Observation of polarized alkali atoms in experiments on optical orientation in a He–Rb and He-Cs mixture under conditions of a pulsed gas discharge

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Observation of polarized alkali atoms in experiments on optical orientation in a He–Rb and He-Cs mixture under conditions of a pulsed gas discharge

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Abstract. It has been demonstrated that optical pumping of alkali atoms (rubidium and cesium) results to a highly efficient indirect optical orientation of metastable He (2 3S1) atoms. However, in an attempt to perform the inverse experiment (i.e. to receive spin-polarization of alkali atoms upon optical pumping of metastable helium atoms) the result was quite unexpected: the magnetic resonance signal of Cs or Rb atoms was very weak (several hundred times weaker compared to conventional optical pumping of helium in the presence of cesium (rubidium)). We propose an explanation for the unusually small ratio of the magnetic resonance signals from Cs (Rb) and metastable He atoms under condition of optical orientation of He atoms. Except of Cs atoms we are the first to have observed magnetic resonance signals from atoms of 85Rb and 87Rb isotopes when using the indirect optical orientation in conditions of helium–rubidium gas discharge plasma. It is shown that the anomaly in the amplitude ratios of the observed MR signals can be explained by the unidirectional action of three different factors (the presence of a large nuclear spin of alkali atoms, depolarization of alkali atoms between collisions, and spin exchange between atoms of rubidium isotopes (for the He-Rb system).

1. Introduction

In the experiments [1,2,3] it has been shown that in alkaline-helium plasma ( HF pulse gas discharge was used ) and under the conditions of a direct optical pumping of rubidium and cesium atoms the collisions of alkali atoms with helium atoms lead to rather effective electronic polarization of the last. However, we demonstrated that in case of the return experiment [4, 5], namely when the direct optical pumping is used for helium atoms, polarization of alkali atoms appears much less effective.

In the present work the emphasis is placed on a theoretical explanation of anormally small ratio of signals of electronic polarization of cesium and helium atoms and also on an experiment about the obtaining polarized rubidium (85Rb and 87Rb) atoms at their interaction with optically pumped helium (2 3 S1) atoms and also the theoretical consideration of the experimental signals.

2. Experimental investigation

The equations describing collisions of rubidium atoms with optically oriented helium atoms are the next:

$$\text{Rb}(5^2S_{1/2}) \uparrow + \text{He}(2^3S_1) \downarrow \rightarrow \text{Rb}^+(4^1S_0) + \text{He}(1^1S_0) + e^- \downarrow,$$

(1)
Rb($^2S_{1/2}$)↑ + He($^2S_{1/2}$)↓↓ ↔ Rb($^2S_{1/2}$)↓+ He($^2S_{1/2}$)↑↑, (2)
Rb($^2S_{1/2}$)↑ + e− ↓ ↔ Rb($^2S_{1/2}$)↓ + e− ↑, (3)

where: the reaction 1 describes process of Penning ionization with $C_1$ speed constant (section of process $- \sigma_1$), the reactions 2 and 3 describe processes of spin exchange with the constants $C_2 (\sigma_2)$ and $C_e (\sigma_e)$, respectively.

The optical orientation of metastable He atoms was produced under conditions of pulsed gas discharge in the absorption chamber filled with a mixture of alkali metal ($^{85}$Rb and $^{87}$Rb) vapor and gaseous helium ($^4$He) at a pressure of $P_{He} \approx 2$ Torr. An absorption chamber with a wall temperature of $\sim 45^\circ$C was arranged inside a magnetic screen that reduced variations of the constant laboratory to a level of $\sim 0.2$ nT. The magnetic field with the induction $B = 4.9$ $\mu$T has been generated by a solenoid. In these experiments, we have monitored both the magnetic resonance (MR) signal for Rb atoms (in the ground state) and MR signal for He atoms by measuring a change in the absorption of pumping radiation in the working chamber containing atoms under the action of a resonance alternating magnetic field generated by a pair of radio-frequency (RF) coils. The pumping light was emitted from high-frequency discharge in the helium capillary lamp and transmitted to the chamber via a condenser lens and circular polarizer.

![Figure 1](image.png)

Figure 1. MR signals of rubidium (the insertion presents the MR signal of $^{87}$Rb atoms in an enlarged view as compared to the main figure) and helium atoms. (1) $^{85}$Rb, (2) $^{87}$Rb and (3) $^4$He ($^2S_{1/2}$).

