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# Shift of the magnetic resonance frequency in collision of atoms with electron spins S = 1

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The paper considers collisions of spin-polarized atoms with electron spin $\mathbf{S} = \mathbf{1}$, in a situation where at least one of them is in an excited state. In this case, both the spin polarization exchange between the colliding atoms and the ionization of atoms due to the internal excitation energy occur during the collision. In the paper, expressions are obtained for the complex cross sections of spin exchange accompanied by ionization, including expressions for the cross sections of the magnetic resonance frequency shift, which is the imaginary part of the complex cross section of spin exchange. Using two metastable helium atoms in the $2^3S_1$-state as an example, the energy and temperature dependences of the frequency shift cross sections were calculated. The frequency shift cross section was found to influence, in the case of the $^4$He isotope, only the alignment, and this influence occurs only during the interference of elastic scattering amplitudes on the singlet and quintet terms of the $He_2$ quasimolecule. It was shown that the ionization process occurring simultaneously with the spin exchange significantly affects the magnitudes of the magnetic resonance frequency shifts in a mixture of helium isotopes. In addition, it turned out that the magnitudes of the frequency shifts caused by the spin exchange are commensurate with the magnetic resonance frequency shifts caused by the metastability exchange between helium atoms in the metastable and ground states.

**Keywords:** atomic collisions, polarized atoms, cross sections, magnetic resonance frequency shifts.

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## Introduction

When polarized atoms collide with each other, a well-known process of spin exchange occurs, i.e. a process of electron polarization in collision of particles. The situation of this kind occur, for example, in collision of atoms of alkali metals in the ground state [1–5]. If one of collision participants is an excited atom and its energy is enough for ionizing a collision partner, then in this case the spin exchange process (an elastic process) is accompanied by ionization of the collision partner due to internal energy of the excited atom (an inelastic process). It is possible, for example, in collision of excited metastable atoms of helium of neon with alkaline atoms, hydrogen atoms, etc. [6]. In this case, there are collisions of atoms with electron spins $\mathbf{S} = \mathbf{1}$ (metastable atoms of helium or neon) and $\mathbf{S} = \mathbf{1/2}$ (the atoms of alkali metals and hydrogen in the ground state). As shown in the study [6], when the metastable helium atoms collide with atoms, for example, of the alkali metal, two processes (elastic and inelastic) that simultaneously occur affect, first of all, a spin-exchange cross-section and atom magnetic resonance frequency shift cross-sections induced by spin exchange. In this situation, expressions for the frequency shift cross-sections and the spin-exchange cross-sections were once obtained in a dependence on phases of scattering on respective terms of a quasi-molecule generated during collision.

Along with the case when the atoms with the spins **1** and **1/2** collide, a situation is possible, in which the atoms with the electron spin $\mathbf{S} = \mathbf{1}$ are involved in collision. For example, the two metastable helium atoms in the $2^3S_1$ state [7], the metastable helium atom and an oxygen molecule in a triplet state $(^3\Sigma_g^-)$ [8]. The metastable helium atom has excitation energy of 19.8 eV and this energy is enough to ionize any atom or molecule except for the atoms of helium and neon in the ground state. When two metastable helium atoms collide with each other, energy is enough to ionize the helium atom ($E_i = 24\,\mathrm{eV}$) [9]. Thus, when the two polarized metastable helium atoms in the $S$-state collide, two simultaneously occurring processes are also possible — spin exchange and chemi-ionization.

As noted above, the spin-exchange collisions result in the magnetic resonance frequency shift, and if the spin-exchange process is accompanied by ionization, it also results in the influence of the inelastic process on the spin-exchange cross-sections [6]. At the same time, unlike collision of the excited atoms with spin $\mathbf{S} = \mathbf{1}$ and ground-state atoms with spin $\mathbf{S} = \mathbf{1/2}$, for which both cross-sections of spin exchange and chemi-ionization as well as frequency shift cross-sections were studied for various pairs of atoms, shift cross-sections in collision of atoms with spins $\mathbf{S} = \mathbf{1}$ were not studied in terms of the influence of collisions on the frequency shifts and there were not expressions for the frequency shift cross-sections.

