Anomalous behavior of metastable hydrogen atoms as they pass through a metal slit

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Experiments on metastable $2s_{1/2}$ hydrogen atoms (with an energy ~20 keV) have shown that as they pass through a metal slit at a large distance from the walls of the slit (e.g., at a distance 10^6 times the first Bohr radius) they go into a superposition state ($2s$–$2p$).

A double atomic interferometer has been used in order to determine the Lamb shift σ ($n = 2$) in a hydrogen atom very accurately (within an error on the order of 2 ppm). The interferometer consisted of tandem systems I and II, with longitudinal electric fields $\mathscr{E}_1$ and $\mathscr{E}$, separated by a variable distance l (Refs. 1–3). An optimum procedure for analyzing the experimental data was adopted after an examination of several possibilities. In this procedure, two measurements had to be carried out during the detection of the flux density of $2p$ atoms emerging from the field $\mathscr{E}$ at each value of l. One measurement was to be carried out with this field directed parallel to the velocity of the atoms, and the second with this field reversed. A condition for determining whether system II (a two-electrode interferometer, which is described in Ref. 4) was operating correctly was that the yield of $2p$ atoms be independent of the sign of the field $\mathscr{E}$ under the condition that the H atoms entered this field in a pure $2s$ state (this condition is met when field $\mathscr{E}_1$ is turned off). In other words, the interference curves describing the yield of $2p$ atoms as a function of the strength of the field $\mathscr{E}$ should coincide when this field is reversed.

As it turned out, however, this independence—within the measurement error—was observed only at certain strictly determined values of the experimental parameters (Fig. 1). More generally, the reversal of $\mathscr{E}$ could cause a substantial discrepancy between the curves (Fig. 2).

What was the reason for this? A detailed theoretical study of the processes which occur in a two-electrode interferometer leads to the following conclusion: The asymmetry of the yield of $2p$ atoms observed experimentally upon a reversal of the field can be explained only on the basis that before an atom interacted with the field it had an initial coherence between $2s$ and $2p$ states. In other words, the initial state of the atoms was a superposition of $2s$ and $2p$ states. By measuring the difference between the yields of $2p$ atoms in the opposite field directions one could find the amplitude and phase of this coherence.

The asymmetry in the yield of $2s$ and $2p$ atoms upon a reversal of $\mathscr{E}$ was studied on the apparatus shown in Fig. 3.

Here *1* is a proton source; *2* is an analyzing magnet; *3* is a charge-exchange chamber; *4* is a weak magnetic field that turns the proton component which is detected