The MR signal of Rb atoms under conditions of indirect optical pumping could be detected due to the spin dependence of reactions (1)–(3). Indeed, the breakage of spin polarization of Rb atoms must lead to an increase in the absorption of light of the helium lamp due to opening of the channel of electron spin polarization transfer from He to Rb atoms via reactions (1)–(3). In this experiment we have observed (see Figure 1) relatively small amplitude of the MR signal for alkali atoms for comparison the MR signal for helium atoms (almost by two orders of magnitude).

3. Magnetic resonance signals during optical orientation in He-Rb system

The magnitude of the MR signal of rubidium atoms can be represented in the following form [6]:

$$S_{He}^{He} = \frac{A_1 \langle S_{He} \rangle}{\sum \left( \frac{1}{\tau_0} + \frac{1}{\tau_p} + \frac{1}{\tau_d} \right) + \alpha \left( \frac{1}{\tau_0} + \frac{1}{\tau_p} + \frac{1}{\tau_d} \right)}$$

where $\alpha = 1/\tau_1 - 1/\tau_0$,
\[ \frac{1}{\tau_0} = \left( \frac{S_{He}^{S} N_{Rb}^{S} }{N_{He}^{S} + \frac{1}{3} \sigma_1 + \frac{1}{2} \sigma_2} \right) \]  

\[ \frac{1}{\tau_1} = \frac{1}{\tau_0} + \frac{1}{\gamma} \left( \frac{S_{He}^{S} N_{Rb}^{S} }{N_{He}^{S} + \frac{1}{3} \sigma_1 + \frac{1}{2} \sigma_2} \right) \]  

Parameter \( \gamma \) is determined by the polarization relaxation of rubidium atoms in the interval between collisions with metastable helium atoms (a more detailed determination of \( \gamma \) is presented in Section 7). Quantity takes into account the redistribution of electron polarization of rubidium atoms in the interval between the same collisions. One can show [6] that the expression for the MR signal of alkali atoms has the form

\[ S_{Rb}^{He} = S_{He}^{He} \frac{1}{\gamma} \frac{1}{\beta} \]  

Therefore, the ratio we are interested in for MR signals of helium and alkali metal atoms is

\[ A = \frac{S_{Rb}^{He}}{S_{He}^{He}} = \frac{1}{\gamma} \frac{1}{\beta} \]  

To calculate quantity \( A \), it is necessary to know the coefficients determining the quantity. It should be noted that, since the rubidium signal is detected by a change in absorption of helium pumping light during the MR, the magnitude of indirect polarization of rubidium is not so important for its detection as its influence on relaxation of optically oriented triplet metastable helium atoms. In what follows, we assume that spin orientation of the ensemble of rubidium and helium atoms (i.e., angular electron momentums averaged over possible states of initial atoms) as a result of a collision is redistributed in proportion to electron spins of atoms without touching on the nuclear spin because the collision duration (~10\(^{12}\) s) is sufficient for the effective spin–spin interaction and is considerably less than the time of hyperfine interaction (~10\(^{10}\) s); therefore,

\[ \langle S_{Rb} \rangle + \langle S_{He} \rangle = \text{const} \]  

where \( \langle S_{He} \rangle \) and \( \langle S_{Rb} \rangle \) are electron orientations of triplet metastable helium and rubidium atoms. Below, we consider in detail main factors having an effect on the formation of the observed signal.

4. Effect of the nuclear spin magnitude

The probability of ionization process (1) directly depends on the polarization degree because the total spin of the system of colliding atoms is preserved in this process; i.e., the total spins of the system of interacting particles at the input and output of the reaction are similar. Then, the acquired immediate polarization of rubidium atoms can be represented in the form

\[ \langle S_{Rb}^{He} \rangle = -\delta \langle S_{He}^{He} \rangle = \frac{1}{3} \langle S_{He}^{He} \rangle, \]  

where \( \delta \langle S_{He}^{He} \rangle \) is the change in the electron orientation of metastable helium atoms during the collision with rubidium atoms. By the time of the next collision of rubidium atoms with metastable \( ^2S_1 \) helium atoms, the spin orientation of the ensemble of rubidium atoms is redistributed among the electron and nucleus (\( S_{Rb} = 1/2 \) and \( I_{Rb} = 5/2 \) for the \(^{85}\)Rb isotope and \( S_{Rb} = 1/2 \) and \( I_{Rb} = 3/2 \) for the \(^{87}\)Rb isotope) in the ratio of 1/6 : 5/6 for \(^{85}\)Rb and 1/4 : 3/4 for \(^{87}\)Rb. If there were no other collisions before the next meeting with a metastable \( ^2S_1 \) helium atom, the electron orientation of the ensemble of rubidium isotope atoms would be equal to (taking into account (9)),

