and \( \bar{\text{H}} \) atoms. As an example, the Lyman-\( \alpha \) transition in a hydrogen atom with the corresponding Zeeman splitting was considered. In this paper, we consider, for the same purpose, the 21 cm absorption line of the hyperfine split ground state in the hydrogen atom. The Zeeman effect, in conjunction with the Faraday effect, is the most precise tool for the determination of the magnitude of the magnetic field in the interstellar medium (ISM). The achieved experimental accuracy in the measurements of the 21 cm absorption line profile makes these measurements a possible tool in the search for antihydrogen atoms in the universe.

The 21 cm absorption line in the hydrogen atom is of special importance in investigations of the factors and mechanisms responsible for the formation of clouds of gas and dust complexes, their role in the evolution of stars, etc. [13]. The achieved accuracy of observations gives a detailed picture of the 21 cm absorption line profile [14,15]. For our purposes, the most important fact is that the Zeeman splitting can be resolvable in such observations [16]. The observation of the radiation polarization in the 21 cm line profile can serve as a tool in the search for antimatter in the universe.

In Ref. [12] it was shown that, in the Zeeman-split Lyman-\( \alpha \) transition for a certain direction of the magnetic field, the high-frequency component for the H atom is right-handed circularly polarized and the low-frequency component is left-handed circularly polarized. In the anti-H atom for the same direction of magnetic field the high-frequency and low-frequency components have opposite circular polarizations. Therefore, to distinguish between the H and \( \bar{\text{H}} \) atoms it is necessary to resolve the Zeeman components, to be able to determine the circular polarizations of these components, and to know the direction of the magnetic field.

Recent experimental success in the observation of the 21 cm absorption line [14,15] makes it possible to apply the procedure suggested in Ref. [12] to the measurement of the circular polarization in the wings of the 21 cm line. The matrix element of the M1 transition rate between the Zeeman components of the ground state in the hydrogen atom can be written in the form [17]:

\[
\langle n F M_F |(\vec{e}[\vec{k} \times \vec{\mu}])|n F' M_{F'} \rangle = \sum_q (-1)^q \langle \vec{e} \times \vec{k} \rangle_{-q} \langle n F M_F |\mu_q |n F' M_{F'} \rangle.
\]  

Here \( \vec{\mu} \) is the magnetic moment of the electron defined as \( \vec{\mu} = \mu_0(\vec{l} + 2\vec{s}) \), where \( \mu_0 = \frac{e\hbar}{2m_e c} \) is Bohr’s magneton, \( m_e \) is the electron mass, and \( c \) is the speed of light. The quantum numbers \( n F M \) represent the principal quantum number, total angular momentum of atom \( F \), and its projection \( M_F \) on the magnetic field direction, \( \vec{l}, \vec{s} \) are the orbital and spin angular momenta of an electron respectively, \( \vec{e} \) represents the polarization vector of the emitted photon, and \( \vec{k} \) is the wave vector of the photon. The form of the emission operator \( \langle \vec{e}[\vec{k} \times \vec{\mu}] \rangle \) for the M1 photon can be found in, e.g., Ref. [18]. Summation over \( q \) in Eq. (1) goes over the spherical components of the vector: \( q = \pm 1, 0 \).

The wave function indexed as \( |n F M_F \rangle \) can be written via the electron and nuclear functions as

\[
\psi_{nFM} = \sum_{M_J M_I} C_{JMJM_1}^{FM} \psi_{nJM_1} \eta_{IM_1},
\]
where $\vec{J} = \vec{l} + \vec{s}$ is the total angular momentum of an electron in an atom, $\psi_{0JM_J}$ is the electron wave function with momentum $J$ and its projection $M_J$, and $\eta_{JM_I}$ represents the nuclear wave function with the momentum $I$ and its projection $M_I$. Since the emission operator does not depend on the nuclear variables, the orthonormalization relation $\langle IM_I|M'_{I'}\rangle = \delta_{II'}\delta_{M_I M_{I'}}$ can be used. Thus, in accordance with the Eckart–Wigner theorem, we arrive at

$$\sum_q (-1)^q [\vec{e} \times \vec{k}]_{-q} \langle nF M_F | \mu_q | n' F' M_{F'} \rangle,$$

where $\langle nJ||\mu^1||nJ \rangle$ is the reduced matrix element for the vector operator $\vec{\mu}$.