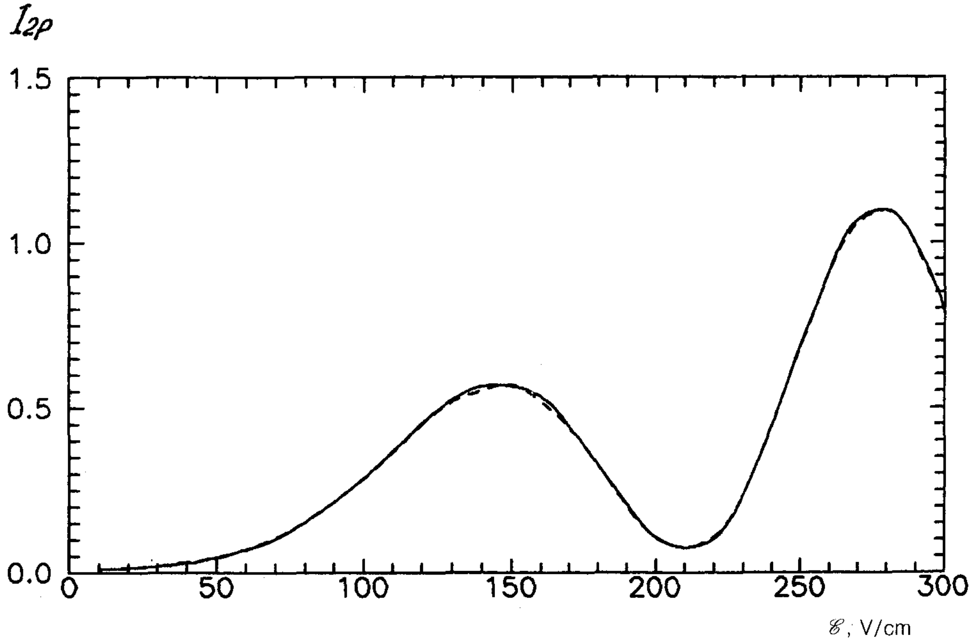

FIG. 1. Interference curves $I_{2p}(\mathscr{E})$ for an H-atom energy of 24.1 keV. Dashed line—The field ℰ is in the same direction as the velocity of the atoms; solid line—the field ℰ has been reversed.

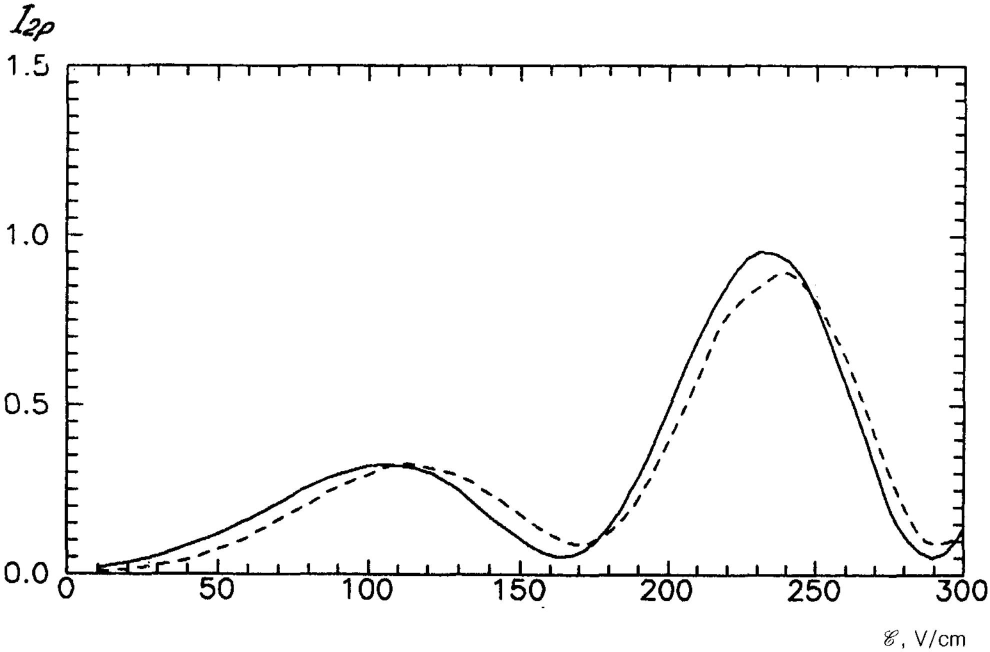

FIG. 2. The same as in Fig. 1, but for an energy of 18.0 keV.

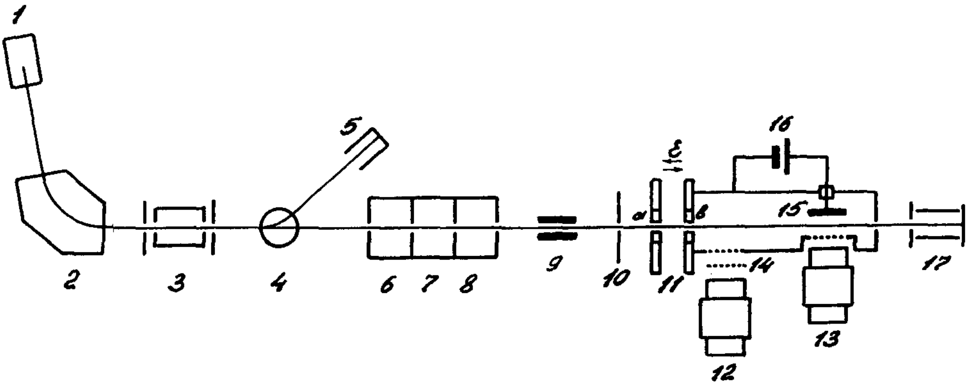

FIG. 3. Experimental layout (see the text proper for an explanation).