The present study has obtained expressions for the frequency shift cross-sections in collision of the atoms with spin $\mathbf{S} = \mathbf{1}$ for the case when spin exchange is accompanied by chemi-ionization. Exemplified by collision of two metastable polarized helium atoms, the frequency shift cross-sections have been calculated on energy. It is shown that a value of the magnetic resonance frequency shift, which is induced by spin exchange (in collision of the two metastable helium atoms), is commensurable with a value of the frequency shift of the metastable helium atom, which is induced by exchange of meta-stability between the helium atoms in the ground state and the metastable state (for the case when the helium isotope — $^3$He is involved in collisions).

## 1. Simultaneously occurring elastic and inelastic processes with involvement of the atoms with electron spin $\mathbf{S} = \mathbf{1}$

In collisions with involvement of polarized excited atoms with electron spin $\mathbf{S} = \mathbf{1}$, it is possible (if atom excitation energy is enough to ionize the collision partner) to have both the spin exchange process, i.e. exchange of spin polarization between colliding atoms:

$$A^*(\uparrow\uparrow) + B(\uparrow\downarrow) \to (AB)^* \to A^*(\uparrow\downarrow) + B(\uparrow\uparrow), \qquad (1)$$

as well as the ionization process:

$$A^*(\uparrow\uparrow) + B(\uparrow\downarrow) \to (AB)^* \to \begin{matrix} A + B^+(\uparrow) + e^-(\uparrow) \\ \\ AB^+(\uparrow) + e^-(\uparrow). \end{matrix} \qquad (2)$$

Here, arrows conditionally indicate a direction of electron spin, while „*“ indicates that the atom is in the excited state. It should be noted that the atom B can also be in the excited state (for example, in case of collision of two polarized metastable helium atoms or metastable neon atoms).

In the reactions (1) and (2), when the atoms collide, the quasi-molecule is formed, which, taking into account spins of the colliding atoms, can be described by interaction potentials that correspond to complete system spins **0** (a singlet term), **1** (a triplet term) and **2** (a quintet term). If the reactions (1) and (2) keep the complete system spin before and after collision, which is true when the atoms in the S-state collide (the Wigner rule [10]), then the reaction (2) proceeds only on the singlet and triple terms. And if following the studies [11,12], then the respective interaction potentials can be written as

$$U^{s,t}(R) = V^{s,t}(R) - (i/2)\Gamma^{s,t}(R) \qquad (3)$$

for the singlet term $(s)$ and the triplet term $(t)$ Here, an imaginary part of the interaction potential — an auto-ionization width — is responsible for death of the particles during ionization. Since ionization on the quintet term $(q)$ is impossible due to unkeeping of complete spin, the quintet term will be real:

$$U^q(R) = V^q(R). \qquad (4)$$

In order to calculate the cross-sections, it is necessary to know phases of scattering on the respective terms.

Since ionization is possible only on the single and triplet terms, the phases of scattering on these two terms are complex, i.e. $\eta_l^{s,t} = \varkappa_l^{s,t} + i\lambda_l^{s,t}$ (the imaginary part of the phase of scattering characterizes death of the particles during ionization), whereas the phases of scattering on the quintet term are real: $\eta_l^{s,t}$. Here $l$ is an orbital quantum number, $s$, $t$ and $q$ correspond to complete spins that are equal to 0, 1 or 2.

The cross-section that are of interest to us can be represented by a scattering matrix Ti [13]:

$$\sigma_{s,s'} = (\pi/k)^2 \sum_{l=0}^{\infty} (2l+1)[1 - T_s(l)T^*_{s'}(l)]. \qquad (5)$$

Here $k$ is a wave number, „*“ indicates complex conjugation. Since in collision of the polarized excited atoms both the elastic process (1) and the inelastic process (2) occurs, the spin exchange process can be described by a complex cross-section of the following kind

$$\sigma_{s,s'} = \overline{\sigma}_{s,s'} + i\overline{\sigma}_{s,s'}. \qquad (6)$$

Here the real part of the cross-section describes the spin exchange process which is accompanied by ionization, while the imaginary part of the cross-section describes the frequency shift induced by spin exchange.

