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Are quantum wave packets observable? Sokolov effect: puzzling generation of 2p states in the 2s hydrogen beam passing trough a wide metal slit

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Abstract. The observation of excitation of $2p$ states in a collimated $2s$ hydrogen beam passing through a wide metal slit with no direct contacts or electric field applied (Sokolov effect) up to now has had no reasonable explanation. A solution presented in this paper is formulated within the standard quantum-mechanical framework with a consecutive wave packet treatment of the atomic center-of-mass wave function. It is found that a very weak interaction of the beam diffraction halo with the slit, though negligible for center-of-mass motion, coherently affects the intrinsic state of an atom in the beam and efficiently induces $2s \rightarrow 2p$ transitions. High sensitivity of this interference phenomena may be used to measure transverse coherence length of the beam.

PACS. 03.65.-w Quantum mechanics

1 Introduction

The first excited doublet $2s_{1/2} - 2p_{1/2}$ states of the hydrogen atom are almost degenerate with the splitting, Lamb shift, $\sim 4 \times 10^{-6}$ eV, but their lifetimes, $\tau_s \simeq 1/8$ s and $\tau_p \simeq 1.6 \times 10^{-9}$ s, differ by a factor of $\sim 10^8$.

Therefore, the excited hydrogen becomes very quickly cleaned from all excited states except $2s$. One of effective way to get an excited hydrogen beam is by electron exchange of the proton beam on gaseous target. The probability of this reaction has maximum at atomic velocity, which corresponds to the kinetic atomic energy near 20 keV. Just those typical beams will be considered in this paper. For such a beam, decay length for $2p$ state is near 3 mm, and after a few centimeters, the beam contains only $1s$ and $2s$ atoms.

In the presence of an external electric field the new eigenstates $|1\rangle$ and $|2\rangle$ are the superpositions of the $|2s\rangle$ and $|2p\rangle$ atomic states. When the beam in the $|2s\rangle$ state non-adiabatically enters the field area it transforms into a combination of $|1\rangle$ and $|2\rangle$. When, after a time interval, the beam leaves the field area, the phases of the $|1\rangle$ and $|2\rangle$ components are different due to their different energies, and they are recombined not back into $|2s\rangle$ but into a superposition of $|2s\rangle$ and $|2p\rangle$. The coefficients in this superposition depend periodically on the phases of the states $|1\rangle$ and $|2\rangle$, *i.e.* the time spent in the electric field and/or field strength. Therefore, a charged capacitor is acting on the hydrogen beam as a typical interferometer (beam splitting — phase shift — beam recombination). The difference from common interferometers is that the beam splitting is not in space but in energy. Interference pattern can be rather simply measured by intensity of Lyman-α photons from $2p \rightarrow 1s$ decays.

With a widespread interest in quantum properties of matter beams, the hydrogen atom seems to be the best candidate for experiments in atomic interferometry. The main obstacle is the very short decay length of the $2p$ state, that requires very precise and miniature equipment. The first successful and so far unique H-atom interferometer was constructed at the Kurchatov Institute by Sokolov [1], where the central interferometer unit is a charged plane capacitor with the slits in its plates for the beam to go through. The width of the slits, a few hundred microns, is much larger than beam width, a few dozen microns. Experiments with this interferometer lead, in particular, to high precision hyperfine structure and Lamb shift measurements [2,3]. But the most interesting, unexpected and puzzling are paradoxical results, which might be explained by an unknown "long-range atom-metal-surface interaction" [13], and was nicknamed as "Sokolov effect" [7]. Just this "paradoxical" experimental results will be the object of this paper.

2 What paradoxical is in experimental results?

The convincing evidence of the effect was obtained with a double interferometer. The scheme is simple: a well

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collimated $2s$ hydrogen beam passes sequentially through the slits of the two capacitor-interferometers separated by the distance L. The electric field in each capacitor is fixed, but the $2p$ amplitudes created in both capacitors interfere. Due to the L-dependent phase difference, an interference pattern, with many periods, is seen when one changes the inter-capacitor distance L. This part of experiment is in agreement with the theory.

