INTERFERENCE OF THE $2p_{1/2}$ *STATE OF THE HYDROGEN ATOM*

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Interference of the $2p_{1/2}$ state of the hydrogen atom observed in experiments on the effect of diabatic electric fields on the metastable H_{2S} atoms is described. With the aid of the "atomic interferometer"—an arrangement permitting one to observe the atomic state interference in a space free from any field, it has been possible to determine the Lamb shift between the $2s_{1/2}$—$2p_{1/2}$ levels of a hydrogen atom.[1)]

1. INTRODUCTION

MANY recent theoretical and experimental papers are devoted to a verification and further development of quantum electrodynamics (QED). The progress attained is to a certain extent exceptional: all the earlier discrepancies between theory and experiment have by now been eliminated, and the validity of QED has been confirmed with exceedingly high accuracy with many physical phenomena as examples. None of the critical tests, both at high and low energies, reveal at present any noticeable deviations from the predictions of the theory.

The decisive role in the change that occurred in the situation prevailing until recently was played by the method of independently determining the fine-structure constant α, based on the Josephson effect, and also by the development of new methods of calculating the radiative corrections of higher orders, which made it possible, in particular, to obtain a more exact value of the fourth-order correction to the Lamb shift and the sixth-order corrections to the anomalous magnetic moment of the electron and muon[2]. In addition, more perfect procedures were developed for the measurement of quantities that depend on QED; for example, agreement was reached between the theoretical and experimental values of the Lamb shift[3,4].

It should be noted, however, that such obvious advances have not only failed to eliminate the most serious difficulties in the development of the theory, but to the contrary have pointed out with particular sharpness its inherent paradoxical nature. Namely, quantum electrodynamics, now one of the most exact theories, is at the same time internally imperfect and contains difficulties of fundamental character. The latter make it particularly important to perform experiments capable of revealing the limits of applicability of QED, for this would lead to a different and deeper understanding of its principles themselves.

An important role among experiments aimed at verifying QED is played by extremely precise measurements of the fine and hyperfine structures of atomic levels, so as to be able to estimate the accuracy with which higher-order radiative corrections are calculated. This includes first of all the determination of the Lamb shift δ and of the hyperfine splitting of the hydrogen atom levels. These quantities are sensitive to the dynamic effects of QED (as is observed starting with the fourth-order perturbation-theory approximation) as well as to relativistic corrections for recoil[2].

In spite of the primary importance of further increasing the measurement accuracy of the quantities that depend on QED, it becomes necessary under the developing conditions to search for new ways of studying the H atom, such that the aggregate of the properties of its levels can reveal themselves in hitherto unknown aspects. Starting from these considerations, one can propose an experiment based on observation of the interference of the states of the hydrogen atom, since an interference pattern registered in a wide range of phase shifts is extremely sensitive to the characteristics of its components. The principles of such a method (which can be called the "atomic interferometer method") are reported in[5].

2. THE METHOD

The interference of atomic states can be observed in principles with the aid of apparatus similar in main outline to an ordinary optical interferometer. The latter can be regarded as a system consisting of three regions separated by active zones that change the states of the photons entering in them. If a light beam passing through an interferometer is split, say, into two components, then the photons on crossing the first "active" zone go over into a superposition of states corresponding to the two channels of the interferometer. In this case there will be observed in the third region (i.e., after passing through the second "active" zone) an interference of two phase-shifted components of the light beam, produced from states connected with the first and second channels.

The operating principle of one of the variants of the "atomic interferometer" constructed in accordance with such a scheme can be illustratively explained in the following manner.

Imagine a beam of metastable $2s_{1/2}$ atoms of hydrogen passing in succession through two spatially separated "active" zones I and II. Inside these zones, the atoms are subject to the action of a perturbation that enables them to go over to other states, say $2p_{1/2}$ and $2p_{3/2}$. A perturbing factor of this kind may be an electric field E that varies non-adiabatically within each of the zones. The criterion of the non-adiabaticity is that

1) This paper is a summary of results obtained in a series of experiments with the "Pamir" installation.

the transit frequency $\omega = v/d$ be larger than or of the order of the Lamb frequency (for the $2s_{1/2} - 2p_{1/2}$ transition) or of the fine-structure frequency (for $2s_{1/2} - 2p_{3/2}$); here v is the velocity of the atom and d is the length of the active zone, i.e., the distance over which the field either increases or decreases. To simplify the picture, we shall continue our analysis with the two-level $2s_{1/2} - 2p_{1/2}$ system as an example. This justified for fields that are not too strong, when the influence of the $2p_{3/2}$ level can be neglected.

It follows from the foregoing arguments that in the simplest version of the interferometer the role of the active zones can be played by the boundaries I and II of the field E, localized in a specified region. Then, when they cross boundary I, the atoms of the beam experience the perturbing influence of a growing field and go over into a superposition of eigenstates φ_1 and φ_2 with energies ϵ_1 and ϵ_2 determined by the value of the field intensity E. At the boundary II, where the field decreases to zero, beam components representing both the state $2s_{1/2}$ and the state $2p_{1/2}$ are produced, and each of the terms φ_1 and φ_2 initiates a pair of such states: $\varphi_1 \rightarrow (2s)_1 + (2p)_1$ and $\varphi_2 \rightarrow (2s)_2 + (2p)_2$. Thus, in the field-free region adjacent to the boundary II the state of the atom is described by a superposition of the four components $(2s)_1$, $(2s)_2$, $(2p)_1$, and $(2p)_2$.

After leaving the field, the amplitudes of the $2s_{1/2}$ and $2p_{1/2}$ states will be determined by the transition amplitudes and by the phase difference between the components of each pair $(2s)_1 - (2s)_2$ and $(2p)_1 - (2p)_2$, which depends on the time of flight in the field and on the frequency of the transition between the terms φ_1 and φ_2 that are split by the electric field. Since the magnitude of such a splitting is determined entirely by the field intensity E, when the latter is monotonically varied there will be observed in the transmitted beam periodic oscillations (in counterphase) of the intensities of the H_{2s} and H_{2p} atom fluxes, due to interference between the $(2s)_1 - (2s)_2$ and $(2p)_1$ and $(2p)_2$ waves produced on boundary II. A similar picture will take place when the time of flight T, i.e., the distance between the field boundaries, is changed.