The cross-sections that are of interest to us can be expressed via the scattering matrix (5), which in turn can be represented via the phases of scattering on the respective terms as follows:

$$T_l^{s,t,q} = \exp(2i \cdot \eta_l^{s,t,q}). \qquad (7)$$

Taking into account that the phases of scattering on the singlet and triplet terms are complex and they on the quintet are real and substituting (7) into (5) we obtain the following expressions for the spin exchange cross-sections that are of interest to us:

1) the cross-section $\sigma_{01}$ is determined by interference of amplitudes of elastic scattering on the singlet $(s)$ and triplet $(t)$ terms. In this case, we obtain the following expressions for the real and imaginary parts of the cross-section (6):

$$\overline{\sigma}_{0,1} = \pi/k^2 \sum_{l=0}^{\infty} (2l+1) \times [1 - \exp(-2\lambda_l^0 - 2\lambda_l^1)\cos 2(\chi_l^0 - \chi_l^1)], \qquad (8)$$

$$\overline{\overline{\sigma}}_{0,1} = \pi/k^2 \sum_{l=0}^{\infty} (2l+1) \times [\exp(-2\lambda_l^0 - 2\lambda_l^1)\sin 2(\chi_l^0 - \chi_l^1)]; \qquad (9)$$

2) the cross-section $\sigma_{02}$ is determined by interference of amplitudes of elastic scattering on the singlet $(s)$ and quintet $(q)$ terms. In this case, we obtain the following expressions for the real and imaginary parts of the cross-section (6):

$$\overline{\sigma}_{0,2} = \pi/k^2 \sum_{l=0}^{\infty}(2l+1)[1-\exp(-2\lambda_l^0)\cos 2(\chi_l^0-\chi_l^2)], \tag{10}$$

$$\overline{\overline{\sigma}}_{0,2} = \pi/k^2 \sum_{l=0}^{\infty}(2l+1)[\exp(-2\lambda_l^0)\sin 2(\chi_l^0-\chi_l^2)]; \tag{11}$$

3) the cross-section $\sigma_{12}$ is determined by interference of amplitudes of elastic scattering on the triplet $(t)$ and quintet $(q)$ terms. In this case, we obtain the following expressions for the real and imaginary parts of the cross-section (6):

$$\overline{\sigma}_{1,2} = \pi/k^2 \sum_{l=0}^{\infty}(2l+1)[1-\exp(-2\lambda_l^1)\cos 2(\chi_l^1-\chi_l^2)], \tag{12}$$

$$\overline{\overline{\sigma}}_{1,2} = \pi/k^2 \sum_{l=0}^{\infty}(2l+1)[\exp(-2\lambda_l^1)\sin 2(\chi_l^1-\chi_l^2)]. \tag{13}$$

As it is clear from the obtained expressions, presence of simultaneous elastic and inelastic processes significantly affects both the spin exchange cross-sections as well as the magnetic resonance frequency shift cross-sections. This influence is expressed in that the relationships (8)–(13) have terms of the kind $-\exp(-2\lambda_l^{s,t})$, which depend on imaginary parts of the complex phases of scattering on the singlet and triplet terms. At the same time, it is also manifested in the spin exchange cross-sections ((8), (10) and (12)) [7,9] and in the frequency shift cross-sections ((9), (11) and (13)). As noted above, the imaginary part of the phase of scattering is responsible for the ionization process. Thus, if during spin-exchange accompanied by ionization probability increases, it results in both a decrease of the spin exchange cross-section as well as a decrease of the shift cross-section, i.e., as a result, in reduction of the magnetic resonance frequency shift.