A "paradoxical" part of the experiments [4,5,13] comes with the fact that the interference pattern in the $2p$ decay intensity is also seen (though with a lower amplitudes) when the field in the second capacitor is absent and even if the capacitor is replaced by an uncharged metal plate with a wide (compared to the beam size) slit. The effect is present even in the simple scheme without a field, with only a collimator and a slit. What might be an origin of this "Sokolov effect"?

Since even a well collimated beam inevitably has a continuous diffraction halo that can overlap the slit matter, one might consider a direct collision-like contact of the atom with the slit resulting in the $2s \to 2p$ transition. For the slit in an infinitely thin plate, the atom would bounce after such a collision. But for a real slit in a thick plate, the forward scattering is possible from the impact of the atom on the inner walls of the slit. Similar to inelastic collisions, this channel for the $2s \to 2p$ transition goes through the reduction of the wave function, and the phases of the $2p$ amplitudes for different atoms would be uncorrelated. This path may yield only a stochastic background rather than a steady interference pattern possible for a smooth average field acting on each atom passing through the slit. So, one should look for a smooth, electric field like potential, acting on the atom during the passage through the slit.

The first candidate could be induced or intrinsic electric field of the metal. Analysis is the most transparent in the rest frame of the hydrogen atom, where the problem is reduced to the interaction of the atom with a moving nearby uncharged metal surface of the slit. In linear approximation in the field $\mathbf{E}(t)$ the admixture of $2p$ state is given by

$$b_p = \frac{|e|}{\mathrm{i}\hbar} \langle 2p \,|\, \mathbf{r} \,|2s\rangle \int_{-\infty}^{\infty} \mathbf{E}\,(t) \exp\left(-\mathrm{i}\Delta t\right) \mathrm{d}t, \qquad (1)$$

where 2Δ is the Lamb shift.

Estimates of possible electric fields (from mirror image charges of the atom, structural non-uniformities in the metal, etc.) give values by many orders of magnitude lower than needed. The only explanation suggested so far was based on an exotic "EPR-correlation" of the atom with each electron of the metal [6,7].

The quantum-mechanical solution for the "Sokolov effect" presented in this paper utilizes the atom-surface contact interaction acting on the halo tails of the atom wave packet. As will be shown, this very weak interaction, being negligible for center-of-mass motion, coherently affects the intrinsic state of every atom and efficiently induces $2s \to 2p$ transitions.

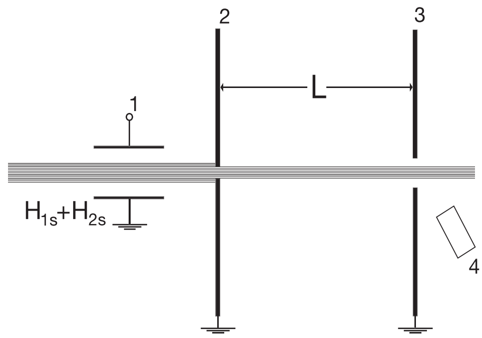

Fig. 1. Scheme of experimental layout. A monochromatic hydrogen beam with $1s$ and $2s$ atoms passed a collimator (2) and then enter more wider slit (3). Decays of created $2p$ states measured by detector (4). For the control, $2s$ states may be eliminated from the beam by switching-on the quenching field (1).

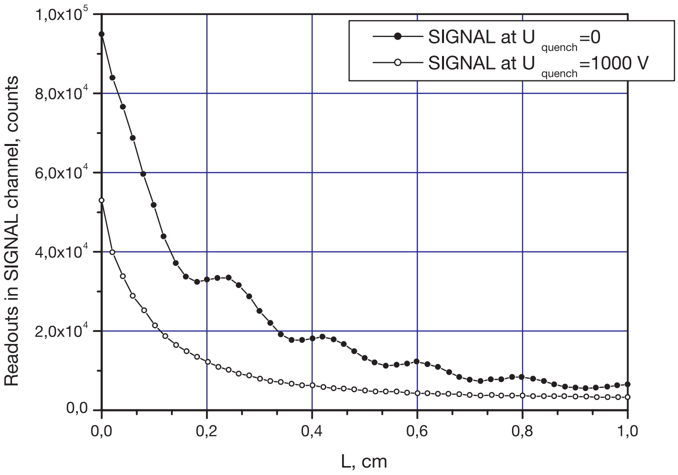

Fig. 2. Example of readouts from experimental setup in Figure 1. Decays of $2p$ states, measured behind the slit as the function of the distance between the collimator and the slit. The beam before the collimator has $1s + 2s$ (black circles) or pure $1s$ (open circles).