For the transition $nF M_F \rightarrow n'F' M_{F'}$ between Zeeman components of the excited ($F = 1$) and ground ($F = 0$) hyperfine sublevels in hydrogen (see Fig. 1), the expression Eq. (3) simplifies to:

$$C_{JM_{F}J_{M_{I}}}^{F'F} = C_{JM_{F}J_{M_{I}}}^{00} = (-1)^{J-M_{F}} \frac{1}{\sqrt{2J+1}} \delta_{J,J} \delta_{M_{F},M_{I}},$$

$$C_{JM_{F}J_{M_{I}}}^{F'F} = C_{JM_{F}J_{M_{I}}}^{1MF} = \frac{1}{\sqrt{2J+1}} \delta_{J,J} \delta_{M_{F},M_{I}},$$

for the hydrogen atom $J = I = 1/2$. Then

$$\langle n1M_F|([\vec{e} \times \vec{k}]_q | n00 \rangle = \sum_q (-1)^q [\vec{e} \times \vec{k}]_{-q} \frac{1}{\sqrt{2}} \times \sum_{M_J,M_{I}} (-1)^{1/2-M_{K}} C_{1M_J}^{1M_F} C_{1M_J}^{1M_F} \left( n\frac{1}{2} || \mu^1 || n\frac{1}{2} \right).$$

Summation over $M_J, M_{I}$ in Eq. (5) [19] yields

$$\langle n1M_F|([\vec{e} \times \vec{k}]_q | n00 \rangle = \sum_q (-1)^q [\vec{e} \times \vec{k}]_{-q} \frac{1}{\sqrt{5}} \delta_{M_J,M_{I}} \left( n\frac{1}{2} || \mu^1 || n\frac{1}{2} \right).$$

The vector product in spherical components can be written in the form:

$$[\vec{A} \times \vec{B}]_{-q} = (-i \sqrt{2}) \sum_{r,s} C_{1r1s}^{1-q} A_r B_s,$$

where $r, s = 0, \pm 1$. Associating the photon emission direction with the $z$-axis that coincides with the field direction ($s = 0$) and summation over $q$, we obtain

$$\langle n1M_F|([\vec{e} \times \vec{k}]_q | n00 \rangle = \left( -i \frac{\sqrt{2}}{2} \right) (-1)_{1M_F} \sum_r C_{1r10}^{1-M_F} e_r k_0 \left( n\frac{1}{2} || \mu^1 || n\frac{1}{2} \right).$$

The Clebsch–Gordan coefficient in Eq. (8) is nonzero at $r = -M_F \neq 0$. Thus the circular polarization with $r = \pm 1$ (clockwise and anticlockwise) arises for the transition between the lower ($M_F = -1$) or upper ($M_F = +1$) Zeeman components of the excited ($F = 1$) and ground ($F = 0$) hyperfine sublevels in hydrogen, respectively. The linear polarization corresponds to the transition $n10 \rightarrow n00 (r = -s, M_F = 0)$ [20].

On the other hand, the Zeeman energy splitting is defined as $\mu g M_F H$, where $g$ is the Landé factor, $M_F$ is the magnetic number of the corresponding state, and $H$ is the magnetic field magnitude. Thus, the $M_F$ values for the lower and upper components of Zeeman splitting for the H and H atoms...
Fig. 1. The level scheme of the ground $1s_{1/2}$ state in hydrogen (H) and antihydrogen ($\bar{\text{H}}$) atoms. The levels are depicted with the account for the nuclear spin (total momentum $F$) and Zeeman splitting that corresponds to the splitting of degenerate sublevels with different magnetic quantum numbers $M_F$. The linear polarization that corresponds to the transition $F, M_F = 1, 0 \rightarrow F, M_F = 0, 0$ is shown by an up–down arrow ↓. The left and right circular polarizations are denoted by circles with arrows.

have opposite signs at the fixed field direction. Therefore, the blue and red wings of the line profile have different polarizations for hydrogen and antihydrogen atoms with the same field direction. The maximum of the effect corresponds to the case of completely separate Zeeman sublevels.