It is necessary to emphasize that observation of interference of the 2s or 2p components of the beam becomes possible in experiments of the described type only if the variation of the field on both boundaries satisfies the non-adiabaticity condition. Indeed, in the case of smooth variation of the field, say at boundary I, the contribution of one of the terms (say, φ_2) to the superposition describing the state of the atom in the field will be small, and accordingly if the field terminates rapidly at boundary II there will be practically no components $(2s)_2$ and $(2p)_2$ due to the term φ_2 and shifted in phase relative to the components $(2s)_1$ and $(2p)_1$. A similar picture (i.e., the presence in the beam of two components, $(2s)_1$ and $(2p)_1$, rather than four paired components $(2s)_1 - (2s)_2$ and $(2p)_1 - (2p)_2$ will be observed if the field varies non-adiabatically at boundary I and adiabatically at boundary II. In the system considered here, the necessary coherence condition is satisfied because the phase difference between the interfering states, which depends on E and T, is the same for all atoms in the beam.

In the simplest case of two levels, assuming a sudden termination of the field at the boundaries, the yield of H_{2p} atoms is proportional to the quantity W defined by the following expression:

$$W = e^{-\gamma T/2}\left\{c_1\frac{x_1^2}{1+x_1^2}\left[\mathrm{ch}\frac{\gamma T}{2(1+x_1^2)^{1/2}} - \cos 2\pi\left(\delta+\frac{2}{3}\nu\right)T(1+x_1^2)^{1/2}\right]\right.$$
$$+c_2\frac{x_2^2}{1+x_2^2}\left[\mathrm{ch}\frac{\gamma T}{2(1+x_2^2)^{1/2}} - \cos 2\pi\left(\delta-\frac{10}{3}\nu\right)T(1+x_2^2)^{1/2}\right]+$$
$$\left.+c_3\frac{x_3^2}{1+x_3^2}\left[\mathrm{ch}\frac{\gamma T}{2(1+x_3^2)^{1/2}} - \cos 2\pi(\delta+2\nu)T(1+x_3^2)^{1/2}\right]\right\}, \quad (1)$$

where γ is the decay constant of the $2p_{1/2}$ state, T is the time of flight, δ is the Lamb frequency, ν is the hyperfine splitting frequency, and c_1, c_2, and c_3 are constants.

In the $2s_{1/2} - 2p_{1/2}$ system there are transitions between the s and p sublevels of the hyperfine structure, with total angular momentum projections 1, 0, and −1 (Fig. 1). The energy differences $2s_{1/2}(F_Z = 1) - 2p_{1/2}(F_Z = 1)$ and $2s_{1/2}(F_Z = -1) - 2p_{1/2}(F_Z = -1)$ coincide, so that the summation in (1) is carried out for three components of the hyperfine splitting. The values of x_i corresponding to them are expressed in terms of the parameter $x = \langle d\rangle E/\pi\hbar\delta$ (where $\langle d\rangle$ is the matrix element of the $2s_{1/2} - 2p_{1/2}$ transition):

$$x_1 = \frac{x}{1+{}^2/_3\nu/\delta}, \quad x_2 = \frac{x}{1-{}^{10}/_3\nu/\delta}, \quad x_3 = \frac{x}{1+2\nu/\delta}.$$

The factor $e^{-\gamma T/2}$ takes into account the finite lifetime of the H_{2p} atom[2)].

It follows from the presented formula that the experimentally obtained dependence of the yield of H_{2p} atoms on E and T makes it possible, in principle, to determine the values of δ and ν.

At the present time, the interference phenomena observed in quantum transitions are widely used in atomic physics for the study of the properties and the structure of the excited states[6,7], including the determination of the Lamb shift[8,9].

In most of these procedures, interference is observed between the light waves emitted by atoms in a superposition of states of close energy (such as Zeeman components with different magnetic quantum numbers). This results in modulation of the radiation intensity, i.e., in beats having a frequency equal to the difference between the frequencies of the combining waves. In the experiment described above, to the contrary, there is interference between the atomic states themselves (more accurately, between phase-shifted components of one and the same state), observed in the field-free space. Such a phenomenon is a pure case of Huygens-Fresnel optics, in which the atomic states play the role of the optical waves.

3. BEAM OF HYDROGEN ATOMS

The practical realization of an experiment aimed at observing the interference of the $(2s)_1 - (2s)_2$ or $(2p)_1 - (2p)_2$ states encounters serious difficulties, mainly because of the unusual and contradictory requirements that must be satisfied by a beam of H_{2s} atoms passing through the electrode system of the interferom-

2) Expression (1) was derived by V. M. Galitskiĭ.

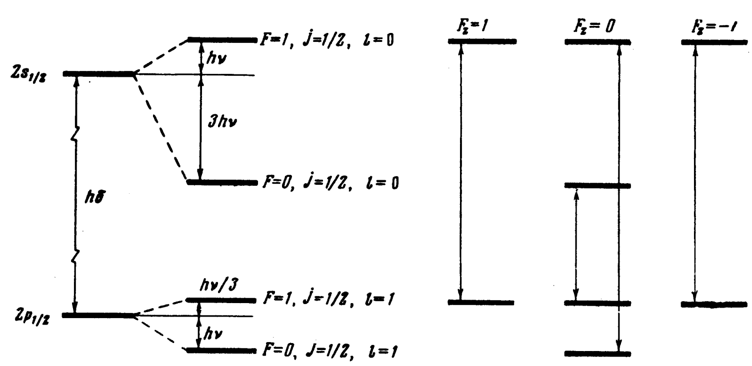

FIG. 1. Hyperfine splitting of the $2s_{1/2}$ and $2p_{1/2}$ levels of the hydrogen atom.