In the studied situation, an ionization cross-section on the singlet and triple terms is represented in a standard way [13]:

$$\sigma^{0,1} = \pi/k^2 \sum_{l=0}^{\infty}(2l+1)[1-\exp(-4\lambda_l^{0,1})]. \tag{14}$$

Thus, knowing the interaction potentials and using the expressions for the frequency shift cross-section obtained in Section 1, one can calculated the cross-sections that are of interest to us.

## 2. Magnetic resonance frequency shift cross-sections in collision of the two metastable He atoms in the $2^3S_1$-state

As noted above, a situation which enables the spin exchange process accompanied by chemi-ionization for the atoms with electron spin $\mathbf{S}=\mathbf{1}$ can be implemented in collision of the two metastable helium atoms in the triplet state [7] or, for example, in collision of the metastable helium atom and the oxygen molecule in the triplet state [8]. However, the frequency shifts in this situation were not studied. Using the expressions obtained for the first time for the frequency shift cross-sections (9), (11) and (13), it is possible in the present study to calculate energy and temperature dependences of sought cross-sections using known complex atom interaction potentials.

The complex interaction potentials of the two metastable helium atoms have been obtained in the study [14]. These potentials were tabularized. Fig. 1 and 2 shows the real and imaginary parts of the potentials, which are constructed from tabular data by a spline method.

As it is clear from Fig. 1, 2, the singlet and triplet potentials are close to each other in a value, wherein it is related both to the real parts as well as the imaginary parts. In Fig. 2, auto-ionization width data obtained in the study [14] are interrupted at an interatomic distance $R \sim 0.5 \cdot 10^{-8}$ cm, although at this distance the real part of the interaction potential is still away from zero. In this regard, it is necessary to extrapolate the auto-ionization widths into larger interatomic distances. As known, the auto-ionization width in the high internuclear distances can be represented by an exponential dependence on the distance.

Thus, knowing the singlet, triplet and quintet terms of the system as well as expressions for the dependence of the

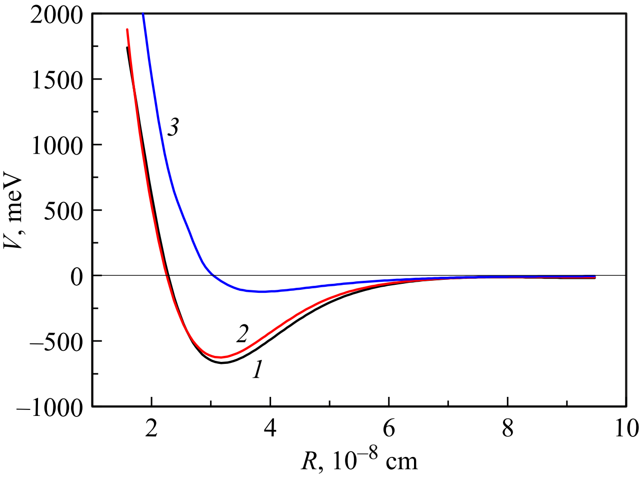

**Figure 1.** Real parts of the interaction potentials of the two metastable helium atoms ($2^3S_1$). *1* the singlet one corresponding to complete spin $\mathbf{S}=\mathbf{0}$; *2* — the triplet term corresponding to complete spin $\mathbf{S}=\mathbf{1}$; *3* — the quintet term corresponding to complete spin $\mathbf{S}=\mathbf{2}$ according to the study [14].