To be more specific, we consider the set-up and the main parameters for one of the actual simple-scheme experiments [1]. A monochromatic (energy near 20 keV, velocity $V = 2 \times 10^6$ m/s) beam of hydrogen $1s + 2s$ atoms goes through a narrow collimator slit 0.06×2.0 mm^2 and, after a variable distance L ($0 < L < 20$ mm) is directed through the second, wider, slit 0.2×4.0 mm^2 strictly in the center, without any observable contact with the slit matter (Fig. 1). The intensity of $2p \to 1s$ decays, measured behind the second slit as a function of L, shows exponentially decreasing interference fringes (Fig. 2). At $L \simeq 20$ mm, where the fringes are not seen, the ratio of $2p$ and $2s$ amplitudes is of the order of 10^{-4}.

3 Beam shape and atomic wave function after the collimator

An atomic beam is often described by a wave function. In fact, only a pure quantum state, or a coherent superposition of them can be described by a wave function. An atomic beam, whose origin is a thermal source, can have coherence only inside single atom packets, while the packets of different atoms do not interfere. The wave function of the whole beam can be formally presented as a random superposition of single-atom coherent packets. In contrast to the beam shape, a directly measurable quantity, the shape and the size of the single-atom packets can be estimated only by atomic interferometry. Numerous split — phase shift — recombine experiments in atom optics [8,9] are sensitive only to the longitudinal coherence. Two-slit diffraction is governed by transverse coherence length, but may give only rough estimates for its value. For what follows, we need a definite assumption on the size of single atom packet. For a well collimated beam with monochromaticity broken only by a finite transverse size, it is reasonable to assume that single-atom packets occupy the whole transverse size of the beam. This assumption is not a principled one. Moreover, one of the results of the paper is just the suggestion how to measure this quantity.

In our case the wave function for the hydrogen atom in the beam can be written as a product of the intrinsic atomic function $\Phi^0(\mathbf{r})$ and that for center-of-mass motion, $\Psi^0_{\mathrm{c.m.}}(\mathbf{R})$. For the intrinsic function we may omit the main $1s$ component and write down a superposition of $2s$ and $2p$ states

$$\Phi^0(\mathbf{r},t) = a_s\phi_s(\mathbf{r}) + a_p\phi_p(\mathbf{r})\exp[2\mathrm{i}\Delta t - t/(2\tau)], \qquad (2)$$

where $2s$ state is assumed to be stable and energies are measured from the $2s$ level. For the center-of-mass function one may write

$$\Psi^0_{\mathrm{c.m.}}(\mathbf{R}) = \Psi^0_{\parallel}(Z)\,\Psi^0_{\perp}(\mathbf{R}_\perp), \qquad (3)$$

where $|\Psi^0_\perp|^2$ is supposed to reproduce the transverse density of the beam. The shape of the transverse packet, $\Psi^0_\perp(\mathbf{R}_\perp)$, is a result of the interaction of the initial beam with collimator slit matter and a consequent spreading. Dynamics of this process seem too complicated for a rigorous theoretical description but we may use simple models and experimental hints.

In an analogy with atomic lithography, the transverse cross section of the beam behind the slit can be treated as a geometric optical image of the slit distorted by diffraction on both sides of a shadow boundary. For the parameters of our problem, diffraction is of the Fresnel type,

$$Kl^2/L \gg 1, \qquad (4)$$

where K is the center-of-mass wave vector, l the slit size and L the distance between the slit and its image (in our case, between the collimator and the slit). Distortions on the light-shadow boundary, fringes on the light side and continuously decreasing tails on the dark side, are described by the well-known Fresnel integrals [10]. In the asymptotic region, where the distance from the shadow boundary $\delta \gg \sqrt{L/K}$, the intensity of the beam is inversely proportional to δ^2,

$$|\Psi_\perp|^2 \approx I_0\frac{L}{\pi K\delta^2}, \qquad (5)$$

where I_0 is the intensity in the center of the beam [10]; the coefficient for the matter wave in (5) is twice as large as that for light waves due to the different dispersion $\omega(\mathbf{k})$. A real slit is not perfect for the atomic de Broglie wavelength $\sim 10^{-13}$ m, and diffraction fringes may be partly washed out, but we shall use only the asymptotic estimate (5) which will be still valid for real slits. In fact, the shape and coherence of the packet may change with time due to random perturbations, as collisions with residual gas in vacuum chamber. These effects, though not expected to be significant, may require numerical corrections for comparison with experiments.