eter. "Pure" beams (i.e., containing no other particles) of metastable hydrogen atoms with thermal velocities, which by now can be readily obtained, are utterly unsuited for this purpose, since they require microscopic interferometer dimensions. The construction of the interferometer becomes feasible at an atom velocity on the order of 2×10^8 cm/sec; but at this velocity it is possible to produce non-adiabatically varying fields (capable of ensuring a sufficient yield of H_{2p} atoms) only if the gap in the electrodes through which the beam passes is not wider than several tenths of a millimeter. Under these conditions, in order for the field to be regarded as homogeneous over the entire cross section of the beam, the transverse dimensions of the latter should not exceed 0.1 mm. It is inconvenient, on the other hand, to increase the dimensions of the interferometer and the beam, and increase accordingly the velocity of the atoms, for the following reasons.

In the proposed experiment one measures the intensity of the 2p component of the beam by registering the quanta corresponding to the 2p → 1s transition, i.e., the resonant line L_α (λ = 1216 Å) of the Lyman series. The beam must therefore not contain noticeable amounts of excited atoms whose cascade emission, accompanied by a transition to the ground state 1s, is capable of producing an appreciable background masking the observed phenomena. At the same time, any of the known methods makes it possible to obtain only a mixed beam of fast hydrogen atoms in all possible states from n = 1 to n ~ 15—20. To produce a suitable beam it is necessary to remove from it all the remaining, particularly the short-lived atoms with n = 2—6, and the only method of removing them is to permit them to radiate during the time of flight. Long-lived highly excited atoms can be removed from the beam by ionizing them in a strong electric field. Control experiments show that an acceptable decrease of the background produced by the excited atoms, at a velocity $v = 2 \times 10^8$ cm/sec, can be obtained over a flight distance not shorter than 200 cm. The foregoing velocity should be regarded as optimal, since the corresponding interferometer dimensions are not too small, and the dimensions of the vacuum apparatus are not too large.

The appreciable length of the beam (reaching 400 cm under real conditions) together with a thickness not exceeding 0.1 mm, at an H_{2S}-atom current on the order of 10^{11} sec^{-1}, needed for reliable registration of the H_{2p} atoms, imposes extremely stringent requirements on the collimation system. An attempt to produce such a beam was undertaken with the "Pamir" installation.

Two methods of obtaining fast H atoms were investigated: charge exchange of pre-accelerated protons in a gas target, and recombination of protons and free electrons moving with equal velocities.

Charge exchange of protons in a gas chamber is a well investigated and widely used method of obtaining a beam of fast hydrogen atoms. The most effective from the point of view of the yield of metastable H_{2S} atoms is charge exchange in cesium vapor[10]. However, the use of a cesium target in an experiment of the described type did not seem essential, since relatively weak currents were sufficient to observe the interference; at the same time, high stability of the neutral-atom beam operating continuously for several hours was of primary importance. Charge exchange of the protons was therefore effected in molecular hydrogen.

As a result of numerous experiments with different ion sources and focusing systems, we succeeded in obtaining a small-aperture beam of protons with E_p ~ 20 keV. To obtain optimal gas-target characteristics in this case, the angular divergence of the beam of neutral atoms was 0.8×10^{-3}. A careful study of the distribution of the current density over the beam cross section at different distances from the exit slit of the gas target, however, revealed an unexpected circumstance. It turned out that at sufficiently high current density of the primary protons entering in the gas target, it was possible to separate from the beam of the obtained neutral atoms an easily recordable fraction with an angle divergence not exceeding 10^{-4}, corresponding to a "transverse" particle temperature on the order of 2°K. It should be noted that such a beam may turn out to be a good source for spectroscopic purposes, since the Doppler broadening of the lines will be quite negligible in this case. One could, for example, repeat the attempt once made to measure the shift of the $2s_{1/2}$ and $2p_{1/2}$ levels of the hydrogen atom (i.e., the Lamb shift) by resolving the hyperfine components of the H_α line[11,12].

In the study of the interaction between superimposed beams of protons and electrons moving with equal velocities, it was observed that hydrogen atoms are produced in various states. It follows from the obtained data that in this case one has not radiative recombination (as initially assumed), but recombination from triple collisions, in which the upper levels of the hydrogen atoms are populated with higher probability. Consequently, and also because of the small scale of the observed effect, all further experiments were performed

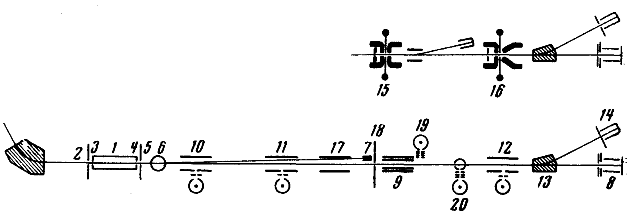

FIG. 2. Diagram of the "Pamir" installation interferometer with a transverse field is shown): 1—charge-exchange chamber; 2–5—separating diaphragms of differential pumping system; 6, 13—magnetic field; 7, 14—Faraday cylinders; 8—pickup measuring the neutral-atom flux; 9—electrodes of interferometer with transverse field; 10–12—pickups measuring the flux of the H_{2s} atoms; 15, 16—high-voltage gaps; 17—electric field destroying the H_{2s} atoms; 18—diaphragm; 19,20—counters.

with the above-described "parallel" beam extracted from the beam of the atoms resulting from the charge exchange of the protons in the gas target.

4. EXPERIMENTAL SETUP

Figure 2 shows a diagram of the "Pamir" installation used to investigate the interference between the beam components pertaining to the 2s and 2p states of the hydrogen atom.

