Production of a nuclear polarization in a gas of atomic hydrogen by means of a microwave pump

S. A. Vasil'ev, A. Ya. Katunin, E. Tjukanov,⁽¹⁾ and I. I. Lukashevich
I. V. Kurchatov Institute of Atomic Energy, Moscow

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It has been demonstrated experimentally, for the first time, that microwave pumping of the forbidden $a \rightarrow c$ transition can be used to increase the degree of nuclear polarization in a gas of atomic hydrogen.

1. A nuclear polarization in a gas of atomic hydrogen ($\mathrm{H}\downarrow\overline{\downarrow}$) causes a pronounced slowing of the decay kinetics of the system and sets the stage for the stabilization of high densities and a transition into the region of Bose condensation. The appearance of a spontaneous nuclear polarization, first observed by Klein *et al.*,[1] is associated with

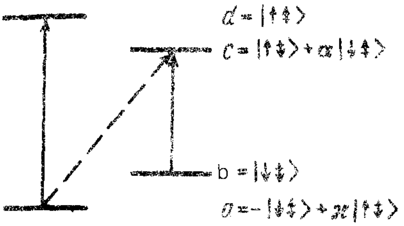

FIG. 1. Energy-level diagram of the hydrogen atom in a strong magnetic field. ↓ and ⇑—Projections of the electron and nuclear spins onto the external magnetic field; $\varkappa = A/4\mu_B B$, where A is the hyperfine-interaction constant.

the depletion of the mixed spin state a (Fig. 1) as a result of recombination at the surface of the helium film by an exchange mechanism. The ESR method makes it possible to not only directly measure the degree of polarization of the nuclear spin[2] but also resolve the fundamental question of whether it can be increased by a microwave pump. In the present letter we show, for the first time, that it is possible to increase the nuclear polarization by pumping the $a \rightarrow c$ forbidden transition.

The experiments were carried out at a temperature $T \sim 0.5$ K and at a density $n_H \sim 10^{15}$–10^{16} cm^{-3} in a magnetic field $B = 5$ T. To detect the populations of spin states a and b, we used 2-mm-range ESR at a low working power, $P \approx 10^{-8}$ W. During pumping of the $a \rightarrow c$ transition, this power was increased to $P \approx 5 \times 10^{-4}$W.

Previous attempts have been made[3] to produce a nuclear polarization by pumping the $a \rightarrow d$ allowed transition. However, those experiments were not successful because of the rapid ($\sigma = 10^{-15}$ cm^2) spin exchanged $d + b \rightarrow c + a$, which effectively equalizes the populations of states a and b. In the case of pumping of the forbidden $a \rightarrow c$ transition, the inverse process $c + a \rightarrow d + b$, on the contrary, causes an additional stimulation of the nuclear polarization.

2. The production and stabilization of atomic hydrogen were carried out by the well-known procedure,[4] involving a dissociation of molecular hydrogen at room temperature and a transport of the atomic beam through an atom duct into a buildup chamber, which was cooled to 0.4–0.8 K by means of a helium-3 refrigerator. The buildup chamber ($V_0 = 0.8$ cm^3) communicated with a volume of a cylindrical resonator ($V_r = 0.02$ cm^3), which was the sensitive element of an ESR spectrometer. The inner surfaces of the walls of the buildup chamber and resonator were covered with a superfluid ^{4}He film with a 0.5% impurity of ^{3}He. This two-chamber arrangement made it possible to reduce the induced recombination of atoms during the recording of the ESR line by a substantial factor ($V_0/V_r \approx 40$), but at the cost of a corresponding decrease in the pumping efficiency. The ESR spectrometer was of the homodyne type with a power modulation ($f_{\rm mod} = 10$ kHz) and a tunable oscillator (a backward-wave tube) which could be tuned over the range[5] $\lambda = 1.65$–2.55 mm. The resonator of the spectrometer was oversized (4.2 mm in diameter, with $l = 3.4$ mm), so it was possible to operate in both the TM and TE modes present in the oscillation spectrum of the resonator. For the pumping experiments, we used the TE_{113} mode ($f = 138$ GHz), whose structure contains a component of the microwave H field which is parallel to the static magnetic field and which is required for exciting the forbidden $a \rightarrow c$ transition.