\[ \langle S_{Rb}^{He} \rangle = \frac{1}{18} \langle S_{He}^{He} \rangle, \]  

\[ \langle S_{He}^{He} \rangle = \frac{1}{12} \langle S_{He}^{He} \rangle. \]
The polarization transferred to rubidium atoms is detected in the next act of collision of a polarized rubidium atom with a metastable \(2^3S_1\) helium atom. It is assumed that the spin orientation of metastable helium atoms is restored during the time between the first and second collisions due to the pumping light. Then, as a result of spin exchange reactions and chemoionization, the electron polarization of the ensemble of metastable helium atoms changes from 1/12 to 1/18 (for the \(87\)Rb isotope) and from 1/18 to 1/27 (for the \(85\)Rb isotope) (taking into account (12) and redistribution of angular momentums in the ratio of \(2 : 1\) for helium). Thus, in expression (10), \(1/\beta = 1/18\) for the \(87\)Rb isotope and \(1/\beta = 1/27\) for the \(85\)Rb isotope. However, polarization of the cesium ensemble can be broken with a high probability in the process of other collisions; therefore, the quantity \(1/\gamma\) should be determined in relationship (7).

5. Effect of spin exchange between rubidium isotopes on magnitudes of observed signal

In the absorption chamber containing a mixture of rubidium isotopes, atoms of different rubidium isotopes can collide with each other. In this process, the spin exchange during collision of two atoms of different rubidium isotopes can play a significant part (cross section \(\sigma_{\text{Rb}} \approx 1.86 \times 10^{-14}\) cm\(^2\) at \(T=320\) K [7]).

When atoms of rubidium isotopes collide with each other, the electron polarization is redistributed among atoms. Indeed, if atoms of one rubidium isotope (polarized in processes (1)–(3)) collide with atoms of another rubidium isotope (nonpolarized ones), polarization is redistributed among them. Since the electron spins of atoms of the \(85\) and \(87\) rubidium isotopes are similar (\(S = 1/2\)), the electron polarization during the collision is redistributed among ensembles of atoms so that each of the ensembles retains half of the initial electron polarization. Then, the electron polarization is redistributed among the electron and nuclear systems of the atoms; atoms with a larger nuclear spin retain less electron polarization. Namely, for \(85\)Rb, the coefficient of redistribution of the initial electron polarization is 1/6 for the electron system and 5/6 for the nuclear system; for \(87\)Rb, 1/4 and 3/4, respectively. Then, the ratio of signals for two isotopes related to the observed electron polarization is \(A_{\text{Rb}}^{85}/A_{\text{Rb}}^{87} = 2/3\).

6. The role of various quenching processes in a gas discharge

With allowance for the high probability of other relaxation processes in a gas discharge (relaxation on fast and slow electrons or on singlet metastable and other excited helium atoms, as well as on molecules and photons, relaxation on walls of the absorption chamber, etc.), the cesium atom orientation decreases by a factor of \(\gamma\) by the instant of the collision with other \(2\) fast and slow electrons or on singlet metastable and other excited helium atoms, as well as on molecules and photons, relaxation on walls of the absorption chamber, etc., the cesium atom orientation decreases by a factor of \(\gamma\) by the instant of the collision with other 2.

Quantity \(\gamma\) can be determined as follows. It follows from the experiment that the width of the MR line of polarized rubidium atoms in a gas discharge plasma due to only collisional processes is on the order of \(\Delta f \approx 1\) kHz (and this value can be considered as a lower bound estimate). The contribution from the spin exchange and chemoionization can be taken into account knowing the transverse cross sections, average relative thermal velocity, and density of metastable helium atoms.