A monokinetic beam of protons with energy on the order of 20 keV was passed through hydrogen-filled chamber 1, where charge exchange produced neutral atoms in all possible states, including the metastable state $2s_{1/2}$. The chamber pressure at which the maximum yield of H_{2S} atoms was observed corresponded to a gas-target thickness on the order of 1×10^{-2} Torr-cm. The charge-exchange chamber equipped with a differential pumping system was separated from the source and from the diagnostic section by a system of diaphragms 2–5. The last separating diaphragm 5 measured 0.4×5 mm. Under these conditions, filling the charge-exchange chamber with gas did not affect the pressure in the diagnostic section, which usually did not exceed 5×10^{-8} Torr. The distance between the ion source and the exit slit 2 was 160 cm.

When monitoring the experimental conditions we measured, besides all possible parameters determining the operating regime of the installation, also the following quantities characterizing the beam as it leaves diaphragm 5.

1) The current of protons passing through the gas target. The mixed beam leaving the charge-exchange chamber passed through a weak magnetic field 6 in which the proton component was deflected through an angle 0.15°, and registered with receiver 7. Under the indicated conditions, no noticeable weakening of the H_{2S} atom current by the Lorentz field took place.

2) The total current of neutral atoms. The measurements were based on the secondary emission and were made with the end pickup 8. The pickup was calibrated by comparing its readings with those of a thermocouple-equipped microcalorimeter. A typical value of the current for a beam with cross section 0.1×4 mm was 0.7 $\times 10^{13}$ atoms/sec.

3) The current of metastable atoms. The constancy of the current of metastable atoms at different sections of the beam trajectory was monitored with pickups 10, 11, and 13. Each such pickup was a parallel-plate capacitor in which a field causing luminescence of the H_{2S} atoms was produced during the measurement. The resultant L_α quanta passed through a hole in one of the plates of the capacitor and were registered with a counter. The H_{2S} atoms were removed from the beam during the calibration experiments by capacitor 17.

It should be noted that the current of metastable atoms can vary quite independently of the current of the atoms in the ground state $1s_{1/2}$. The latter is due mainly to the influence of the random electric fields resulting from the appearance of insulating films on the walls of the vacuum chamber. Inconstancy of the H_{2S} current is observed also in the case of rapid oscillations of the current in the primary proton beam, which takes place if the source operates under non-optimal conditions. The fluctuating fields produced thereby destroy the $2s_{1/2}$ states in the section where the H_1^0 and H_1^+ beams have a common trajectory. To eliminate these disturbances, special measures were adopted; in particular, all the interferometer parts were coated with gold and cleaned periodically. Before the measurements, the chamber was conditioned for a long time under vacuum; this increased significantly the stability of the H_{2S}-atom beam.

In addition to the indicated beam characteristics, measurements were made in some experiments (for example, in the investigation of the background) of the current of protons produced in the beam by ionization of the H atoms by the residual gas, and the population of the highly-excited levels was analyzed. The secondary-proton current was measured with a system consisting of deflecting magnet 13 and Faraday cylinder 14 connected to an electrometer. The magnet 13 and the pickup 14 were used also to determine the populations of the upper levels at a given distance from the gas target. In this case an analyzer with two high-voltage gaps 15 and 16 (unlike the single gap as proposed in[13]) was placed in the path of the beam ahead of magnet 13. The field intensities in the gaps were chosen such that the first ionized atoms with $n = n_i$ and the second gap, where the field was somewhat stronger, ionized the level with $n = n_{i-1}$. By placing such an analyzer at various distances from the gas target, it is possible to measure the lifetimes of the excited states, by successively separating levels with different n.

It was noted above that the background produced by cascade transitions of the excited atoms to the state $1s_{1/2}$ can be lowered by suitably moving the observation point from the slit 5, the minimum distance from which was assumed, on the basis of control experiments, to be 200 cm. Starting from this distance, the background due to the radiation of the excited atoms was small enough. At the experimental geometry described below, which was determined by the mutual location of the beam, counter, and collimator through which the registered L_α radiation passed, the background amounted to 0.1–10% of the observed effects. The background due to the collisions of the H_{1S} and H_{2S} atoms with residual-gas particles, at a residual-gas pressure 5×10^{-8}–1×10^{-7} Torr in the setup, was much smaller.

The highly-excited atoms with $n > 7$ produced no noticeable noise in the measurements, since the level population decreases in charge exchange in proportion to n^{-3}. The highly-excited atoms can be removed from the beam by ionizing them in a strong electric field. For the indicated purpose, the mixed beam was passed in certain experiments through two gaps in tandem (each 0.3 mm wide), in which an electric field of intensity up to 550,000 V/cm was produced; such a field caused ionization of atoms with $n \geq 7$. Under these conditions, the background due to the beam became smaller than the natural background of the counter and could not be determined with sufficient degree of reliability.

The measurements have shown that the background registered by the counter of the effect with the interferometer electrodes grounded is proportional to the total neutral-atom current measured by pickup 8. This circumstance was used to determine the background in most experiments, during which three quantities were registered simultaneously: 1) the readings of the counter of the effect, 2) the register of the counter of the monitor measuring the current of the H_{2S} atom, and 3) reading of the end pickup 8.

To register the L_α quanta emitted by the beam, we used iodine-quenched photon counters equipped with lithium fluoride windows, or open photomultipliers with copper-beryllium electrodes. The load characteristic of each counter was measured and used to obtain the corrections needed to determine the true number of quanta absorbed in the counter. Experience has shown that the use of oxygen filters is not essential under the conditions in question, since the radiation from the beam is limited to the L_α line in the spectral sensitivity region of the counter (1100–1340 Å).

5. INTERFEROMETER

Two interferometer systems were used in the described experiments, with transverse and longitudinal fields relative to the atom direction. The interferometer with transverse field was used to study the dependence of the effect on the field intensity at a constant flight time T. The interferometer with longitudinal field has made it possible to determine the dependence of I_{2p} on both E and T. In most experiments, the interferometer was located 200 cm away from the slit 5.