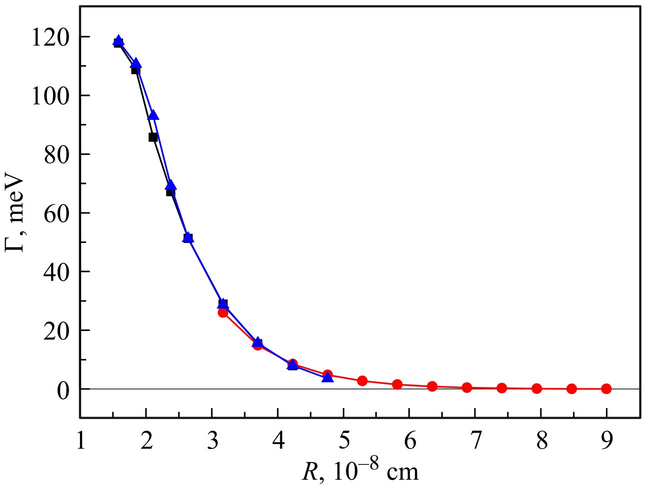

**Figure 2.** Dependence of the auto-ionization width on the distance: ■ — data from the study [14] for the triplet term, ▲ — data from the study [14] for the singlet term, ● — extrapolation of data into the large distances by means of the exponential dependence.

frequency shift cross-sections on the phases of scattering on the respective terms, one can calculate the dependences of the cross-sections that are of interest to us on collision energy of the metastable helium atoms.

The phases of scattering can be calculated by a standard way in the quasi-classical approximation [13]:

$$\delta_l = \int_{R_0}^{\infty} F_1(R)dR - \int_{R'_0}^{\infty} F_0(R)dR, \tag{14}$$

where

$$F_1^S(R) = \left[2\mu(E - V_S(R) - \frac{(l+1/2)^2}{2\mu R^2}\right],$$

$$S = s,\ t,\ q, \tag{15}$$

$$F_0(R) = \left[2\mu E - \frac{(l+1/2)^2}{R^2}\right].$$

Here $E$ is collision energy, $\mu$ is a reduced mass of the colliding atoms, $R$ is an interatomic distance, $l$ is an orbital quantum number, $R_0$ and $R'_0$ are roots of equations $F_1^S(R) = 0$ and $F_0(R) = 0$ (whereas for $F_1^S(R)$ the largest root is taken), $V_S(R)$ is an interaction potential corresponding to complete spin $\mathbf{S}$ ($\mathbf{0}$, $\mathbf{1}$ or $\mathbf{2}$). At the same time, according to (3) the interaction potentials for the singlet and triplet terms are complex, while for the quintet term they are real.

Fig. 3 shows dependences of the magnetic resonance frequency shift cross-section on collision energy, which are obtained in the present study. As it is clear from Fig. 3, the cross-section determined by interference of amplitudes of elastic scattering on the singlet and triplet terms ($\overline{\overline{\sigma}}_{0,2}$) is significantly smaller in a value than the cross-sections induced by interference of amplitudes of elastic scattering on the singlet and quintet terms as well as on the triplet and quintet terms. It is due to presence of exponential multipliers in the expressions (9), (11) and (13), which depend on imaginary parts of the complex phases of scattering. In case of the singlet and triplet terms, an argument of the exponential multiplier includes a sum of imaginary parts of the phases of scattering on the singlet and triplet terms, whereas in two other cases it includes only the imaginary parts of either the singlet term or the triple term, since the quintet term is real. Since the real and imaginary parts of the singlet and triplet interaction potentials are close to each other in a value as follows from Fig. 1 and 2, then the phases of scattering on these terms are close to each other in a value, respectively, so are both their real and imaginary parts. It results in the fact that the argument of the exponential term in the formula (9) is in two times higher than in the formulas (11) and (13) (the arguments are included in the formulas with a minus sign), thereby resulting in reduction of a value of the obtained cross-section. Besides, an argument in the sinus function in the expression (9) is also close to zero.

The shift cross-sections were calculated for the case of collision of two helium isotopes — $^3$He. For the case of collision of the atoms $^3$He with the atoms $^4$He and of the atoms $^4$He with the atoms $^4$He the calculation took into account a difference in reduced masses of the systems. Since the metastable state of helium is populated in gas-discharge conditions, it should be borne in mind that the gas discharge of helium includes both metastable atoms, whose concentration is usually about $10^{10} - 10^{11}\,\mathrm{cm}^{-3}$, as well as