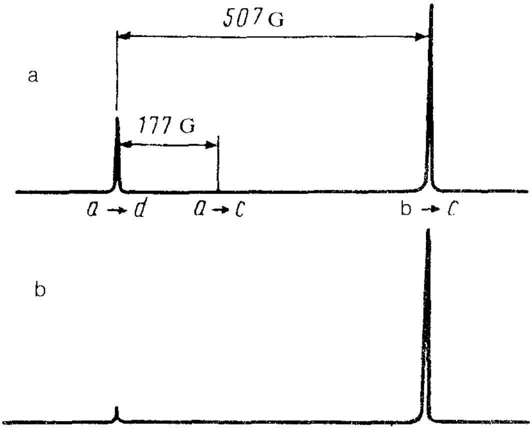

FIG. 2. Electron-spin-resonance spectrum of hydrogen atoms ($f = 138$ GHz) (a) before and (b) after the pumping of the $a \to c$ transition.

Figure 2 shows some typical spectra of atomic hydrogen in the measurement chamber before and after the pumping of the $a \to c$ transition. The observed lines in the spectrum correspond to two allowed transitions, $a \to c$ and $b \to c$. Measurement of the areas under the absorption curves of these lines makes it possible to calculate the populations of the a and b states, respectively. Also shown in this figure is the position of the $a \to c$ transition, which can be found easily by using the familiar expressions for the energy levels of states a, b, c, and d as functions of the magnetic induction[6] B_0. At the time at which the pump was turned on, the microwave power applied to the

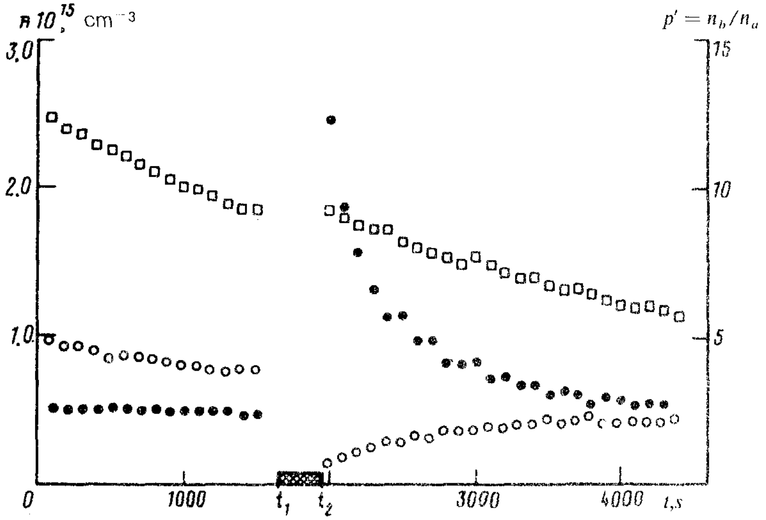

FIG. 3. Kinetics of the decay of the H gas. ○—n_a; □—n_b; ●—p'. During the time interval $t_1 - t_2$, the $a \to c$ transition was pumped.

working resonator increased to its maximum value $P_{\max} = 5\times10^{-4}$ W. In some typical experiments, we measured the populations of states a and b as functions of the time after the buildup of the sample and also after the pumping of the $a\rightarrow c$ transition. The results of one of these experiments are shown in Fig. 3. We see that the $a\rightarrow c$ pumping increases the polarization ratio $p' = n_b/n_a$ by a factor of 5 in comparison with the value achieved spontaneously.

3. These results can be explained on the basis of balance equations for the populations of states a, b, c, and d (Ref. 7 for example). An analysis of the experimental data available in the absence of a pump shows that p' is limited primarily by the first-order nuclear relaxation involving magnetic impurities at the walls of the measurement chamber. The rate of this process turned out to be $G_{ab} \sim 10^{-4}$ s^{-1}. At densities $n_H \sim 10^{16}$ cm^{-3}, by making use of the circumstance that the recombination processes are slow in comparison with the realization involving impurities, one can show that the steady-state value of p', which is reached in the course of the pumping, is given by

$$p' = \frac{W_{ac}}{G_{ba}} + 1 , \tag{1}$$

where W_{ac} is the pumping rate, which was $W_{ac} \sim 2\times10^{-3}$ s^{-1} under our conditions. The value found for p' from (1) agrees with the experimental value.

4. These results indicate that there is a real possibility of using all $a\rightarrow c$ pumping to increase the degree of nuclear polarization in a $H\downarrow$ gas. This possibility looks particularly attractive for the development of polarized targets for nuclear-physics experiments.

In particular, under our experimental conditions ($V_0/V_r \sim 40$) the placement of the entire gas volume in the resonator would have led to $p' \sim 10^2$. A further increase in p' by about an order of magnitude could be achieved by removing the magnetic impurities.

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[1)]Wihuri Physical Laboratory, University of Turku, Turku, Finland.

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