4 Coherent interaction of the beam with a wide slit

The problem may be formulated as a Schrödinger equation

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\Psi(\mathbf{R},\mathbf{r},t) = [H_{\mathrm{c.m.}} + H_h + U(\mathbf{R},\mathbf{r})]\Psi(\mathbf{R},\mathbf{r},t), \qquad (6)$$

where an interaction of the slit matter with center-of-mass motion and the hydrogen electron, $U(\mathbf{R},\mathbf{r})$, is added to the free Hamiltonian of the atom in the beam.

Generally, the atom-surface interaction can be described by a potential only near the surface. The passage through the matter accompanied by the medium ionization is a complicated process, semi phenomenologically described by Bethe-Bloch equation. In metal, the energy loss is mostly due to electron exchange between the atom and Fermi see of the metal. Evidently, this process breaks down the coherence of atomic intrinsic states. In our case, the atom interacts with the metal only by halo tails during the packet stream over the slit edge. This very weak interaction can not initiate electron transitions in the metal, its degrees of freedom do not come into play, and the atom-metal interaction can be reduced to the interaction of the atomic electron with electrons of the metal by a repulsive potential, which depends only on the distance from the atomic electron to the metal plane surface. (We may disregard a deviation from this dependence in a small area, of the order of Bohr radius, near the slit edge.)

The general features of atom-slit interaction, discussed above, can be qualitatively described by a model potential

$$U(\mathbf{R},\mathbf{r}) = U_0(Z + z - Z_0)\ S\,(\mathbf{R}_\perp)\,, \qquad (7)$$

where the variable $Z + z - Z_0$ corresponds to the distance from the electron to the metal surface, and geometrical factor, $S(\mathbf{R}_\perp)$, is zero for $\mathbf{R}_\perp$ inside the slit and one otherwise.

The impact can be viewed as the packet halo penetrates into a potential region up to the depth where the halo loses its longitudinal velocity and streamlines the slit edge. The details of this process supposed to be described by solution of the equation (6). But some general results may be obtained without an explicit solution.

The total loss of the atomic longitudinal momentum due to the passage through the slit can be estimated simply as the fraction of the total atom momentum transferred to the slit,

$$\delta P \approx -MV\Theta, \tag{8}$$

where Θ is the packet-slit overlap parameter,

$$\Theta = \int \left|\Psi_\perp^0(\mathbf{R}_\perp)\right|^2 S(\mathbf{R}_\perp)\, \mathrm{d}\mathbf{R}_\perp \tag{9}$$

defined with geometrical factor $S(\mathbf{R}_\perp)$, introduced in (7).

The natural assumption, that the potential range is much larger then Bohr radius, allows in the expansion

$$U_0(Z+z-Z_0) \approx U_0(Z-Z_0) + z\frac{\mathrm{d}}{\mathrm{d}Z}U_0(Z-Z_0) \tag{10}$$

to treat the last term as a small perturbation. This term may be neglected for the center-of-mass dynamics, but only this term provides a binding between the center-of-mass and the intrinsic motion. Thus, for the equation (6), one may use the approach similar to Born-Oppenheimer's for molecule: first, to find solution for the center-of-mass, neglecting the binding with intrinsic state, and then consider intrinsic dynamics caused by given center-of-mass motion. Intrinsic dynamics is natural to consider in the atom rest frame, where the center-of-mass function becomes time-dependent due to the moving slit ($Z_0 = Vt$) and is determined by the equation

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\Psi_{\text{c.m.}}(\mathbf{R},t) = [H_{\text{c.m.}} + U_0(Z-Vt)\; S(\mathbf{R}_\perp)]\Psi_{\text{c.m.}}(\mathbf{R},t). \tag{11}$$