Figure 2 shows a diagram of the transverse-field interferometer. The beam, shaped by diaphragm 18, passes between flat electrodes 9 and then past the counters 19 and 20 that register the emission of the 2p component produced by the field E. The system of electrodes of an interferometer of this type is shown in Fig. 3, together with the variation of the field at the edges of the plates, which can be switched in such a way that the variation is either non-adiabatic (curve H) or has a smoother "adiabatic" character (curve A). The transverse dimensions of the beam are determined by the diaphragm 18 with a slit-like window measuring 0.01 × 0.4 cm. The electrode length is 0.29 cm, corresponding, with allowance for the stray field, to a time of flight on the order of 1.6×10^{-9} sec, i.e., of the order of the hydrogen lifetime in the 2p state. The region in which the counters are located was surrounded by a gold-coated screen with narrow slits for the passage of the beam. The slits keep out electric fields capable of destroying the metastable states. The monitor used in this case to determine the $I_{2p}(E)$ dependence was pickup 11, with a weak static field, causing de-excitation of some fraction of the H_{2S} atoms, applied between the counter electrodes.

A diagram of the interferometer with longitudinal field is shown in Fig. 4. Plane electrodes 1 and 2 were constructed in the form of plates 0.5 cm thick. Slits 0.0247 cm wide were cut in the centers of the plates. A precision mechanism was used to vary the distance between the plates from 0 to 1.5 cm; at an atom velocity on the order of 2×10^8 cm/sec this corresponded to a minimum time of flight 7.5×10^{-9} sec. The change of the distance between plates could be measured accurate to 2×10^{-5} cm; the parallelism of the plates was maintained with accuracy on the order of 5×10^{-5} cm.

The flux of the H_{2p} atoms was measured by counter 4 installed in a screening chamber connected to the rear plate. This type of interferometer equipped with a monitor in the form of a parallel-plate capacitor through which there passes part of the beam bounded by the diaphragm 5. The L_α quanta produced when a voltage was applied to the capacitor electrodes emerged through the opening in one of the plates and were registered by counter 3. Slit 6 with a window measuring 0.005 × 0.2 cm was placed ahead of the entrance electrode of the interfereometer and mounted in such a way that the beam passed exactly in the middle of the slits in plates 1 and 2. The accuracy of the slit setting was checked optically during the adjustment of the instrument on the wall of the vacuum chamber.

6. MEASUREMENT OF ATOM VELOCITY

To determine the Lamb shift δ by the described method it is necessary to know the velocity of the H_{2S}

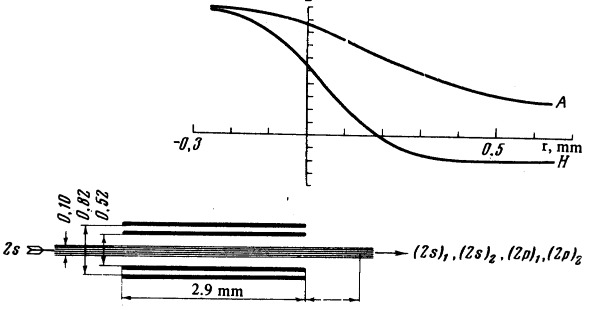

FIG. 3. Electrode system of interferometer with transverse field.

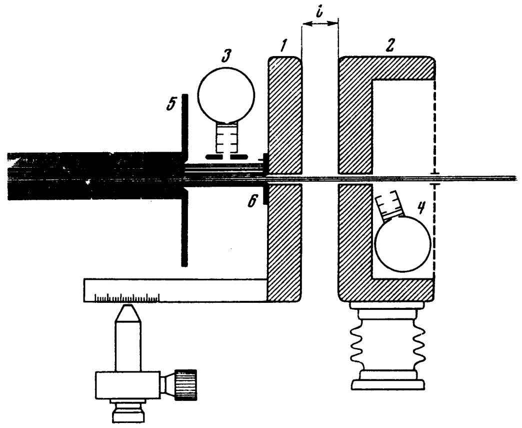

FIG. 4. Interferometer with longitudinal field: 1, 2–interferometer electrodes; 3, 4–counters; 5, 6–diaphragms.

atoms. It was determined by analyzing the dependence of the H_{2p}-atom luminescence intensity on the distance r between the two pickups measuring the L_α radiation of the beam. The slope of the ln $I_{2p}(r)$ line determines the value of the product $v\tau$ in the expression $I_{2p} = I_{02p}\exp(-r/v\tau)$. Calculation of the regression-line parameters shows that the employed apparatus makes it possible to measure v with accuracy not less than 10^{-4}.

To verify the method used to determine the velocity and to estimate the really attainable accuracy, a calibration experiment was performed, in which the velocity of the H_{2p} atoms produced upon photoexcitation of H atoms from the ground state 1s to the state 2p was compared with the velocity of the H_{2p} atoms produced by the action of a non-adiabatically varying field on H_{2S} atoms. The H_{1S} and H_{2S} atoms should differ in energy by 10.2 MeV. This difference is consumed in excitation in the case of charge exchange that leads to the formation of atoms with n = 2. The possibility of measuring this difference at a total atom energy $\sim$ 20 keV would be an essential characteristic of the resolving power of the apparatus. The experimental setup is shown in Fig. 5.

In the former case (i.e., in photoexcitation), the mixed beam coming from the charge exchange chamber was passed in succession through a magnetic field to deflect the proton component, through the above-described system with 550 000 V/cm electric field, and through capacitor 17, where the metastable states were destroyed. The beam filtered in this manner, consisting only of H_{1S} atoms, was exposed to a flux of L_α quanta from a capillary hydrogen lamp L of 2.2 kW power. The quantum flux was measured with a KFL ionization chamber having an LiF window and filled with nitrogen oxide. Under typical experimental conditions, the flux of quanta incident on the beam through a window measuring 0.3×0.4 cm was $\sim 10^{13}$ sec^{-1}. In this experiment, the current of H_{1S} atoms in a beam of cross section 0.016×0.4 cm was 1.4×10^{13} sec^{-1}. At these flux values, the obtained number of H_{2p} atoms was large enough to be registered[3)].

