Observation of magnetization transfer in spin-exchange collisions of cesium and rubidium atoms

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Abstract. Spin exchange is one of the effective processes for obtaining spin-polarized atoms. Such mechanism of spin polarization is usually used to transmit and observe the longitudinal (along magnetic field) component magnetization of atoms. However, spin-exchange collisions can also lead to the transfer of the transverse component of magnetization, which occurs when the atoms involved in the collisions are exposed to an alternating resonant magnetic field. This article describes experiments to observe the transmission of transverse magnetization between alkali metal atoms 133Cs and 85Rb in spin-exchange collisions. The calculation of the spin exchange in a mixture of Cs and Rb under magnetic resonance conditions gave a qualitative agreement with the experimental results.

1. Description experiment

Spin exchange is usually used to transmit and observe the longitudinal (directed along a constant magnetic field) component of the spin magnetization (see, for example, [1–3]). However, spin-exchange collisions can also lead to the transfer of the transverse component of magnetization, which occurs when the atoms involved in the collisions are exposed to an alternating resonant magnetic field. This paper is devoted to the experiment to observe the transmission of transverse magnetization between alkali metal atoms 133Cs and 85Rb in spin-exchange collisions.

The two-beam scheme of the experiment on the optical polarization of atoms was used. The working cell contained mixture of alkali metals (rubidium and cesium) and a gas-neon as a buffer gas. We used rubidium with a natural isotopic composition: 28% 87Rb and 72% 85Rb. The circularly polarized radiation of rubidium spectral lamp was directed (along the constant magnetic field B0) to the cell to create the longitudinal magnetization of rubidium atoms. The excitation of the transverse magnetization was achieved by exposing the atoms to a perpendicular (with respect to B0) alternating magnetic field of B1 cos ωt with a frequency close to the Larmor precession frequency of the alkali atoms. To observe the effect (as a result of spin-exchange collisions) of the transfer of transverse magnetization of rubidium atoms to cesium atoms and vice versa we used or the second rubidium lamp, or the cesium lamp. The radiation of these lamps was circularly polarized and directed perpendicular to the magnetic field B0. The magnetic resonance signals (on the Larmor precession frequency ω=γRb,Cs B0) were registered using a narrow band low-noise amplifier with the amplitude detecting of the output signal. The experiment was carried out at the cell temperature of ~600°C. For this aim the cell was heated by the stream of hot air. The experimental signals were recorded by scanning the value of B0 under the constant value of the frequency (6.5 KHz) of the alternating magnetic field B1.
2. Experiment result

Alkaline atoms in the ground $^2S_{1/2}$ state have two sublevels of the hyperfine structure, differing in the value of the total angular momentum quantum number $F$: $F^± = I ± 1/2$ ($I$ is the spin of the nucleus.) The eigen (Larmor) frequencies for these sublevels depend on the magnitude of the longitudinal magnetic field: $\Omega_L (F) = -g(F) \mu_0 B_0$. Here $g(F) = \mp 2/(2I + 1)$ is the g-factor of the $F$ states, $\mu_0 = \mu_B / \hbar$, $\mu_B$ - is the Bohr magneton. For atoms $^{87}\text{Rb}$ ($I = 3/2$), $^{85}\text{Rb}$ ($I = 5/2$) and $^{133}\text{Cs}$ ($I = 7/2$) the values $|g(F)| \mu_0 / 2\pi$ are 700, 466 and 350 Hz/mG. The condition for the resonance of atoms in the $F$-sublevel is equality $\omega = \Omega_L (F)$.

For the Rb-Cs mixture in the light of the cesium lamp it was observed (see figure 1) the resonant “cross signal” under $B_0 = 13.92$ mG. The appearance of this signal is due to the transfer of the transverse spin magnetization from $^{85}\text{Rb}$ atoms to Cs atoms in spin-exchange collisions. In other words it is observed the spin precession of transverse magnetization of cesium atoms on the Larmor frequency of rubidium atoms. When we use the second rubidium lamp it was observed the opposite process. Figure 2 shows the resonance of the transverse magnetization of $^{85}\text{Rb}$ atoms in a magnetic field of 18.57 mG corresponding to the magnetic resonance of $^{133}\text{Cs}$ atoms. It should be noted that the “cross signal” presented in figure 2 was received at triple scanning of magnetic field $B_0$. The experimentally observed spin-exchange signals were extremely small (~ µV). These signals were recorded using a low-noise selective amplifier with a bandwidth of ~ 1 Hz.