Given solution $\Psi_{\text{c.m.}}(\mathbf{R},t)$, the equation for the intrinsic state can be represented as that for the atom in electric field:

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\Phi = [H_h + zG(t)]\,\Phi, \tag{12}$$

where

$$G(t) = \int \mathrm{d}\mathbf{R}\; |\Psi_{\text{c.m.}}(\mathbf{R},t)|^2\, S(\mathbf{R}_\perp)\,\frac{\mathrm{d}}{\mathrm{d}Z}U_0(Z-Vt). \tag{13}$$

The admixture of $2p$ state after the passage through the slit is easily obtained from (12). In approximation linear in $G(t)$ one has

$$b_p = \frac{1}{\mathrm{i}\hbar}\langle 2p\,|z|\,2s\rangle \int_{-\infty}^{\infty} G(t)\exp(-\mathrm{i}\Delta t)\,\mathrm{d}t. \tag{14}$$

This amplitude is similar to that generated by time-dependent longitudinal electric field (1). "Effective electric field" $G(t)$ can be, in principle, found from (13) and solution of the equation (11). In fact, the latter is not easy to solve, since the potential term, though small, is the only essential for the halo deformation and cannot be treated as small perturbation. Fortunately, we can estimate $G(t)$ by (8). From Heisenberg operator equation for momentum with the Hamiltonian from (11), one has

$$\mathrm{i}\hbar\frac{\mathrm{d}}{\mathrm{d}t}\hat{P}_z = \left[\hat{P}_z, H\right] = -\mathrm{i}\hbar S(\mathbf{R}_\perp)\,\frac{\mathrm{d}}{\mathrm{d}Z}U_0(Z-Vt). \tag{15}$$

Comparing (15) with (13), one may conclude that the following relation holds

$$G(t) = -\frac{\mathrm{d}}{\mathrm{d}t}\langle\Psi_{\text{c.m.}}|\,\hat{P}_z\,|\Psi_{\text{c.m.}}\rangle\,. \tag{16}$$

The depth of the halo penetration into the slit surface matter (and the width of $G(t)$, respectively) is, evidently, much less then Lamb phase variation length V/Δ (which is in our case near 0.3 mm). Therefore, in the integral (14), one may replace the exponent by unity. Then the integral from (16) gives the total loss of the longitudinal momentum. As a result we have

$$b_p = \frac{-1}{\mathrm{i}\hbar}\langle 2p\,|z|\,2s\rangle\,\delta P. \tag{17}$$

Using (8) for δP and value ξa_0 for the matrix element (numerical parameter $\xi = 3$ for nonrelativistic case, and $\xi = \sqrt{3}$ if selection is made for transition onto hyperfine component $2p$ ($F=1;\ F_z=0$)), one finds

$$b_p \approx \frac{1}{\mathrm{i}\hbar}\xi a_0 MV\Theta = -\mathrm{i}\xi\Theta\frac{M}{m}\frac{V}{v_{\text{at}}}, \tag{18}$$

where, in the last equality, electron mass, m, and atomic velocity, $v_{\text{at}} = e^2/\hbar$, are introduced to simplify numerical estimates.

To evaluate the overlap factor Θ, one can make use of equation (5). For long and narrow ("one-dimensional") slits with widths l_1 and l_2, respectively, the tail starts at $\pm l_1/2$ from the center of the beam and meats the wide slit from $\pm l_2/2$, and so the overlap starts from $\delta = (l_2 - l_1)/2$ and goes to infinity on both sides. With the intensity $I_0 = 1/l_1$, one has

$$\Theta \simeq \frac{L}{\pi K l_1} 2 \int_{(l_2-l_1)/2}^{\infty} \frac{\mathrm{d}\delta}{\delta^2} = \frac{4}{\pi K l_1}\frac{L}{(l_2-l_1)}\cdot \tag{19}$$

For our illustrative numerical parameters this gives $\Theta \sim 10^{-7}$; then equation (18) results in $b_p \sim 10^{-4}$.

