Atomic Interferometer and Coherent Mixing of 2S and 2P States in the Hydrogen Atom

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Abstract. New direct observation data on the $2S$–$2P$ atomic states coherent mixing upon hydrogen atoms passage through a metal-wall slit are presented. The experimental results are interpreted in terms of atomic states interference.

1 Atomic interferometer method

A comprehensive analysis of the experiments on the measurements of the hydrogen atom state parameters (e.g. the Lamb shift) has shown, that the accuracy of such measurements can be greatly improved by observing the interference of the $2S$ or $2P$-state of the hydrogen atom with an interferometer similar to the two-beam optical one. Several feasible schemes of such a device have been considered and this is what came of it Fig. 1 .

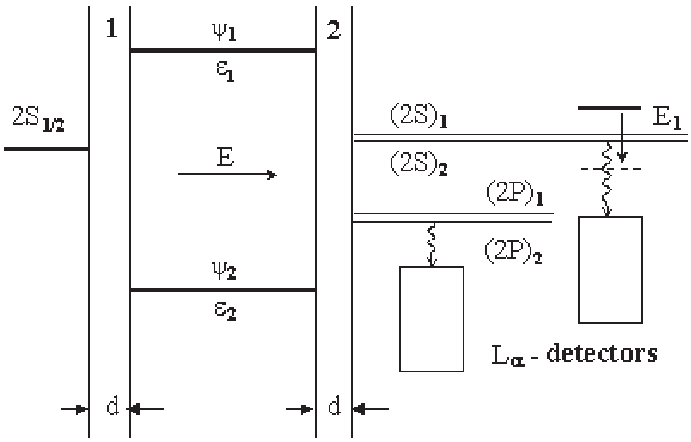

Fig. 1. Principle diagram of the atomic interferometer

Imagine a beam of metastable hydrogen atoms passing through an electric field E that is nonadiabatically terminated at the boundaries. The criterion of nonadiabaticity is the condition that the flight frequency $\omega = v/d$ (where v is the velocity of atom and d is the width of the region where the field grows or decreases) should be greater or of the order of the Lamb frequency (for the transition $2S_{1/2}$–$2P_{1/2}$), or the fine-structure splitting frequency (for the transition $2S_{1/2}$–$2P_{3/2}$).

After crossing the boundary I the atoms pass into the superposition of eigenstates ϕ_1 and ϕ_2 with the energies ϵ_1 and ϵ_2 determined by the magnitude of the field E. On boundary II, where the field wanes to zero, components of the beam arise that represent both the state $2S$ and the state $2P$, and each of terms ϕ_1 and ϕ_2 gives rise to a pair of such states: $(2S)_1$–$(2S)_2$ and $(2P)_1$–$(2P)_2$.

Leaving the field, the amplitudes of $2S$ and $2P$ eigenstates will be determined by the amplitudes of transitions and the phase difference between the components of each pair. This difference depends on the time of flight in the field and on the frequency of transition between the terms ϕ_1 and ϕ_2 split by the electric field. Since the magnitude of such a splitting depends wholly on the field strength, its monotone variation will give rise to periodic oscillations (in counterphase) of the intensity of $2S$ and $2P$ fluxes in the outgoing beam, caused by the interference between $2S$ and $2P$ components. A similar pattern will be observed if the time of flight is gradually varied by changing the distance L.

An interferometer based on this principle is rather similar to the two-beam optical one, where any individual photon interferes with itself. In our case, the $2S$ or $2P$ state interferes with itself. The interference is due to the fact that the resulting amplitudes of these states contain contributions caused by the evolution along different paths – ϕ_1 or ϕ_2, which gives rise to the phase difference. The second channel ϕ_2 arises because the electric field plays the role of semitransparent mirror splitting the paths of evolution. It mixes the states with opposite parity and in such a way initial state $2S$ gets a coherent admixture of the $2P$ state. It will be wrong to view the situation in such a way, that the eigenstates $2S$ and $2P$ are composed of $(2S)_1$–$(2S)_2$ and $(2P)_1$–$(2P)_2$-components–in reality they do not exist–and only serve to facilitate the understanding of the processes inside the interferometer.

To forestall misinterpretation of Fig. 1, we ought to point out that the “components” $(2S)_1$ and $(2S)_2$ have the same energy as do the “components” $(2P)_1$ and $(2P)_2$. There is no separation of the trajectories of $2S$ and $2P$ states either inside or outside the interferometer.

