Dependence of the probability for Penning ionization on the relative spin orientation of the colliding atoms

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(Submitted October 8, 1975)
Zh. Eksp. Teor. Fiz. **70**, 899–907 (March 1976)

The dependence of the cross section for ionization in Penning collisions of atoms with zero orbital momenta on both diagonal and off-diagonal elements of the density matrix of the colliding atoms is found under the assumption that the total spin and its projection are conserved. An expression is obtained for the signals of the variation of the electron density in a plasma at magnetic resonance in the 2^3S_1 metastable state of He^4 atoms under optical pumping conditions. Comparison of the theory with the available experimental data yields results that agree with the assumption that total spin is conserved in Penning collisions.

PACS numbers: 34.50.Hc, 52.20.Hv

There have been obtained in recent years experimental data which indicate that the probability of Penning ionization essentially depends on the relative spin orientation of the colliding atoms.[1–6]. It is precisely the existence of such a dependence that made it possible to explain the experimentally observed influence of the optical orientation of metastable orthohelim atoms on the electron density in a plasma,[1–3, 5, 6] as well as on the polarization of the electrons in a plasma.[4] The spin dependence of the Penning collisions also explained the experimentally observed influence of the relative spin orientation of Rb and metastable orthohelium atoms on the electron density in a plasma.[7]

The spin dependence of Penning collisions is explained by the conservation of total spin in such collisions.[8, 4] Thus, it was shown, in particular[8, 4], that in collisions of metastable orthohelium atoms with each other or with alkali-metal atoms total-spin conservation should lead to the forbidding of the Penning-ionization reaction if the spins of the colliding atoms have the same orientation, since the total spin of the initial atoms in this case exceeds the largest possible value of the total spin of the reaction products.

The verification of the assumption that total spin is conserved, as well as the extraction of quantitative information about the spin dependence of Penning collisions from experimental data requires a detailed theory. The previously employed[4, 5] approach to the solution of this problem cannot be considered to be satisfactory, since it is based on the arbitrary assumption that all the allowed channels of the Penning reaction are equally probable. Furthermore, there (i.e., in[4, 5]) the authors allowed for the dependence of the Penning-ionization cross section on only the populations of the magnetic sublevels of the colliding atoms, whereas a full interpretation of experimental data requires allowance for the dependence of the cross section on coherence.

The aim of the present paper is to consider the spin dependence of the Penning collisions of atoms in S states with allowance for the diagonal elements of the density matrices (i.e., for the populations) of the colliding atoms, as well as for the off-diagonal elements (i.e., for coherence). The analysis is based on the assumption that total spin and its projection are conserved in Penning collisions.

1. DEPENDENCE OF THE PENNING-IONIZATION PROBABILITY ON THE SPIN STATE OF THE COLLIDING ATOMS

The Penning reaction during the collision of a metastable atom A^* with the atom B (the ionization potential of the atom B is smaller than the excitation energy of the atom A^*) can be written in the form

$$A^*+B\rightarrow A+B^++e^-. \tag{1}$$

The products of this reaction are the atom A in the ground state, the ion B, and an electron. In the present paper we assume that the initial atoms, as well as the products of the reaction (1), possess only spin angular momenta (the orbital angular momenta are equal to zero): S_1 is the spin of the atom A^*; S_2 is the spin of the atom B; S_{12} is the total spin of the initial atoms A^* and B ($S_{12}=S_1+S_2, \ldots, |S_1-S_2|$); S is the total spin of the products of the reaction (1); m_1, m_2, m_{12}, and m are the corresponding components of these spins along the z axis of the laboratory system of coordinates.

The wave function, Ψ_{12}, of the system consisting of the atoms A^* and B before the collision can be expanded in a series in terms of the eigenfunctions, $\psi_{S_{12}m_{12}}$, of the total spin angular momentum $\hat{S}_{12}$:

$$\Psi_{12}=\sum a_{S_{12}m_{12}}\psi_{S_{12}m_{12}}.$$

After a collision with ionization of the atom B, the wave function, Ψ of the products of the reaction (1) can be expanded in terms of the eigenfunctions, ψ_{Sm}, of the total spin angular momentum, $\hat{S}$, of the products of the reaction (1):