In the second variant of the experiment, we observed the H_{2p} atoms produced from metastable H_{2S} atoms under the influence of a non-adiabatic field E (the plates of capacitor 17 were grounded and lamp L was turned off).

To register the emission of the H_{2p} atoms (with lifetime $\tau = 1.595 \times 10^{-9}$ sec, counters 19 and 20 of the interferometer with transverse field were used. The counter 9, placed in a fixed position, was equipped with a collimator whose field of view covered a beam section approximately 0.01 cm long and located directly at the edges of electrodes 9. Counter 20 could be moved continuously along the beam trajectory in a range of 5 cm. The displacement was determined with a measuring microscope with accuracy 0.2 μ. A collimator was placed in front of the window of this counter in such a way that a section of the beam 0.07 cm long entered the field of view of the counter. A cylindrical mask secured to the end of the collimator prevented quanta emitted by the remainder of the beam or reflected from the walls of the instrument from entering the counter.

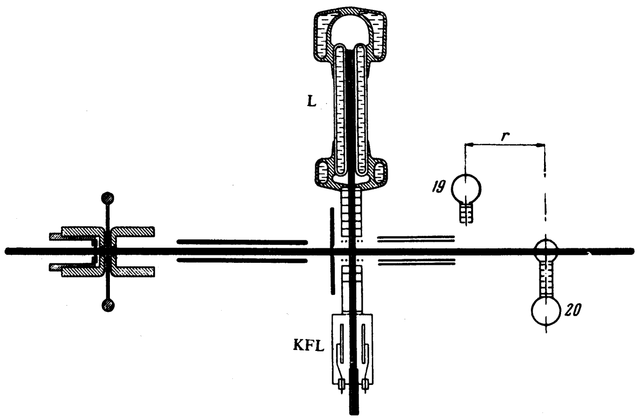

FIG. 5. Experiment in which the $1s \rightarrow 2p$ transition of the hydrogen atom was photoexcited and the velocities of the H_{1s} and H_{2s} atoms measured. The notation is the same as in Fig. 2.

The estimated difference between the energies of the H_{1S} and H_{2S} atoms if of the order of 8 eV, but this is only an approximation. It turns out that observation of the $1s \rightarrow 2p$ photoexcitation is at the limit of the experimental capabilities. When working with a capillary lamp it is extremely difficult to get rid of the background due to the L_α quanta scattered by the powerful flux from the lamp, since the region of beam illumination and the region where the H_{2p} atoms are registered should be immediately adjacent to each other, owing to the short lifetime of the H_{2p} atoms. Nonetheless, the described experiment has shown that the previously obtained estimate of the accuracy with which v is determined (not lower than 10^{-4}) is perfectly realistic.

From an analysis of the $I_{2p}(r)$ plots obtained in a number of experiments it follows that the energy spread $\Delta E/E$ of the H_{2S} atoms in a beam of 0.005×0.2 cm cross section does not exceed 10^{-4}. It was also established that within the limits of measurement accuracy the atom velocity remains constant for 2—3 hours, which is long enough to perform the experiment. Such a stable state was attained after conditioning and heating the setup for approximately 4 hours. It should be noted that the velocity changes somewhat after the apparatus is turned on again. The velocity was therefore measured in each individual experiment on the determination of $I_{2p}(E, T)$.

7. OBSERVATION OF INTERFERENCE OF 2p STATE. RESULTS

To obtain the interference curves we used mainly longitudinal-field interferometers, in which the phase shift between the $(2s)_1 - (2s)_2$ and $(2p)_1 - (2p)_2$ components could be varied either by varying the time T or by varying the field intensity E.

The intensity of the short-lived 2p component of the beam was measured with the aid of pickup 4, which was mounted near the rear boundary of the field (Fig. 4). Pickup 12 (Fig. 2) was used to observe the interference of the 2s state. Simultaneous measurement of the intensity of the 2s and 2p components shows that the oscilla-

[3)]The KFL chamber and iodine counters measured the absolute value of the L_α-quantum flux with relatively low accuracy. Nonetheless, it was of definite interest to estimate the cross section of the $1s \rightarrow 2p$ photoexcitation, which turned out to equal 4.3×10^{-10} cm^2.

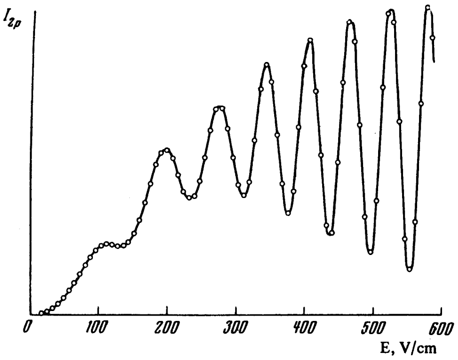

FIG. 6. Plot of $I_{2p}(E)$, $v\tau = 0.33228$, $l = 1$ cm.

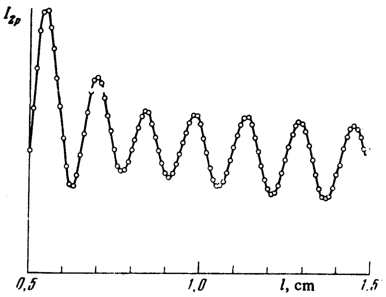

FIG. 7. Plot of $I_{2p}(l)$. $v\tau = 0.32704$, E = 200 V/cm.

tions of the curves pertaining to them are 180° out of phase.

Figures 6 and 7 show typical plots of $I_{2p}(E)$ and $I_{2p}(l)$, where l is the flight distance. Both curves reveal a distinct interference pattern which is the optical analog of the effect predicted by Pais and Piccioni for the system of K^0 and $\bar{K}^0$ mesons [14].