To simplify the analysis at the initial qualitative stage we can consider the two-level system $2S_{1/2}$–$2P_{1/2}$, that is justified for fields that are not too strong; the effect of the $2P_{3/2}$-level can be taken into account by small corrections.

If we set $x = \langle d\rangle E/(\pi h\delta)$, where $\langle d\rangle$ is the matrix element of the $2S$–$2P$ transition, E is the field strength, and δ is the Lamb shift, than the yield of $2P$ atoms is proportional to the quantity:

$$W(E,T) = \exp\left(-\frac{\gamma T}{2}\right)\frac{x^2}{1+x^2}\left[\cosh\left(\frac{\gamma T}{2\sqrt{1+x^2}}\right) - \cos\left(2\pi T\delta\sqrt{1+x^2}\right)\right],$$

where T is the time of flight, γ is the decay constant of $2P$-state (the hyperfine splitting is not taken into account).

The interference pattern of the $2P$-state can be registered by measuring the flux of L_α-quanta that result from the radiative deexcitation of the short-lived

$2P$ atoms. The interference of the $2S$ state is recorded with the aid of a quenching field E_1.

The simplest version of the atomic interferometer consists of two electrodes with the slits for passing the beam, separated with the variable gap L. For Lamb shift measurement corresponding interferometer is made of two two-electrode systems with longitudinal electric fields, mixing $2S$ and $2P$-states. The systems were separated with a field-free gap of variable length L. This implies, that it is possible to write an exact expression for the probability $W(L)_{E_1,E_2}$ of the yield I_{2P} of $2P$-atoms from the double system and determine, by processing the experimental dependence $I_{2P}(L)$, the Lamb shift value δ.

Important advantage of this method consists in the default of distortion of the theoretical dependence $W(L)$, produced by various physical factors, resulting in appearance of systematic errors. Result, obtained with the atomic interferometer: $(H, n = 2) = 1957.8514(19)$ MHz [1].

In a two-electrode interferometer the yield of $2P$-atoms is independent of the field sign, provided that only the atoms in the pure $2S$-state get into that field. If, however, the initial wave function is a superposition of states with different parity ($2S$ and $2P$), then the yields for the opposite signs of the field will be different.

There were experiments, when we had all grounds to assume that the atoms enter the interferometer in the pure $2S$-state. However, the experiments revealed that the yield of $2P$-atoms depends on the direction of the field–the interference curves were not the same for opposite directions of the field.

Now the question is, what is the cause of dissimilarity of interference curves, when the field is reversed? The observed asymmetry of the $2P$-atoms yield with respect to the field inversion indicates, that before the interaction with the interferometer field E, the atom possess an initial coherence between $2S$ and $2P$ states. Thoroughly performed experiments have shown, that such a coherence appears due to the interaction between the atoms and metallic slit walls. In other words, $2S$-atom, flying over a metal surface, acquires a coherent admixture of $2P$ state as a result of some interaction.

It is not so much the interaction itself which is stunning, but the immense distance over which it occurs–up to 0.7 mm.

All attempts to explain the observed effect by the force interaction of an excited atom with a metal surface failed, since the relevant contributions were orders of magnitude smaller than those observed.

A possible explanation of the production of the ($2S$–$2P$) superposition is based on the assumption that there are electric charges on the metal surface creating the electric field, that mixes $2S$ and $2P$ states. To refute such arguments a series of experiments had been executed in conditions when the influence of any stray fields inside the interferometer was completely excluded [2]. It appeared however, that all taken measures were unable to annihilate the observed long-distant interaction effect. At last we had to conclude that we were dealing with some kind of previously unknown long-range interaction. Further experiments confirmed such an assumption.

One of them–the simplest one and at the same time giving the opportunity of unequivocal interpretation is shown in Fig. 2. The ($H_{1S} + H_{2S}$)-beam with energy 22 keV, passes successively through the flat capacitor with transverse electric field E_q quenching, if it is necessary, $2S$-atoms and then through two metal slits 1 and 2 separated by a variable gap L, that can be changed in limits from 0 up to 15 mm. The slit 1, 0.05 mm wide , plays simultaneously the role of a collimator. Width of the slit 2 is 0.5 mm. L_α-quanta, appearing due to the deexcitation of $2P$-atoms, are registered by detector placed behind the slit 2 at a constant distance.