$$\Psi=\sum b_{Sm}\psi_{Sm}.$$

The connection between the coefficients $a_{S_{12}m_{12}}$ and b_{Sm} gives the transition matrix $\hat{T}$:

$$b_{Sm}=\sum_{S_{12}m_{12}} T_{Sm}^{S_{12}m_{12}}a_{S_{12}m_{12}}. \tag{2}$$

Under the assumption that the total spin and its component along the z axis are conserved, the $\hat{T}$ matrix is diagonal. Furthermore, the $\hat{T}$ matrix cannot depend on the magnitude of m_{12} (owing to the isotropy of space). Thus,

$$T_{Sm}^{S_{12}m_{12}} = T_S \delta_{SS_{12}} \delta_{mm_{12}}. \tag{3}$$

The formulas (2) and (3) allow us to express the density matrix, $\hat{\rho} = \hat{b}\hat{b}^+$, of the products of the reaction (1) in terms of the density matrix, $\hat{\rho}^{(12)} = \hat{a}\hat{a}^+$, of the initial atoms. The total probability, w, for ionization during a collision is equal to the density matrix $\hat{\rho}$ averaged over all the spin states of the products of the reaction:

$$w = \mathrm{Sp}\,\hat{\rho} = \sum_{Sm} A_S \delta_{SS_{12}} \delta_{mm_{12}} \rho^{(12)}_{S_{12}m_{12}S_{12}m_{12}}, \tag{4}$$

where $A_S = |T_S|^2$ is the ionization probability for the channel of the reaction (1) with total spin S.

Using the formulas for the wave function of coupled momenta,[9] we can express the density matrix $\hat{\rho}^{(12)}$ in the formula (4) in terms of the product of the density matrices $\tilde{\rho}^{S_1}$ and $\tilde{\tilde{\rho}}^{S_2}$ of the atoms A* and B:

$$w = \sum_{\substack{m_1 m_2 \\ m_1' m_2'}} W_{m_2 m_2'}^{m_1 m_1'} \tilde{\rho}^{S_1}_{m_1 m_1'} \tilde{\tilde{\rho}}^{S_2}_{m_2 m_2'}; \tag{5a}$$

$$W_{m_2 m_2'}^{m_1 m_1'} = \sum_{Sm} A_S (2S+1) \begin{pmatrix} S_1 & S_2 & S \\ m_1 & m_2 & -m \end{pmatrix} \begin{pmatrix} S_1 & S_2 & S \\ m_1' & m_2' & -m \end{pmatrix}. \tag{5b}$$

In the formula (5b) the summation index S assumes all the possible values of the total spin of the products of the reaction (1). Into the formula (5a) enter the diagonal, as well as the off-diagonal, elements of the density matrices of the colliding atoms. Thus, the expression (5) completely determines the dependence of the Penning ionization probability on the spin state of the colliding atoms.

To find the dependence of the ionization probability on the relative spin orientation of the colliding particles, it is convenient to go over in the expression (5) from the density matrices in the mm'-representation to density matrices in the $\varkappa q$-representation with the aid of the formulas given by D'yakonov in[10]. As a result of such a transition the expression (5) assumes the form

$$w = \sum_{\varkappa_1 \varkappa_2} D_{\varkappa_1} \sum_{q_1 q_2} (-1)^{q_1} \tilde{\rho}^{\varkappa_1}_{q_1} \tilde{\tilde{\rho}}^{\varkappa_2}_{-q_2} \delta_{\varkappa_1 \varkappa_2} \delta_{q_1 q_2}, \tag{6a}$$

$$D_{\varkappa_1} = \sum_S A_S (-1)^{S_1+S_2+S} \frac{(2S+1)(2\varkappa_1+1)}{[(2S_1+1)(2S_2+1)]^{1/2}} \begin{Bmatrix} S & S_2 & S_1 \\ \varkappa_1 & S_1 & S_2 \end{Bmatrix}. \tag{6b}$$

(The values of S here are the same as in the formula (5b).)