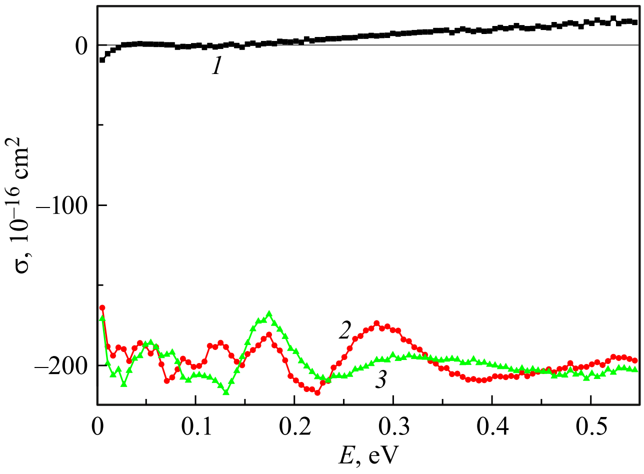

**Figure 3.** Dependence of the magnetic resonance frequency shift cross-sections on collision energy: *1* — the frequency shift cross-section ($\overline{\overline{\sigma}}_{0,1}$), which is determined by interference of amplitudes of elastic scattering on the singlet ($s$) and triplet ($t$) terms; *2* — the frequency shift cross-section ($\overline{\overline{\sigma}}_{0,2}$), which is determined by interference of amplitudes of elastic scattering on the singlet ($s$) and quintet ($q$) terms; *3* — the frequency shift cross-section ($\overline{\overline{\sigma}}_{1,2}$), which is determined by interference of amplitudes of elastic scattering on the triplet ($t$) and quintet ($q$) terms.

Dependences of the magnetic resonance frequency shift cross-sections on the temperature in collision of two metastable helium-3 atoms

| $T$, K | $\overline{\overline{q}}_{0,1}$, $10^{-16}$ cm$^2$ | $\overline{\overline{q}}_{0,2}$, $10^{-16}$ cm$^2$ | $\overline{\overline{q}}_{1,2}$, $10^{-16}$ cm$^2$ |
|---|---|---|---|
| 50 | $-5.7$ | $-154.9$ | $-162.8$ |
| 100 | $-3.6$ | $-178.7$ | $-189.0$ |
| 150 | $-2.2$ | $-183.3$ | $-194.5$ |
| 200 | $-1.4$ | $-183.1$ | $-196.1$ |
| 250 | $-0.9$ | $-181.5$ | $-196.7$ |
| 250 | $-0.9$ | $-181.5$ | $-196.7$ |
| 350 | $-0.4$ | $-179.2$ | $-197.3$ |
| 400 | $-0.2$ | $-178.8$ | $-197.5$ |
| 450 | $-0.1$ | $-178.9$ | $-197.5$ |
| 500 | 0.06 | $-179.2$ | $-197.5$ |

ground-state atoms, whose concentration is about $10^{16}$ cm$^{-3}$ in conditions of an experiment of optical orientation of atoms. At the same time, collisions between the metastable helium atoms and the ground-state helium atoms also result both in widening a magnetic resonance line of metastable helium as well as a frequency shift [15]. These widenings of the magnetic resonance line and its shift are induced by the process of exchange of meta-stability, i.e. transfer of excitation from the excited (metastable) atom to the ground-state atom.

In order to use the above-obtained shift cross-sections and to estimate a shift value, it is necessary to transfer from energy to temperature dependences of the cross-sections. For this purpose, a Maxwellian averaging of the cross-sections was performed across the rates:

$$q(T) = \frac{\langle q(E)v\rangle}{\langle v\rangle} = \frac{1}{(kT)^2}\int\limits_0^\infty \overline{\overline{\sigma}}(E)E\exp(-E/kT)dE, \tag{16}$$

Here $T$ is a temperature in a working chamber, $v$ is an average relative thermal rate of colliding particles, $\overline{\overline{\sigma}}$ is the shift cross-section, $E$ is collision energy, $k$ is the Boltzmann constant.

Table shows the magnetic resonance frequency shift cross-sections averaged across the rates.