The results of such an experiment (number of L_α-counts as a function of distance L) are shown in Fig. 3.

If the quenching field E_q is put off, that is the $2S$-atoms pass through the slit system, distinct intensity oscillations of the $2P$-atom flux are observed, that is the interference of this state (curve run 1 in Fig. 3. On contrary, when $2S$-atoms are removed from the beam (quenching field is put on), $2P$ intensity oscillations disappear completely–curve run 2 . This curve is the sum of exponential decay curves of excited H-atoms with $n = 2, 3, \ldots$ arising due to collisions of the H_{1S}-beam with the collimator walls. Subtracting the background curve run 2 from the curve run 1, we get the pure interference pattern (Fig. 4).

The picture observed could arise only under following conditions: in the slit 1, owing to the interaction of $2S$-atoms with its metallic walls, coherent mixing of $2S$ and $2P$ states occurs, that is the formation of $2S$-$2P$ superposition. In the second slit, under the influence of similar interaction, the additional coherent mixing of these states takes place, and owing to that, with change of the distance L, oscillations of the $2P$-component intensity are observed. It should be emphasized–such an interference pattern can arise only due to considered mechanism–any other reasons cannot cause it.

This effect has been thoroughly investigated in numerous experiments that result in the following conclusion: the interaction of the excited hydrogen atom with a metal surface has a specific nature and only phenomenologically can be

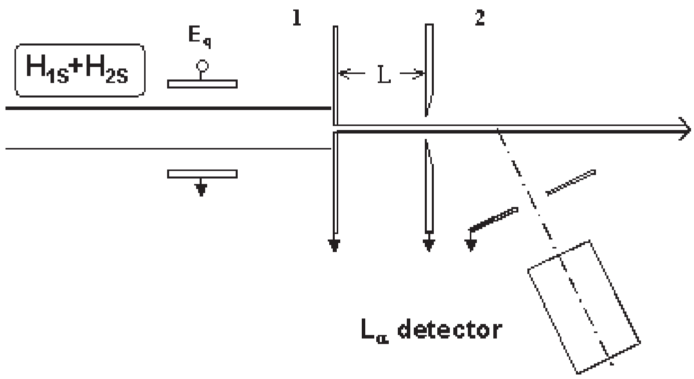

Fig. 2. The simplest version of the interference experiment

described to the action of some effective electric field E_{eff}. This field is not a real physical field and consequently cannot be registered by any macroscopic device.

An explanation of the effect nature, compatible with the experimental data, was proposed by B. Kadomtsev [3]. It is based on assumption, that the atom, flying over the metal surface, interacts with the conductive electrons and holes in a thin surface layer . This results in an entangled state of the atom with a huge number of electrons and holes. Such an interaction gives rise to appearance a coherent admixture of the $2P$-state to initial state $2S$. The amount of this addition from each individual electron is infinitesimally small, but the net effect is observable because of great number of electrons. Thus, according to Kadomtsev, the effect observed is due to coherent superposition of EPR-interactions, and ought to be considered in terms of correlations (like Pauli-principle) rather than in terms of forces.

But, unfortunately, this theory had not been completed. Professor Kadomtsev untimely died two years ago.

Nevertheless, his hypothesis, even in its present form, allows for some quantitative comparisons between experimental results and theoretical predictions. First of all, experiments were implemented to determine the strength and direction of the effective field E_{eff} with respect to the direction of the atom velocity. For this purpose the system with longitudinal (that is. parallel or antiparallel to the atom velocity vector) electric field was installed. If the electrodes, creating the field are shortened and grounded, then, with change of distance L, distinct $2P$-interference pattern is observed, produced by the field E_{eff} . With presence of an external electric field coinciding with the velocity direction, the amplitude of beets is increased, and the character of the interference curve testifies coincidence of the phases of beets caused by the external field and the field E_{eff} .