The elements of the density matrix $\rho_q^\varkappa$ in the $\varkappa q$-representation that figure in the formula (6a) (the polarization moments of the density matrix) are connected by simple relations with the mean values of the circular components of the spin operator $\hat{\mathbf{S}}$:

$$\rho_q^1 = (-1)^q \langle \hat{S_q} \rangle [S(S+1)]^{-1/2};$$

ρ_q^2 is equal to a linear combination of the quantities $\langle \hat{S}_a \hat{S}_b \rangle$ $(a+b=q)$, etc.[9,10] The quantity $\rho_0^0 = \mathrm{Sp}\hat{\rho} = 1$. (For the first- and second-rank polarization moments ($\varkappa = 1$ and 2) we shall use below the frequently employed designations: orientation and alignment.)

It can be seen from the formula (6a) that the ionization probability w is expressible in terms of a sum of polarization-moment products, the cofactors in these products being moments of the same rank $\varkappa$. The sum over $q_1 q_2$ in the formula (6a) is a scalar product of moments of order $\varkappa_1 = \varkappa_2$ (the components of the moments are circular). It follows from the properties of the $6j$ symbols that the quantity $\varkappa_1$ entering into the formula (6) can assume values from zero to $2S_{min}$, where S_{min} is the smaller of the quantities S_1 and S_2.

With allowance for the coupling of the quantities $\rho_q^\varkappa$ with the spin components, the formulas (6) give the dependence of the Penning ionization probability on the relative spin orientation of the colliding atoms.

Above we did not take into account the fact that the nuclei of the atoms involved in the Penning collisions have spins. The effect of the nuclear spin can be neglected if the coupling of the nuclear and electron spins is weak, so that the nuclear-spin component does not have time to change over the period of interaction as the atoms approach each other. In this case the Penning ionization probability can be computed from the formulas (5) or (6), in which under the density matrices we should understand spin density matrices averaged over the nuclear states. Inverting the formula for the wave function of the coupled moments[9] and summing over all possible values of the nuclear-spin component, we can express the averaged—over the nuclear states—spin density matrix in terms of the density matrix in the (F, m_F) representation ($\mathbf{F} = \mathbf{I} + \mathbf{S}$, where I is the nuclear spin):

$$\rho^S_{mm'} = \sum_{\substack{Fm_F \\ F'm_F' \\ n}} (-1)^{2I-2S+m_F+m_F'} [(2F+1)(2F'+1)]^{1/2} \times \begin{pmatrix} I & S & F \\ n & m & -m_F \end{pmatrix} \begin{pmatrix} I & S & F' \\ n & m' & -m_F' \end{pmatrix} \rho_{Fm_F, F'm_F'}. \tag{7}$$

A quantitative condition of applicability of the approximation used is the fulfillment of the inequality $\Delta E_{HFS}/\hbar \ll v/\sigma^{1/2}$, where ΔE_{HFS} is the hyperfine interaction energy, σ is the Penning ionization cross section, and v is the mean relative velocity of the colliding atoms. Since the quantity σ is usually of the order of 10^{-14}–10^{-15} cm^2 [11] and $v \approx 10^5$ cm/sec, this inequality is fulfilled for all the specific participants, considered in the present paper, of the Penning collisions (for He^3, the alkali-metal atoms, and hydrogen, $\Delta E_{HFS}/\hbar = (0.14-5.8)\times 10^{10}$ sec^{-1}).

Thus, when at least one of the two colliding atoms has a nonzero nuclear spin, the dependence of the Penning-ionization probability on the orbital state of the collision partners is determined by the relation (5), in which the spin density matrices should be expressed in terms of the density matrices in the (F, m_F) representation with the aid of the formula (7).

2. SPIN DEPENDENCE OF THE CROSS SECTION FOR PENNING IONIZATION IN COLLISIONS OF METASTABLE HELIUM ATOMS WITH EACH OTHER AND WITH ALKALI-METAL ATOMS

The expression for the total Penning-ionization cross section σ can be obtained as a result of the integration of the ionization probability w (the formulas (5) and (6)) over the impact parameter and the averaging over the relative velocities of the colliding atoms. Actually, only the quantities A_S in the formulas (5) and (6) get transformed in the process. Furthermore, averaging over the A*- and B-atom ensembles, which leads to the replacement of the atomic density matrices in the formulas (5) and (6) by the density matrices averaged over the ensembles of the corresponding atoms, is necessary. Thus, the formulas (5) and (6) with the substitution

$$w\to\sigma,\quad A_S\to\sigma_S \tag{8}$$

(and the replacement of the atomic density matrices by the averaged matrices) give the dependence of the total Penning-ionization cross section σ on the spin state of the collision partners (σ_S is the cross section for ionization in the channel of the reaction (1) with total spin S). The terms in the formula (5) then acquire the meaning of ionization cross sections for different combinations of the mm' states of the colliding atoms. It is significant that all these cross sections are expressible in terms of the quantities σ_S, of which there are a small number.