A reduction of the obtained data, aimed at comparing the theoretical and experimental $I_{2p}(E, T)$ plots at different values of E and T, and also at determining the Lamb shift, was based on an analysis performed by V. M. Galitskiĭ and V. P. Yakovlev. To simplify the analysis it is advantageous to subdivide the interval of the values of the field intensity E into a region of "normal" fields and a region of "strong" ones. By normal fields are meant fields for which the condition $x = \langle d\rangle E/\pi\hbar\delta \sim 1$ is satisfied, i.e., they produce in the $2s_{1/2}$ and $2p_{1/2}$ levels a Stark shift of the same order as the Lamb shift (here $\langle d\rangle$ is the matrix element of the $2s_{1/2} - 2p_{1/2}$ transition, E is the field intensity, and δ is the Lamb shift). In the region of normal fields, the influence of the Lamb shift is most pronounced; to the contrary, the presence of the $2p_{3/2}$ level is weakly manifested, so that the problem can be reduced to an examination of the two-level system $2s_{1/2} - 2p_{1/2}$. The influence of the $2p_{3/2}$ level can be taken into account in this case by introducing small corrections.

The action of this level is manifest primarily in that the $2s_{1/2} - 2p_{1/2}$ transition makes a definite contribution to the registered L_α radiation. In normal fields, however, the amplitude of such a transition is of the order of 0.1, so that the correction to the measured intensity does not exceed 0.01. Under real conditions this quantity is even smaller, since the frequency of the transition to the $2p_{3/2}$ level is approximately 10 times the frequency of the $2s_{1/2} - 2p_{1/2}$ transition. The corresponding estimates show that in the region of normal fields in the employed interferometer systems, the non-adiabaticity condition is satisfactorily fulfilled only for the $2p_{1/2}$ level but not for the $2p_{3/2}$ level.

The observed $I_{2p}(T)$ interference pattern comprises a superposition of curves pertaining to transitions to both the $2p_{1/2}$ and the $2p_{3/2}$ levels. Under the conditions in question, the oscillations of the latter curves will have a frequency $\nu_f/\delta \sim 10$ times larger and an amplitude not exceeding 0.01 of the amplitude corresponding to the transition to the $2p_{1/2}$ level. Thus, the influence of the transitions on the $2p_{3/2}$ level in the region of normal fields can be eliminated in principle, or at least considerably decreased by drawing a certain averaged curve through the experimental points.

The presence of the $2p_{3/2}$ level produces also another more important effect, due to the mutual perturbation of states with equal n but different l of a hydrogen atom situated in an electric field. As a result, the presence of the $2s_{1/2} - 2p_{3/2}$ transition changes the Stark splitting of the $2s_{1/2} - 2p_{1/2}$ levels. A calculation of the corresponding correction shows that it is likewise of the order of 0.01, but since this correction enters in the phase shift, its effect is more noticeable. At large times of flight, this circumstance necessitates a phase correction of the order of unity, which must be taken into account in the derivation of the $I_{2p}(E, T)$ relation.

The solution of the problem for the simplest interferometer variant (Fig. 4) is also made complicated by the fact that the field E can be specified only with a certain approximation, both in the central region between the electrodes and on the edges, where the slits for the beam passage exert their influence. In addition, if the $I_{2p}(E)$ is determined in the experiment, the analysis of the obtained data is made difficult by the fact that an increasing field brings about not only an increase in the influence of the edge effect but also an increase in the amplitude of the transition to the $2p_{3/2}$ level, the contribution of which reaches 0.1 at E ~ 600 V/cm. In this respect, it is more convenient to determine $I_{2p}(T)$ at a constant value of E, since the boundary conditions change much less when the distance between electrodes is varied than when the field intensity is varied. Estimates show that the characteristics of the field remain constant in this case accurate to d^2/l^2, where d is the width of the boundary region and l is the distance between electrodes. The best results (in the sense of the accuracy with which the Lamb shift is determined) can be obtained by introducing into the expression for $I_{2p}(E, T)$ parameters that represent the aggregate of the field characteristics. The approximate expression for the dependence of the yield of the H_{2p} atoms on the flight path l in a field of intensity E can then be represented by

$$I(l) = e^{-l/2l_0}\sum_{i=1}^{3} c_i\left[\operatorname{ch}\left(\mu_i \frac{l}{2l_0}+\gamma_i\right)+\cos\left(\lambda_i\frac{2\pi\delta l\tau}{l_0}+\alpha_i\right)\right], \qquad (2)$$

where

$$\lambda_i(x, \xi_i) = \left\{(1+\xi_i)^2 + x^2\left[1-\frac{\delta}{\nu_f}(1+\xi_i)\right.\right.$$

$$-\frac{1}{4}\left(\frac{\delta}{\nu_f}\right)^2 x^2-(4(2\pi\delta\tau)^2(1+x^2))^{-1}\Big]\Big\}^{1/2},$$

$$\mu_i(x,\xi_i)=\frac{1+\xi_i-\delta x^2/2\nu_f}{\lambda_i(x,\xi_i)},$$

c_i, γ_i, and α_i are parameters that depend on the field, τ is the lifetime of the H_{2p} atom, v is the velocity of the atoms, $l_0 = v\tau$, $\xi_1 = -{}^{10}\!/_3\, v/\delta$, $\xi_2 = 2\nu/\delta$, $\xi_3 = {}^2\!/_3\, \nu/\delta$, $x = {}^1\!/_{238.7} E$ (V/cm), δ is the Lamb shift, ν_f is the frequency of the fine splitting, and ν is the hyperfine splitting frequency.

The functions λ_i and μ_i, as well as the parameters c_i, γ_i, and α_i, pertain to individual curve components connected with the hyperfine structures of the levels $2s_{1/2}$ and $2p_{1/2}$.

The theoretical curve determined by (2) is fitted to the experimental points by selecting the parameters, which may include the frequencies δ, ν, and ν_f (or one of them, say the Lamb shift, if the others are assumed specified). To decrease the number of parameters, expression (2) can be reduced to a form that includes in place of the three parameters c_i, γ_i, and α_i only two parameters, $a_i = 2c_i \cosh \gamma_i$ and $b_i = 2c_i \cos \alpha_i$. The experimental $I(l)$ comparison curve can also be reduced to this form.