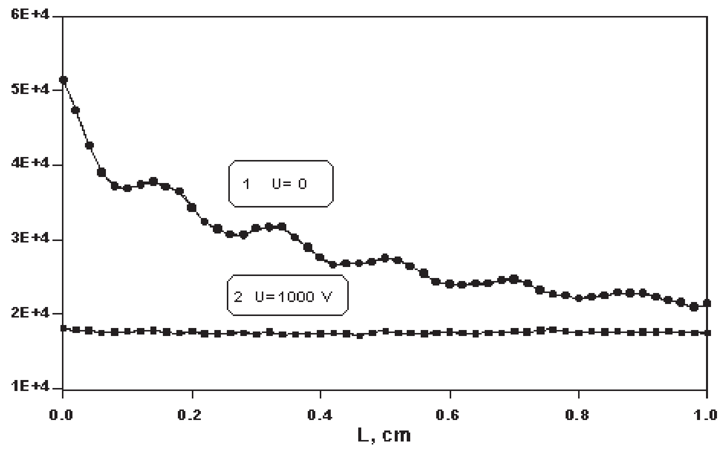

Fig. 3. The result of the simplest experiment

In case of opposite direction of the field the amplitude of beets is decreased and the mismatch of phases occurs. The processing of data obtained shows, that the direction of the field E_{eff} coincides with the direction of the atom velocity, as it follows from the Kadomtsev's theory and its intensity (for the used geometry of slits) is equal to 4.6 V/cm. Such a value is also in satisfactory agreement with Kadomtsev's prediction.

Besides, an experiment with a single slit with the variable width (0.2–1.8 mm) was implemented to verify the theoretical dependence of the effect scale on the distance between atoms and metal surface. The slit was formed by two rectangular plates 0.7mm thick. The results obtained show a satisfactory agreement with theory. If the slit is formed by two sharp edges, the dependence $I_{2P}(L)$ becomes exponential and simply reduces to $\exp(-2\pi L/\Delta_L)$, where $\Delta_L = v/f_\delta$ (v is the atom velocity, f_δ is the Lamb frequency). The "Lamb wavelength" Δ_L, that is the period of spatial oscillations of the interference curve, is immense on the atomic scale and does not involve any characteristic of the metal surface. Hence it follows that the observed effect is indeed a long range interaction and is a universal phenomenon.

While the period of the interference curve does not depend on the properties of a metal surface, the magnitude of effect, that is the amplitude of the interference curve, can reveal a strong dependence of such a kind. Indeed, Kadomtsev's theory is based on the assumption, that the atom interacts with quasi-free electrons in the thin surface layer. Therefore, the state of such electrons must be tightly connected with the properties of such a layer–for instance its temperature and crystal structure.

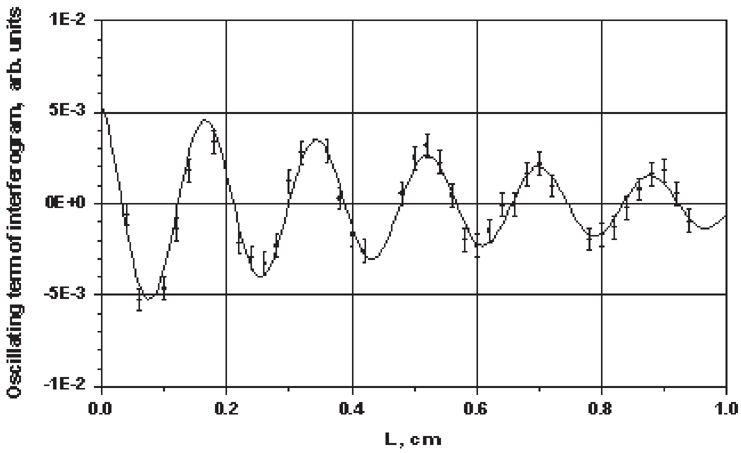

Fig. 4. Interference of the 2p-state

2 Discussions

Two types of experiments have been performed. In both of them, the controlled superposition of the $2S$ and $2P$ states induced by a longitudinal (along the atom velocity) electric field, passes subsequently through a slit in a grounded metal plate separated from the field area by a varying distance L (analogous to the experiment shown in Fig. 2). An additional coherent mixing of the states due to passage through the slit results in the L-dependent interference pattern in the output yield of $2P$-atoms.

The first series of experiments was devoted to determination of the effect scale on the slit temperature. In the second series of experiments we used the slits formed by massive plates of gold-silver alloy and pure palladium, varying considerably their microstructure. Namely, they were initially highly cold-hardened samples and later on the ones annealed at the recrystallisation temperature. In other words, we deal with either fine-grained or coarse-grained metal surfaces.

The main result is that for both metals the mixing amplitude displays a severalfold, by the factor of 5–7, increasing after annealing . Indeed, it is highly likely that such a phenomenon points to the strong dependence of the effect scale on the state of conductive electrons.

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