by detector *5*; and *6–8* are microwave cavities tuned to frequencies of 909, 1087, and 1147 MHz. These cavities are intended for "quenching" the components of the $2s_{1/2}$ state of the H atom with total angular momenta ($F=0$, $F_Z=0$), ($F=1$, $F_Z=1$), and ($F=1$, $F_Z=0$). In addition, *9* is an electric field which "quenches" the $2s$ component of the beam; *10* is a collimation slit; *11* is a two-electrode interferometer with interchangeable slits *a* and *b*; *12* and *13* are *Lα* detectors, which detect $2p$ and $2s$ atoms, respectively; *14* is a protective grid electrode; *15* is a second quenching field, produced by source *16*; and *17* is the end detector, which measures the beam current.

The energy of the hydrogen atoms passing through the system could be varied from 18 to 26 keV. The beam current was 3×10^{-9} A; $\sim98\%$ of the beam consisted of $1s$ atoms, $\sim2\%$ consisted of $2s$ atoms, and about 1.5×10^{-5} of the beam consisted of long-lived, highly excited H atoms with $n\geqslant8$.

The resulting curves of $I_{2p}(\mathscr{E})$ were analyzed by fitting the experimental points by theoretical curves calculated under the assumption of an initial coherence. This analysis showed that when the amplitudes and phases are chosen optimally, the fit turns out to be quite satisfactory. It follows that the state of the atoms arriving at the front boundary of the field $\mathscr{E}$ is indeed a superposition ($2s$–$2p$). But just how, and in what part of the system shown in Fig. 3, could such a superposition arise?

In the absence of an external field, a coherence relaxes at a rate of $\gamma/2$, where γ is the decay constant of the $2p$ state. In other words, it relaxes over a distance $2v/\gamma=0.6$ cm if the atoms are moving at a velocity of 2×10^{8} cm/s. It follows that the "source" of the coherence must be near the interferometer. It also follows that this source must be independent of the field $\mathscr{E}$.

A detailed analysis of all the experimental conditions showed that the source would have to be associated with interferometer entrance slit II*a*. In other words, as a $2s$ atom passes through this slit, some interaction operates to create a coherence between $2s$ and $2p$ states, i.e., a superposition of these states.

The suggestion that the metal slit was affecting the $2s$ atoms passing through it was confirmed by a direct experiment, involving the passage of these atoms through a slit similar to entrance slit II*a* (with a width of 0.20 mm and a length of 6 mm). At this slit width, the atoms pass at a distance from the surface of the slit greater than the first Bohr radius by a factor of about 10^6. The *La* detector behind the slit detected the flux of $2p$ atoms. The relative population of the $2p$ state turned out to be $\sim 7 \times 10^{-4}$. This figure agrees within 20% with the results of an analysis of the interference curves, which yielded 9×10^{-4}.

We analyzed various possible explanations of the appearance of an asymmetry in the intensity of the emission by the atomic beam under the substitution $\mathscr{E} \to -\mathscr{E}$. We considered mechanisms which might have led to the appearance of a $(2s\text{–}2p)$ superposition or which might have simulated such a superposition, by which we mean they might have caused a change in the flux density of *La* photons in some way or other when the field in the interferometer was reversed. In all cases, however, the scale of the effects which were caused turned out to be negligible in comparison with the observed asymmetry.

In summary, just what did these numerous experiments accomplish?

Together, these experiments draw a consistent picture which apparently confirms the existence of a specific interaction inside a slit which gives rise to a coherence of $2s$ and $2p$ states. The nature of this interaction, however, remains a total mystery.

If the conclusion which we have reached is correct, then it would become possible in principle to construct an atomic interferometer without an electric field: An interference pattern should be observed when the distance between the entrance and exit slits, held at an identical potential, is varied.

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