For typical magnetic fields of order $\sim 10 \mu G$, the separation of hyperfine sublevels is significantly smaller than the line width of the 21 cm line. The corresponding Zeeman splitting in the field $10^{-5}$ G is about 14 Hz and the line width exceeds the order of kHz at the temperature 100 K due to a large Doppler broadening. Therefore, in order to detect the Zeeman effect, the absorption lines are usually chosen: absorption lines arise in colder gas. Weakness of the Zeeman splitting in the interstellar medium allows it to be observed only in the regions where interstellar fields are stronger and the gas temperature is lower than average, i.e. in sufficiently dense clouds [21]. Thus, observing two separate peaks in the line profile is not possible in general. At the same time, there are situations when the Zeeman effect in the 21 cm line has been detected [22]. The polarization of hyperfine sublevels is a potentially measurable quantity if the magnetic field strength is such that the magnitude of the difference between left- and right-handed polarizations is larger than the detector noise [23]. It has been suggested [24] that the intensity difference between the line wings could be observed, not connected with the possibility of distinguishing H and $\bar{\text{H}}$ atoms. The idea was based on the measurement of the Stokes parameters. Since then many new Zeeman observations with high resolution based on the technique [24] have been widely reported in the literature; see, e.g., Ref. [16]. Thus, in principle, for the search for the antihydrogen atom, it is not necessary to observe the Zeeman splitting; it would be enough to fix the different polarizations in the blue and red wings of the 21 cm line profile.

Another effect that can also distinguish between H and $\bar{\text{H}}$ atoms in a magnetic field is the Faraday rotation, i.e. the rotation of the plane of linear polarization around the direction of light propagation. The central component of the 21 cm line profile that corresponds to the $M_F = 0 \rightarrow M_F = 0$ transition (see Fig. 1) is linearly polarized and the plane of this polarization rotates around the direction of light propagation in opposite directions in H and $\bar{\text{H}}$ atoms. Thus, the Faraday effect on this central line can also be used to distinguish between H and $\bar{\text{H}}$ atoms, provided that the direction of the external magnetic field is known. The Faraday rotation is frequently used for observations of the polarization and emission geometry of pulsars [15]; see also Refs. [25–27]. A short history of astronomical polarimetry can be found in Ref. [28] and references therein.

High-resolution observations of Zeeman absorption in the HI region toward radio sources were reported in Refs. [16,29]. The Faraday rotation of the plane of linear polarization for the 21 cm absorption line was also discussed in Ref. [30] (not for the search of $\bar{\text{H}}$). The magnetic fields can
also be measured for galaxies at high redshifts [31]. Thus, in principle, observations of the 21 cm absorption line profile can be used as a tool in the search for antimatter in the universe.

The only question that still remains is the determination of the field direction independent of the Zeeman or Faraday effects in the hydrogen atom. For example, taking into account the large-scale structure of magnetic fields, the polarization of dust can serve as an independent tool for determination of the field direction [32]. On the other hand, the Faraday rotation of linearly polarized light can also be observed for pulses of synchrotron radiation from pulsars [33]. In particular, Faraday rotation measurements of polarized radio signals from extragalactic radio sources were used to estimate both the electron density distribution and the direction and strength of the magnetic field [34,35], thus defining the field direction. It was noted that the Faraday rotation of pulsar radiation is the best available method for mapping magnetic fields on large scales [36,37]. Finally, the existing magnetic field maps can be used for the determination of field direction. In conclusion, we can also note that photon polarization can be observed in the wings of the absorption/emission line profile in modern astrophysical experiments.

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