Below we give expressions for the total cross section σ, obtained with the aid of the formula (6) and the substitution (8). We retain for the averaged—over the atomic ensembles—density matrices the notation adopted for the atomic density matrices.

1. Collisions of helium atoms in the metastable 2^3S_1 state:

$$\mathrm{He}(2^3S_1)+\mathrm{He}(2^3S_1)\to\mathrm{He}(1^1S_0)+\mathrm{He}^+(1^2S_{1/2})+e^-. \tag{9}$$

In this case $S_1=S_2=1$ and $S=0$ or 1,

$$\sigma=\bar\sigma\left[1-C_1\sum_q(-1)^q\rho_q^1\rho_{-q}^1-C_2\sum_q(-1)^q\rho_q^2\rho_{-q}^2\right], \tag{10a}$$

$$\bar\sigma=\frac{1}{9}(\sigma_0+3\sigma_1),\quad C_1=\frac{3}{2}\left(\frac{3r_{10}+2}{3r_{10}+1}\right),$$
$$C_2=\frac{5}{2}\left(\frac{3r_{10}-2}{3r_{10}+1}\right),\quad r_{10}=\frac{\sigma_1}{\sigma_0}. \tag{10b}$$

(In the formula (10a) the density matrices do not have the signs ~ and ≈, since the colliding atoms in the case under consideration are identical.)

It can be seen from the formula (10a) that the cross section for ionization in collisions of metastable orthohelium atoms depends on both the orientation of the colliding atoms and their alignment. The relative magnitude of the contribution made by these polarization moments is determined by the quantities C_1 and C_2, which, according to the formulas (10b), depend on the cross sections σ_0 and σ_1 for the channels of the reaction (9) with total spin $S=0$ and $S=1$ (the singlet and triplet channels). It is interesting that, depending on the magnitude of the ratio, r_{10}, of these cross sections, the contribution of the alignment to the total cross section σ can be positive ($r_{10}<\frac{2}{3}$), negative ($r_{10}>\frac{2}{3}$), or equal to zero (when $r_{10}=\frac{2}{3}$), whereas the contribution of the orientation is always negative.

The values of $6W^{m_1m_1}_{m_2m_2}/\sigma_0$ for Penning collisions of He atoms in the metastable 2^3S_1 state.

m_2	m_1: 1	0	−1
1	0	$3r_{10}$	$2+3r_{10}$
0	$3r_{10}$	2	$3r_{10}$
−1	$2+3r_{10}$	$3r_{10}$	0

The cross sections for the triplet and singlet ionization channels can be computed from the formulas (18) of the paper[12] by Garrison *et al.*, using the potential curves for the $^3\Sigma_u^+$- and $^1\Sigma_g^+$-terms of the He_2 molecule formed during the collision of helium atoms in the 2^3S_1 state. The potential curves computed in the same paper[12] for these terms virtually coincide, and the same values are obtained for the cross sections σ_1 and σ_2, so that $r_{10}=1$. Similar potential curves tabulated in the paper[13] by Klein differ somewhat, and for the ratio r_{10} is obtained the value $r_{10}\approx1$. The magnitude of r_{10} is estimated from the available experimental data in the following paragraph.

In the table we give the matrix $6\hat W/\sigma_0$ computed from the formula (5b) (with the substitution (8)) for the case when only the diagonal elements of the density matrix of the colliding metastable orthohelium atoms are different from zero. The $6\hat W/\sigma_0$ matrix elements in the table give the relative magnitude of the ionization cross sections corresponding to different combinations of the m states of the colliding atoms. It can be seen from the table that the ionization cross section is equal to zero (the reaction (9) is forbidden) if the colliding metastable atoms are in states with $m_1=m_2=\pm1$. The existence of such a prohibition follows directly from the assumption that total spin is conserved in the collisions.[5] It can also be seen from the table that the ionization cross sections for all the remaining (allowed) combinations of the m states of the colliding atoms are not, in the general case, equal to each other, and depend on the quantity r_{10}. And what is more, it follows from the table that there does not exist a value of r_{10} at which all these cross sections would be equal to each other. Thus, the assumption that the cross sections for all the allowed combinations of the m states of the colliding atoms have the same value is not fulfilled.