The shift cross-sections were also calculated for the case of isotopes $^3$He–$^4$He and $^4$He–$^4$He. The calculation took into account the reduced masses of colliding atoms, wherein for all the cases the interaction potentials were taken from the study [14].

It was calculated to show that the calculated cross-sections for various pairs of isotopes differ by values that were smaller than accuracy of the performed calculations. Therefore, it is possible to use data that are given in Table for a case of all three pairs of isotopes.

## 3. Influence of the isotope composition of colliding helium atoms on the magnetic resonance frequency shear cross-sections

In the experiments of optical orientation of the metastable helium atoms, it is possible to use two stable isotopes — $^4$He and $^3$He. These two isotopes have zero electron spin in the ground state ($\mathbf{S=0}$, the state $^1$S$_0$), but unlike the isotope $^4$He the isotope $^3$He has nuclear spin $\mathbf{S=1/2}$. Presence of nuclear spin in the isotope $^3$He significantly affects a process of collision of these atoms.

In particular, during optical orientation of the metastable helium atoms in the gas discharge, along with collisions between the metastable atoms, there are also collisions between the metastable atoms and the ground-state atoms. Collisions between the metastable helium atoms and the ground-state atoms $^3$He in particular result in transfer of polarization into the ground state, since the atom $^3$He has nuclear spin $\mathbf{S=1/2}$. These collisions also result both in widening the magnetic resonance line of the metastable helium atoms as well as in the magnetic resonance line frequency shift.

Since the atoms $^4$He are indistinguishable, in collisions between atoms of the isotope $^4$He (in the metastable state) only the cross-sections (10) and (11) turn out to be observable. At the same time, spin exchange does not affect orientation ($\langle\mathbf{S}\rangle = Tr(\rho\mathbf{S}), \rho$ is a density matrix) of the metastable helium atoms, while variation of alignment ($\langle Q\rangle^{\alpha\beta} = Tr(\rho Q_{\alpha\beta})$) is correspondingly determined by the cross-section $\overline{\overline{\sigma}}_{0,2}$. Whence, it follows that spin exchange accompanied by chemi-ionization affects alignment only, i.e. „classical" quantum magnetometers [16] designed to operate on optically oriented helium atoms either lack the above-described shifts that are determined by the cross-section $\overline{\overline{\sigma}}_{0,2}$ or have a vary low value of this shift, since during optical orientation of helium with circularly polarized light orientation of the atoms significantly exceeds alignment.

It should be noted that the recent times have seen a proposition and a start of active development of helium quantum magnetometers designed to operate on the aligned atoms [17–20]. Using the aligned atoms in devices will allow eliminating dead zones in instruments, which are present at some angles of observation. Such studies are performed both with alkaline atoms (Cs) [18] as well as with the metastable atoms $^4$He [17,19,20]. In particular, a helium scalar magnetometer without the dead angles has been proposed and it can be implemented in a totally optical method [17]. In this situation, the magnetic resonance frequency shifts (which are induced by spin exchange between the metastable atoms ($\overline{\overline{\sigma}}_{0,2}$)) considered in the present study turn out to be relevant in terms of determining accuracy characteristics of the devices of this kind and shall be taken into account when they are created.

At the same time, if collisions occur between atoms of the isotope $^3$He or the isotopes $^3$He and $^4$He, then since the isotope $^3$He has nuclear spin, the atoms turn to be distinguishable and these collisions results both in widening the magnetic resonance line as well as in the magnetic resonance line frequency shift [15]. At the same time, all the cross-sections $(8)-(13)$ turn out to be observable.