In addition to the foregoing factors, the accuracy with which δ is determined depends on the accuracy with which E and v are measured. In the described experiments, the error in the determination of E by measuring the voltage U and the distance l did not exceed 6×10^{-5}. v was measured with accuracy not lower than 10^{-4}.

The Lamb shift determined in the considered simplest variant of the experiment by averaging 12 independent measurements is $\delta = 1058.3 \pm 0.04$ MHz. The error equals one standard deviation.

This result is somewhat higher than the value that should presently be regarded as the most reliable ($\delta_{exp} = 1057.9 \pm 0.1$ MHz[3], $\delta_{theor} = 1057.91 \pm 0.16$ MHz[4]). The reason for the difference is that δ was determined from the approximate expression (2). This is equivalent to introducing a certain systematic error. At the same time, the small value of the standard deviation obtained from 12 measurements shows that the apparatus is stable and has sufficiently good measuring characteristics.

8. CONCLUSION

The observed phenomena allow us to speak of "optics of atomic states" (more accurately, of a certain analog of ordinary optics) which, in addition to its fundamental aspects, is of interest because the "atomic interferometer" considered here can be used to develop a method for determining the Lamb shift and the frequencies of the fine and hyperfine splitting of the hydrogen and deuterium atom levels.

The following circumstance must be noted, however. There is a definite optimal relation between the character of the performed experiment and the procedure for reducing the data. This relation depends on the accuracy with which the final results must be obtained. It turns out that in the case when the Lamb shift is to be determined with an error not exceeding 10^{-5} this relation can not be satisfied by using the simple interferometer shown in Fig. 4. Although the functions $I_{2p}(T)$ and $I_{2p}(E)$ contain all the information on the structure of the H-atom levels with n = 2, it is practically impossible to extract this information with accuracy to 10^{-5}. Nonetheless, it follows from the experience gained from working with various types of interferometers, that there exist relatively simple methods of reducing the error in the determination of δ. A detailed theoretical analysis by V. P. Yavkovlev has shown that the limitations imposed mainly by the uncertainty of the characteristics of the field E and the complicated behavior of the atom in it can be completely eliminated by modifying the geometry of the interferometer electrodes. The most rational is an interferometer consisting of two independent active zones separated by a variable distance l that determines the time of flight. Such active zones may be two parallel-plate capacitors with slits for the passage of the beam. Since the field is equal to zero over the length l, the eigenstates in this region will be $2s_{1/2}$ and $2p_{1/2}$. In this case the problem of determining $I_{2p}(E, T)$ has an exact solution that takes into account the influence of the $2p_{3/2}$ level at all values of the field E. Further appreciable simplification of the data reduction can be attained by eliminating the $2s_{1/2}$ components with F = 1 from the beam, using one of the existing methods[15]. The observed effect will then be due only to the transition $2s_{1/2}$ (F = 0, $F_z = 0$) $\rightarrow 2p_{1/2}$ (F = 1, $F_z = 0$), thus reducing to a minimum the number of unknown parameters when fitting the theoretical curve to the experimental one.

Besides the exact determination of δ and ν, i.e., problems of pure metrological character, particular interest attaches to a comparison of experiment with theory in the case of interference that develops in a large phase-shift interval, when the most subtle properties of the atomic levels can come into play.

Experimental procedures based on the use of "parallel" beams of neutral atoms and non-adiabatic field make it possible to observe the time behavior of a superposition of states produced after the atoms leave the region of the field E (the idea of such an experiment was proposed by V. M. Galitskiĭ). A superposition including 2s and 2p components was observed at distances up to 200 cm from the point of its occurrence (i.e., up to flight times on the order of 10^{-6} sec). In spite of the fact that the 2p component should attenuate completely over such distances, careful measurements have revealed weak L_α radiation of the beam, clearly connected with the action of the non-adiabatic field on the H_{2S} atoms. The origin of this radiation could not be attributed to any trivial causes, but the possible influence of the latter cannot be completely refuted on the basis of the performed experiments. A new procedure must be developed to explain the nature of the described effect.

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[1] B. N. Taylor, W. H. Parker and D. N. Langenberg, Rev. of Mod. Phys., 41, 375, 1969.

[2] S. J. Brodsky, SLAC-PUB-795, (TH) and (EXP), August 1970 (paper presented at International Conference on Exact Measurements and Fudnamental Constant), National Bureau of Standards, Gaithersburg, Md., August, 1970).

[3] R. T. Robiscoe and T. W. Shyn, Phys. Rev. Lett. **24**, 559, 1970.

[4] T. Appelquist and S. J. Brodsky, Phys. Rev. Lett. **24**, 562, 1970.

[5] Yu. L. Sokolov, ZhETF Pis. Red. **11**, 524 (1970) [JETP Lett. **11**, 359 (1970)].

[6] B. W. Series, Phys. Rev. **136**, A684, 1964.

[7] E. B. Aleksandrov, Opt. Spektr. **16**, 377 (1964).

[8] T. Hadeishi, Phys. Rev. Lett. **21**, 957, 1968.

[9] C. W. Fabjan and F. M. Pipkin, Phys. Rev. Lett. **36A**, 69, 1971.

[10] B. L. Donnally et al., Phys. Rev. Lett. **12**, 502, 1964.

[11] W. V. Houston, Phys. Rev. **51**, 446, 1937.

[12] R. C. Williams, Phys. Rev. **54**, 558, 1938.

[13] A. C. Riviere and D. R. Sweetman, Phys. Rev. Lett. **5**, 560, 1960.

[14] A. Pais and O. Piccioni, Phys. Rev. **100**, 1487, 1955.

[15] B. L. Donnally, Lamb shift sources, Proc. of the III-d Intern. symposium on the polarisation phenomena in nuclear reactions, Madison, 1971, p. 295.

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