When comparing with the experiment, one should take into account another, incoherent, channel for the $2p$ excitation which was discussed in Section 2. Being weak for a wide slit, this process can be important for narrow slits, in particular for the collimator. It plays a role of a background for the coherent effect. To clarify this point, we consider a simplified scheme mentioned in Section 2.

5 Schematic experiment: collimator and slit separated by the distance L

Let A_{1s}, and A_{2s} be the amplitudes of $1s$ and $2s$ components, respectively, in the beam before the collimator. There are several paths for atoms to finish with a non-zero $2p$ component after the slit. First, there is a pure coherent path with the final amplitude

$$A_{2s}\left(b_p^{(1)}\gamma \mathrm{e}^{\mathrm{i}\Delta(L/V)} + b_p^{(2)}\right), \tag{20}$$

where $b_p^{(1)}$ and $b_p^{(2)}$ are the coherent $2p$ admixtures to the $2s$ state due to the passing through the collimator and the slit, respectively, and γ is a damping factor,

$$\gamma = \exp(-(2V\tau)^{-1}L). \tag{21}$$

There exist also paths with incoherent interactions of the atom with the collimator (discussed in Sect. 2), when $1s$ is converted into $2s$ or $2p$ with probability amplitudes $\xi_s^{(1)}$ and $\xi_p^{(1)}$ and $2s$ goes into $2p$ with the amplitude η_p. The corresponding $2p$ admixtures on the slit are

$$A_{1s}\xi_s^{(1)}b_p^{(2)}; \quad A_{1s}\xi_p^{(1)}\gamma; \quad A_{2s}\eta_p^{(1)}\gamma, \tag{22}$$

where we have omitted phases.

The intensity of $2p$ decays is determined by the coherent sum of all $2p$ amplitudes (more precisely, the amplitudes $b_p^{(1,2)}$ should be added coherently while $\xi_{s,p}$ and η_p are to be considered as random quantities) and has the form

$$C + D\gamma^2 + 2B\gamma\cos\left(\frac{2\Delta}{V}L + \phi\right), \tag{23}$$

where the coefficients can be directly obtained from equations (20, 22). Making use of reasonable assumptions $A_{2s} \ll A_{1s}$; $b_p^{(2)} \ll 1$, one finds for the coefficients in (23)

$$B \simeq |A_{2s}|^2|b_p^{(1)}b_p^{(2)}|;$$
$$C \simeq |A_{1s}\xi_s^{(1)}b_p^{(2)}|^2; \quad D \simeq |A_{1s}\xi_p^{(1)}|^2. \tag{24}$$

The structure of (23) has experimentally observed form (Fig. 2), namely, oscillating term with the period $2\Delta L/V$ with the amplitude $\sim\gamma$, a term, proportional to γ^2 and L-independent term. The specific L-dependence in (23) allows us to extract the numerical values of the coefficients with the aid of the experimental curve. The only unknown function of L is $b_p^{(2)}$. The linear dependence, which follows from (18) and (19), was obtained in a simple packet model and is, certainly, only a rough estimate.

Remark. In reality, the passage through a collimator is more complicated process then have been considered. In strong contact impact, many higher states may be excited and then, after cascade transitions populate $2s$ or $2p$. More precise experiment would be with a "clean" $2s$ beam ("cooled" after the collimator) passing through two separated wide slits.

6 Results and discussion

The question arises why the traditional approach, "an atom at rest at the nearby moving surface", is not correct. The answer is: it is correct, but for another problem, namely the one with a fixed position of the atom as the initial state. Such an initial state should be specially prepared. It would be the case if one could select from the beam only the atoms passing through the slit at a fixed position inside the slit frames. Our preparation of the initial state is quite different. We have no information on exact positions of the atoms. The situation is analogous to the classical two-slit experiment, where the final interference pattern disappears if one makes a selection of atoms passing through a certain slit.

The crucial point of our approach is the description of the atom in the beam as a wave packet. Such a description might be naively understood as a spatial distribution of atoms over the cross section of the beam. In this incoherent picture only a tiny fraction of the atoms in the tails of the distribution would be strongly (and randomly) perturbed by the slit. For a wide slit it would lead to rare unobservable events and, what is more important, could not exhibit any interference pattern.