It follows from the study [15] that in case of a mixture of the helium isotopes $^3$He and $^4$He the magnetic resonance line frequency shift during exchange of meta-stability is proportional to a meta-stability exchange cross-section ratio during collisions of $^3$He–$^4$He and $^3$He–$^3$He, a portion of the atoms $^3$He $(\alpha)$ and it also depends on a temperature of the working chamber as $\sim T^{7/2}$, which is determined by a ratio of temperature dependences of the meta-stability exchange cross-sections $(\beta)$ during collisions of the same ($^3$He–$^3$He) and different ($^3$He–$^4$He) helium atoms. Then the frequency shift of the metastable atoms $^4$He can be represented by the following expression:

$$\delta\omega_{\mathrm{He}^4} = -\frac{6}{7}\,\frac{N^2 v_1^2 \sigma_1^2}{\omega_m}\,\beta^2\alpha(1-\alpha). \tag{17}$$

Taking into account values of variables of (17), for $T = 77\,\mathrm{K}$, the magnetic field of 1 Oe and a portion of atoms $^3$He in the mixture we obtain a shift value $\alpha = 0.1$ . At the same time, the frequency shifts induced by interference of amplitudes of elastic scattering on the triplet and quintet levels (according to the table data) provide the shift value of about $\delta\omega_{\mathrm{He}^4} = 660\,\mathrm{Hz}$, $\delta\omega_{12} = 340\,\mathrm{Hz}$ ($\delta\omega_{12} \sim Nv\overline{\overline{q}}_{1,2}$, here $N$ is a concentration of the metastable atoms He, $v$ is an average relative rate of colliding particles, $\overline{\overline{q}}_{1,2}$ are cross-sections from Table). For the case of the frequency shift $\delta\omega_{02}$ wee obtain similar shift values due to proximity of values of the cross-sections $\overline{\overline{q}}_{1,2}$ and $\overline{\overline{q}}_{0,2}$ . At the same time, the shift induced by interference on the singlet and triplet terms $(\delta\omega_{01})$ is by two orders smaller, since the respective shift cross-section is by two orders smaller.

It is clear from the given calculation that the magnetic resonance frequency shifts induced by spin-exchange collisions between the polarized metastable atoms are commensurable in a value with the shifts related to meta-stability exchange and shall be taken into account when studying processes that occur in the helium gas exchange in the mixture of helium isotopes.

Since at the temperature of about $T = 77\,\mathrm{K}$ the magnetic resonance line width, for example, of the metastable atoms $^4$He is several kHz (for the case when the portion of the helium isotope — $^3$He in the mixture is about 10 %) the considered frequency shifts can be observed and the shifts related to meta-stability exchange and spin exchange can be separated by extrapolating by a concentration of the metastable atoms (varying intensity of discharge in the working chamber), on which the spin-exchange shifts depend and the frequency shifts related to meta-stability exchange do not depend.

## Conclusion

Thus, the study has considered the influence of the process of spin exchange accompanied by chemi-ionization on the frequency shifts in collision of the atoms with electron spins $\mathbf{S} = \mathbf{1}$. We have obtained the expressions for the frequency shift cross-sections. For the case of collision of the polarized metastable helium atoms, both in case of the pure isotope $^4$He as well as in the mixture of the isotopes $^4$He–$^3$He we have calculated the respective cross-sections and showed the influence of the imaginary part of the complex interaction potential (of the imaginary part of the phase of scattering) on the shift cross-section values induced by spin exchange. It is shown that with an increase of probability of the ionization process there is reduction of a value of the respective spin exchange cross-section and, therefore, the magnetic resonance line frequency shift. It is shown that in case of collisions with involvement of the atoms of the isotope $^3$He within the low temperatures (of about 77 K) the magnetic resonance frequency shift of the metastable atoms, which is induced by spin exchange, is commensurable with the frequency shift related to meta-stability exchange. It is found that the frequency shift cross-section affects alignment in case of collisions in the pure isotope $^4$He, wherein it takes place only during interference of amplitudes of elastic scattering on the singlet $(s)$ and quintet $(q)$ terms of the quasi-molecule $\mathrm{He}_2^*$. Presence of this shift shall be taken into account when designing the helium quantum magnetometers with optical polarization of atoms, which are designed to operate on the aligned atoms $^4$He.

### Conflict of interest

The author declares that he has no conflict of interest.

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