2. Collisions of helium atoms in the metastable 2^3S_1 state with atoms X of an alkali metal or hydrogen in the ground $^2S_{1/2}$ state:

$$\mathrm{He}(2^3S_1)+\mathrm{X}(^2S_{1/2})\to\mathrm{He}(1^1S_0)+\mathrm{X}^+(^1S_0)+e^-. \tag{11}$$

In this case: $S_1=1$, $S_2=\frac{1}{2}$, $S=\frac{1}{2}$,

$$\sigma=\bar\sigma\left[1-\sqrt{6}\sum_q(-1)^q\tilde\rho_q^1\tilde{\tilde\rho}_{-q}^1\right],\quad \bar\sigma=\frac{1}{3}\sigma_{1/2}. \tag{12}$$

It follows from the formula (12) that the spin dependence of the cross section for ionization in the reaction (11) is determined by the scalar product of the mean values of the spin angular momenta of the collision partners. This result is corroborated by previously-obtained experimental data for a Rb–He mixture.[7] As can be seen from the formula (12), the cross section σ in the present case does not depend on the alignment of the helium atoms.

Experimentally, the spin dependence of the Penning-ionization cross section is usually detected by observing the variation of the electron density in a plasma as the spin state of the Penning-collision partners is varied.[1,3,5–7] It can be seen from the formulas (10) and (12) that the total ionization cross section σ can be represented in the form of a sum

$$\sigma=\tilde{\sigma}+\delta\sigma, \tag{13}$$

in which only the term $\delta\sigma$ depends on the spin state of the colliding atoms. The experimentally attainable polarization of atoms is usually small (it does not exceed a few percent), so that the quantities ρ_q^1 and ρ_q^2 in the formulas (10) and (12) are much smaller than unity and, consequently, $\delta\sigma \ll \tilde{\sigma}$. The fulfillment of this inequality allows us to represent the electron density n_e in a plasma also in the form of a sum $n_e=\tilde{n}_e+\delta n_e$ in which only the term δn_e depends on the spin state of the Penning-collision partners, it being necessary that the magnitude of this term be directly proportional to the quantity $\delta\sigma$:

$$\delta n_e \sim \delta\sigma. \tag{14}$$

The relations (14) and (13) and the formulas (10) and (12) (or (5)–(7) with the substitution (8)) allow us to compute (up to a constant factor) the signals of electron-density variation in a plasma that are observed when the spin state of the Penning-collision partners is varied. An example of such a computation for metastable orthohelium is given below.

3. DEPENDENCE OF THE ELECTRON DENSITY IN A PLASMA ON THE SPIN STATE OF METASTABLE 2^3S_1 HELIUM ATOMS

Such a dependence was observed in[1,3,5,6]. Of greatest interest from the point of view of a comparison with theory are the experiments performed by Sevast'yanov and Zhitnikov[1] and Hill *et al.*[5]

In particular, the variation of the electron density in a plasma was observed[1] at magnetic resonance in the metastable 2^3S_1 state of He^4 atoms under conditions of optical pumping by circularly polarized and unpolarized light.

To compute the resonance electron-density-variation signals in this case, we can use the expressions for the polarization moments ρ_q^1 and ρ_q^2 from D'yakonov's paper.[10] The use of the results of this paper is justified, since in the case of 2^3S_1 He^4 atoms the general equations for the density matrix[14] under conditions of optical pumping by low-intensity light (after going over to the $\varkappa q$-representation) coincide with the equations, obtained by D'yakonov,[10] for the polarization moments $\rho_q^\varkappa$. The difference lies only in the expression for the function of $F_q^\varkappa$ (describing the excitation by the light), whose explicit form for 2^3S_1 He^4 atoms is not given below.