Contrary to that classical picture, we have considered the packet form for the center-of-mass wave function. When passing the slit, only small parts of the packet, tails of the halo, penetrate a surface and reach the high field area. So, the field acting on the packet is strongly nonuniform and inevitably fluctuates from packet to packet, since it is unrealistic to assume the packets of each atom in the beam are identical in shape, size and position in the beam. On the other hand, intrinsic state of the atom feels the field averaged over the whole center-of-mass packet. This averaged field is smooth and practically the same for each atom in the beam, that provides the stable in time (from atom to atom) interference. The averaging of the contact field, acting on the far tails of the packet, over the whole packet looks very paradoxical for classical packets but inevitably follows for the packet wave function.

A strong field, that acts on the halo tails becomes very weak after averaging over the whole packet. Observation of the effect is possible due to the extremely sensitive "apparatus" utilizing the $2s \to 2p$ transition between close levels. For large Δ (when V/Δ is much smaller then penetration depth), the integral in (14) would be negligible.

The strength of the coherent beam-slit interaction is very sensitive to the shape and size of the atomic packet that was assumed to occupy the full transverse size of the beam. In fact, the packet shape can be studied with the varying width of the slit. It seems very promising to direct the beam successively past edges of two metal plates placed on the opposite sides of the beam. Then one can investigate the coherence between the opposite sides of the halo and, in fact, measure the packet size. The transformation of the packet halo tails after passing the metal barrier can also be studied in those experiments.

The packet structure of the beam is transformed during the passage through the collimator. A theoretical analysis of this process is problematic, and it is certainly of interest to make experiments with varying parameters of the collimator. The atom-surface interaction can be investigated by varying shape, structure and material of the slit. The interference is very sensitive mean for investigation of these effects.

The beam-slit interaction was quantitatively described by the simple model potential (7), which may be attributed to a infinitely thin surface slit. The impact of the beam halo with such a slit results in the full loss of the halo momentum. For other front surface shape, the effect may be reasonably predicted by the ratio of momentum loss. If, say, front edges of the slit are at the angle $\theta \neq \pi/2$ to the beam velocity, then the effect should be multiplied by the factor $(1 - \cos\theta)$.

Effect of the longitudinal walls of the slit frame needs a special investigation. Here we shall confine ourself to some general comments. Interaction of hydrogen atom with metal surface is a vast field of active research. The typical problems solved are atomic levels, their shifts and broadening as a function of the atomic distance from metal surfaces. For the upper atomic levels, these effects may be quite large up to distances of dozens of Bohr radius [14,15]. To obtain the effective electric field, acting on the intrinsic state, one should average the surface field over the center-of-mass packet. For symmetric packets, the effects from two opposite edges of the slit cancel each other. For asymmetric packets, one may get non zero result, but in any case the effective field will be of transverse type. A transverse field results in the transitions on to $2p$ states with non zero momentum projections, which do not interfere with the state produced by longitudinal field. So, the only effect (if any) of this atom-surface interaction might be a background.

An effective longitudinal field could be originated from a beam-surface friction. Not to speak of a nature of the friction, one may suggest a possible experimental observation of its existence. It is natural to assume that the friction is proportional to the pressure and/or the beam density near the surface. On the other hand, the cut of halo tails at the front surface of the slit, naturally, initiates transverse oscillations of the beam. The number of oscillation periods, and, consequently, friction pulses, will depend on the slit frame length. So, non uniform dependence of the interference pattern intensity on the slit frame length might be an evidence of the beam-surface friction.

A final remark of a more general nature. Packet states are common objects in quantum mechanics. Their “reduction” and “spreading” are mentioned in numerous monographs and textbooks, but mostly in relation to general methodological problems whereas the plane waves are routinely used in practical applications. Validity of replacing wave packets by plane waves for calculating scattering cross sections was shown by Goldberger and Watson [11]. However, the use of asymptotic plane waves is inadequate for bremsstrahlung processes with colliding beams when the relevant impact parameters exceed the beam size [12]. Is there any other physical situation where the use of packet states is of principal necessity and the problem cannot be understood otherwise? Evidently, such specific effects might be small, and their observation would be possible only in special experimental conditions. Just one of such effects was considered in this paper.

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