The width of the MR line of polarized cesium atoms due to chemoionization and spin exchange is \(\Delta f \approx 20\) Hz. Thus, the ratio of \(\Delta f\) to \(\Delta f\) yields an estimate of \(\gamma \approx 15\). Then, if the MR signal of rubidium atoms is detected from a change in absorption of helium pumping light, it is proportional to the following quantity (with allowance for (8)):

\[
S_{he}^{He} \sim \sqrt{\frac{1}{15}} \frac{1}{27} N_{he} \langle S_{he}^{He} \rangle,
\]

(11)

\[
S_{he}^{He} \sim \sqrt{\frac{1}{15}} \frac{1}{18} N_{he} \langle S_{he}^{He} \rangle.
\]

For the magnetic resonance signal of metastable helium atoms, the following proportionality takes place:

\[
S_{he}^{He} \sim N_{he} \langle S_{he}^{He} \rangle.
\]

(12)
Thus, the ratio of MR signals of atoms of rubidium isotopes and metastable helium atoms upon optical orientation of helium atoms is
\[ A_{87} = \frac{S_{87}^{\text{He}}}{S_{87}^{\text{Rb}}} = \frac{1}{\gamma} \frac{1}{\beta} = \frac{1}{15} \frac{1}{27} = 2.5 \times 10^{-3}, \]
(13)

With allowance for the ratio of densities of rubidium isotopes in a natural mixture \( K_1 = 72/28 = 2.57 \) for the 85 isotope and ratio of signals determined by relationship (13) yielding the value \( K_2 = 2.5/3.7 = 0.68 \) not for the 85 rubidium isotope, we obtain \( A^{85}/A^{87} = 0.68 \times 2.57 = 1.73 \). Taking into account the effect of the spin exchange on MR signals for two rubidium isotopes, which was mentioned in Section 5, we come to the final result \( A^{85}/A^{87} = 1.73 \times 2/3 = 1.16 \). The ratio \( A^{85}/A^{87} \approx 1 \) detected in the experiment (Figure 2) almost coincides (with allowance for the signal-to-noise ratio) with the value obtained from the theoretical consideration. In addition, as follows from the experiment (Figure 1), the ratio of MR signals of atoms of rubidium isotopes and metastable helium amounts to \( \sim 7 \times 10^{-3} \) [8], which rather well corresponds to estimates presented by expressions (13).

7. Magnetic resonance signals during optical orientation in He-Cs system

The amplitude of the observed signal at the magnetic resonance for Cs atoms has the form similar to (4) and (5) with the replacement of Rb by Cs (4). Then (6) takes the form
\[ S_{\text{Cs}}^{\text{He}} = S_{\text{He}}^{\text{He}} \frac{1}{\gamma} \frac{1}{\beta}, \]
(14)

and the ratio of the signals is equal to
\[ A = \frac{S_{\text{Cs}}^{\text{He}}}{S_{\text{He}}^{\text{He}}} = \frac{1}{\gamma} \frac{1}{\beta}, \]
(15)
to determine the value of A, one needs to know the coefficients entering into this equation.

7.1. The influence of nuclear spin.

The redistribution of electronic angular momentum between the ensembles of helium and cesium atoms in collisions of optically oriented He (2\(^3\)S\(_1\)) (electron spin \( S_{\text{He}}^{\text{He}} = 1 \)) with unpolarized Cs (electron spin \( S_{\text{Cs}}^{\text{Cs}} = 1/2 \)) is a result of chemiionization and spin exchange proportionally to the electronic spins. The ensemble of Cs atoms acquires 1/3 of the angular momentum of the ensemble of the optically oriented He (2\(^3\)S\(_1\)) atoms, leaving remaining 2/3 to He (2\(^3\)S\(_1\)) atoms. The acquired instantaneous polarization of the cesium atoms can, then, be represented in the form
\[ \langle S_{\text{Cs}}^{\text{He}} \rangle = -\delta \langle S_{\text{He}}^{\text{He}} \rangle = \frac{1}{3} \langle S_{\text{He}}^{\text{He}} \rangle, \]
(16)

where is the change in the electron orientation of He (2\(^3\)S\(_1\)) in collisions with Cs. Before the next collision with a He (2\(^3\)S\(_1\)) atom, the spin orientation of the Cs atom is redistributed between the electron and the nucleus (\( S_{\text{Cs}} = 1/2, I_{\text{Cs}} = 7/2 \)) in the ratio 1/8 : 7/8; if there were no other collisions before the next encounter with a He (2\(^3\)S\(_1\)) atom, the electronic orientation of an ensemble of Cs atoms would be equal (taking into account (13)) to
\[ \langle S_{\text{Cs}}^{\text{He}} \rangle = \frac{1}{24} \langle S_{\text{He}}^{\text{He}} \rangle, \]
(17)

Registration of the polarization transferred to a given Cs atom takes place in the next collision with a polarized He (2\(^3\)S\(_1\)) atom. It is assumed that during the time interval between the first and second collisions, the pump light restores the spin orientation of He (2\(^3\)S\(_1\)). Then, as a result of spin exchange reactions and chemiionization, the electronic polarization of the He (2\(^3\)S\(_1\)) ensemble is changed from
1/24 to 1/36 (taking into account (12) and the angular momentum redistribution in the ratio of 2 : 1 in favor of helium). Thus, in (9) \(1/\beta = 1/36\).