![Figure 1](image1.png)  ![Figure 2](image2.png)

Figure 1. The signal in the light of Cs lamp  Figure 2. The signal in the light of Rb lamp

A preliminary theoretical analysis showed that the amplitude of the cross-signals is inversely proportional to the square of the difference between the Larmor frequencies of the colliding alkali
atoms. So the process of transverse magnetization transfer is much less efficient than the transfer of longitudinal magnetization. This is the reason for the small amplitude of the observed cross signals. It should be noted that the above-mentioned dependence of the “cross signal” on the frequency difference, as well as the isotopic composition of rubidium, can be the reason for the absence of the “cross signal” for a pair $^{87}$Rb-$^{133}$Cs.

3. Results of calculation of transfer of transverse orientation of alkaline atoms in spin-exchange collisions Rb and Cs

The polarization of alkali atoms on the F-sublevels of the ground $^2S_{1/2}$-ground state is usually characterized [4] by a set of polarization moments (PM):

$$f_{k,q} (F) = \sum_{m=1}^{2F+1} (-1)^{F-m} \binom{F}{m} \binom{k}{q} f_{am}.$$  

Here $k = 0, 1, \ldots, 2F$, $q = -k, -k+1, \ldots, k$, $f_{am}$ is the density matrix of the atom in the F-state.

In the problem of spin-exchange, we can restrict ourselves to considering the evolution of only PM of rank $k = 1$. This is a vector with cyclic components $q = 0, +1, -1$. It is called the orientation vector and we will use it instead of the magnetization vector used above, which is proportional to it.

The problem of spin exchange in a vapor mixture of two alkali metals A and B was considered in [5]. It produced a system of equations describing the evolution of the orientations $f_{1,q} (F^\pm)$ and $f_{2,q} (F^\pm)$ of atoms in the mixture under the conditions of magnetic resonance excited by a rotating RF field. In addition to spin-exchange collisions, the equations took into account depolarizing collisions of alkali atoms with atoms of the buffer gas Ne and diffusion to the walls of the working cell, on which depolarization of atoms A and B occurred.

The choice of a rotating RF field instead of the commonly used oscillating one allows separate observation of resonances at two sublevels differing only in the sign of g-factors.

The system of equations was numerically solved for a mixture of Rb$^{85}$ and Cs atoms in the first approximation in terms of the intensity $J_{ph}$ of the pump light flux and in the first approximation in the amplitude $b_1$ of the rotating RF field. The presence of Rb$^{87}$ isotope atoms in the cell was not taken into account. The speed of pumping by a light of a rubidium lamp was calculated using the formulas of [6] assuming that the amplitudes of all 4 HFS components in the spectrum of the $D_1$ line of the lamp are equal. The values of spin exchange cross sections, depolarization cross sections in collisions with Ne atoms, and diffusion coefficients in the buffer gas, necessary for calculating, were taken from the review [7].

In the calculation it was believed that the right-rotating RF field $b_1(t)$ with Cartesian components is used

$$b_{x} = 0, \quad b_{z} = b_{m} \sqrt{2} \cos \omega t, \quad b_{y} = b_{m} \sqrt{2} \sin \omega t.$$  

Such a field excites a resonance in the F-state with a negative value of the g-factor, that is, in the $F^-$ state. Resonance in the $F^+$ state it excites at a negative field value: $B_0 = B_2 < 0$.

The results of the calculation are presented in figure 3. From the figure it is clear that for each of the 4 $F$-sublevels ($F^+_d, F^-_d, F^+_g, F^-_g$) 4 resonances are observed. One resonance with a large amplitude occurs when the Larmor frequency $\Omega_\omega (F)$ of this $F$-sublevel coincides with the frequency of the RF field $\omega$. The remaining 3 resonances with small amplitudes arise at values of $B_0$, corresponding to resonances on the other 3 sublevels.

The reason for such a response to the resonances of "other" sublevels is the connection of all transverse orientations of atoms in the cell through spin exchange.

In the experiment, not a rotating, but an oscillating RF field was used. Therefore, such a detailed picture of the mutual influence of resonances on all $F$-sublevels, as in figure 3, could not be obtained. Nevertheless, Fig. 3b clearly reproduces the small resonances shown by figure 1 and figure 2, which are resonances due to the cross effect of the $F^-$-sublevels of the Rb$^{85}$ and Cs atoms.
Figure 3. The dependence of the logarithm of the moduli of orientations $|f_{l,1}^A(F_A)|$ and $|f_{l,1}^B(F_B)|$ of $F$-sublevels of Cs (A) and Rb$^{87}$ (B) atoms on the magnetic field $B_0$: a, b – (bold line - $F_A = 4$, thin line - $F_B = 3$); c, d – (dashed line - $F_A = 3$, points - $F_B = 2$).

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