The change, Δn_e, in the electron density at magnetic resonance can be found by substituting the expressions for ρ_q^1 and ρ_q^2 (the formulas (21) and (23) from[10]) into the formulas (10), (13), and (14), and subtracting the "backing"—the value of δn_e for $\Delta\omega\to\infty$. As a result, we obtain for Δn_e the expression

$$\Delta n_e \sim \tilde{\sigma}\left\{C_1\left(\frac{F_0^1}{\gamma_1}\right)^2\frac{\omega_1^2}{\gamma_1^2+(\Delta\omega)^2+\omega_1^2} +C_2\left(\frac{F_0^2}{\gamma_2}\right)^2\frac{3\omega_1^2[\gamma_2^2+4(\Delta\omega)^2+\omega_1^2]}{[\gamma_2^2+(\Delta\omega)^2+\omega_1^2][\gamma_2^2+4(\Delta\omega)^2+4\omega_1^2]}\right\}. \tag{15}$$

Here $\omega_1=\mu_0 gH_1/\hbar$, $\Delta\omega=\omega-\omega_0$ ($\omega_0=\mu_0 gH_0/\hbar$, μ_0 is the Bohr magneton, g is the g-factor, H_0 is a constant magnetic field, and $2H_1$ is the amplitude of a resonance radio-frequency magnetic field oscillating with a frequency ω); γ_1 and γ_2 are the decay rates of the polarization moments ρ_q^1 and ρ_q^2 (of orientation and alignment) due to depolarizing collisions. The functions F_0^1 and F_0^2 are determined by the relations

$$F_0^1=\frac{7k+2}{36\sqrt{3}}\Gamma_0'\Phi_0^1, \quad F_0^2=-\frac{7k-2}{36\sqrt{3}}\Gamma_0'\Phi_0^2. \tag{16}$$

The quantities Φ_0^1 and Φ_0^2 are equal respectively to $1/\sqrt{6}$ and $-1\sqrt{30}$ for clockwise-polarized pumping light, 0 and $-1\sqrt{30}$ for unpolarized pumping light.

The formulas (16) for the quantities F_0^1 and F_0^2 were derived under the asumption that the pumping is done by light from a helium lamp. The spectrum of such a lamp in the $\lambda=1.08-\mu$ region consists of two lines: the D_0 line, corresponding to the $2^3S_1–2^3P_0$ transition, and the D_3 line, corresponding to the forbidden $2^3S_1–2^3P_1$ and $2^3S_1–2^3P_2$ transitions.[15] The coefficient k in the formula (16) is equal to the ratio of the spectral densities of the emissions at the maxima of the D_3 and D_0 lines: $k=I_{D_3}/I_{D_0}$. The quantity Γ_0' is proportional to the intensity of the pumping light ($\Gamma_0'=1/T_p^0$ is the rate of pumping by the light of the D_0 line). The formula (15) is valid for low pumping-light intensities, when the inequality $\Gamma_0'\ll\gamma_1,\gamma_2$ is fulfilled. Moreover, in deriving the formula (15), we assumed that the optical thickness of the plasma for the pumping light was small.

At exact resonance ($\Delta\omega=0$) the maximum value, $(\Delta n_e)_{max}$, of the electron-density-variation signal is, in accordance with the formula (15), obtained when there is radio-frequency saturation ($\omega_1\gg\gamma_1,\gamma_2$). The ratio, $Q=(\Delta n_e)c_{max}/(\Delta n_e)^u_{max}$, of the maximum signal values obtained with circularly-polarized and unpolarized pumping light depends, when (10b) is taken into account, on the quantity r_{10}. Consequently, the quantity r_{10} can be computed from the experimentally measured ratio Q. The formulas for the computation of r_{10} have the form

$$r_{10}=\frac{2}{3}\left(\frac{c+1}{c-1}\right), \quad c=\frac{1}{4}(\tilde{Q}-1)\left(\frac{7k-2}{7k+2}\right)^2\left(\frac{\gamma_1}{\gamma_2}\right)^2, \quad \tilde{Q}=\frac{(\Gamma_0')_u^2}{(\Gamma_0')_c^2}Q. \tag{17}$$

Here $(\Gamma_0')_u/(\Gamma_0')_c$ is equal to the ratio of the intensity of the unpolarized pumping light to that of the circularly-polarized pumping light.