### 7.2. The role of quenching processes in gas discharge

The value of \(\gamma\) can be estimated as follows. According to the experimental results, the magnetic resonance line width of polarized Cs atoms in the discharge plasma is determined only by collisional processes and is of an order of \(\Delta f \approx 1\, \text{kHz}\) (this value can be considered as the lower-bond estimate).

A typical He (2\(^3\)S\(_1\)) concentration in alkali-helium gas discharge plasma is \(N_{\text{He}} \approx 10^{10}\, \text{cm}^{-3}\) (this value is characteristic for a continuous gas discharge in the absorption chamber; taking into account the use of a pulse discharge in our experiments, and the presence of Cs atoms in the absorption chamber, which are easily ionized, this value can be considered as the upper bond estimate); the rate constants \((C = \sigma v)\) of spin exchange and chemionization are known, \(C_2 = (2.8 \pm 0.8) \times 10^{-9}\, \text{cm}^3\, \text{s}^{-1}\) and \(C_1 = (1.0 \pm 0.3) \times 10^{-9}\, \text{cm}^3\, \text{s}^{-1}\) respectively; the discharge temperature is \(T = 300\, \text{K}\) [9]. For these values the magnetic resonance line width of polarized Cs atoms determined by chemionization and spin exchange is \(\Delta f_1 \approx 20\, \text{Hz}\). Thus, the estimate from the \(\Delta f/\Delta f_1\) ratio gives \(\gamma \approx 15\).

Thus, the ratio of the magnetic resonance signals under the condition of the optical orientation of He (2\(^3\)S\(_1\)) atoms is [10]

\[
A_C = \frac{S^\text{He}}{S^\text{Cs}} \sim \frac{1}{\gamma} \frac{1}{\beta} = \frac{1}{15} \frac{1}{36} \sim 2 \cdot 10^{-3}
\]

This value is in a good agreement with the experimental value, which is in the \((2-5) \times 10^{-3}\) region [4].

### Conclusions

Thus, as follows from above consideration, the small value of MR signal for the polarized rubidium and cesium atoms under the collisions with the optically oriented helium atoms is determined by presence of a large nuclear spin of alkali atoms, significant role of depolarization collisions for alkaline atoms and helium atoms and indirect registration of polarization of alkali atoms. It should be noted also that account under the theoretical consideration in case of mix of rubidium isotopes and helium the existence (unlike a case cesium-helium) additional process of spin exchange - between atoms of various isotopes of rubidium has allowed to receive.

### References

[1] Keiser G M, Robinson H G and Johnson C E 1975 Phys. Lett. A 51 5
[2] Blinov E V, Zhitnikov R A and Kuleshov P P 1976 Sov. Tech. Phys. Lett. 2 117
[3] Blinov E V, Zhitnikov R A and Kuleshov P P 1987 Optical Orientation of Atoms and Molecules, Collection of Articles (VSVOAM, Leningrad) 12
[4] Dmitriev S P, Dovator N A, Kartoshkin V A, and Okunevich A I 2014 Opt. Spectrosc. 116 216
[5] Dmitriev S P, Dovator N A, Kartoshkin V A 2016 Tech. Phys. Lett. 42 85
[6] Dmitriev S P, Dovator N A, Kartoshkin V A, Klementiev G V 2016 Opt. Spectrosc. 120 207
[7] Kartoshkin V A Opt. Spectrosc. 2016 119 594
[8] Dmitriev S P, Dovator N A, Kartoshkin V A, Klementiev G V 2016 Opt. Spectrosc. 121 649
[9] Dmitriev S P, Dovator N A, Kartoshkin V A 1999 Tech. Phys. 44 641
[10] Dmitriev S P, Dovator N A, Kartoshkin V A, Klementiev G V 2016 Opt. Spectrosc. 120 207