For the estimation of r_{10} we can use the results obtained by Sevast'yanov and Zhitnikov.[1] It follows from the graph given in their paper that the ratio of the amplitude of the electron-density-variation signal obtained with circularly-polarized pumping light to the amplitude of the signal obtained with unpolarized pumping light virtually did not depend on the discharge strength, and was equal to 24 (in a strong discharge this ratio decreased to 20). The intensity of the unpolarized pumping light was roughly three times higher than the intensity of the circularly-polarized pumping light, since there was, in the case of pumping by unpolarized light, no polarizer to absorb about 70% of the light.

The quantity k for helium pump lamps is usually equal to 2–3.[15] There are no published data on the quantities γ_1 and γ_2 for metastable orthohelium. Under the assumption that these quantities are equal at $k = 3$, $(\Gamma_0')_u/(\Gamma_0')_c = 3$, and $Q = 24$, we obtain from the formulas (17) for the quantity r_{10} the value $r_{10} = 0.7$. This value does not differ very much from the above-obtained theoretical value of $r_{10} \approx 1$. It should, however, be borne in mind that the computation of the quantity r_{10} from the experimental data[1] is of the nature of an estimate, since it is not known whether the assumptions made above in deriving the formulas (17) that the pumping-light intensity was low, that the plasma layer was optically thin, and that there obtained radio-frequency saturation were fulfilled in the experiment. Irrespective of whether these assumptions were fulfilled or not, the experimental data[1] allow us, however, to establish for r_{10} with the aid of the formulas (10) a lower boundary: $r_{10} > \frac{2}{3}$. The fulfillment of this inequality is indicated by the fact that the electron-density-variation signals obtained with circularly-polarized pumping light and those obtained with unpolarized pumping light have the same polarity.

All the results of the present paper have been obtained under the assumption that total spin is conserved in Penning collisions. This assumption needs to be experimentally verified in each specific case. With the object of accomplishing such a verification in the case of Penning collisions of metastable orthohelium atoms, Hill and his co-workers carried out in[5] a comparison of the experimentally obtained value for the electron-density change that arises upon the destruction of the orientation of metastable 2^3S_1 atoms of He^3 with the corresponding theoretical value. Theoretical curves were obtained for several values of the parameter f, which was defined in such a way that the value $f = 0$ corresponded to the absence of spin dependence (i.e., to nonconservation of spin), while the value $f = 1$ corresponded to spin conservation. In the paper by Hill *et al.*,[5] it was assumed that the ionization cross sections for all the allowed combinations of the m states of the colliding metastable atoms were equal. If the discrepancies between the values of these cross sections are taken into account (in accordance with the data given in the table), then to the conservation of spin should correspond the theoretical curves in[5] with the value of f given by:

$$f = \frac{9r_{10}+6+(3r_{10}-2)P^2}{10r_{10}+4+2r_{10}P^2}, \tag{18}$$

where P is the polarization of the He^3 atoms in the ground state.

According to the formula (18), for $P = 8\%$ (such was the polarization in the experiment[5]) we obtain for the quantity f the values: $f = 1.07$ for $r_{10} = 1$ and $f = 1.12$ for $r_{10} = 0.7$. It can be seen from Fig. 2 in[5] that within the limits of experimental error the experimental data agree with such values of f, which indicates the conservation of total spin in Penning collisions of metastable orthohelium atoms.

A comparison with the data obtained by Hill *et al.*[5] shows that the total change in the electron density depends weakly on the relative value of the ionization cross sections corresponding to the various allowed combinations of the m states of the colliding atoms. For a more detailed comparison with the theoretical values (and, consequently, for a more exact verification of the conservation of total spin), a direct experimental determination of such cross sections is necessary. In the case of atoms with nuclear spin $I \neq 0$ information about the relative value of these cross sections could be given by a separate observation (in a sufficiently strong magnetic field) of the resonance electron-density-variation signals during the excitation of resonance transitions between different Zeeman (or HFS) sublevels of the Penning-collision partners.

In conclusion, the author considers it his duty to thank V. I. Perel' and R. A. Zhitnikov for useful consultations and for interest in the work, as well as B. N. Sevast'yanov for a discussion of the experiment data used in the present paper.

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Translated by A. K. Agyei.