experiment for the measurement of the relaxation characteristics of the studied effect, the thermal relaxation time falls in the range from 10 to 100 μsec, which is several orders of magnitude higher than the relaxation time τ of the studied effect.

Thus, we can draw the conclusion that, under the conditions of our experiment, the contribution of the heat change $\Delta\varepsilon_T$ and the thermal relaxation τ_T to the measured values of $\Delta\varepsilon$ and τ is vanishingly small.

1)The numerical coefficient $2/\sqrt{3}$ was omitted in Eq. (1) of[5].

2)Here and later in the text, the values of the constants for ND_3 are taken from[11,12]. In those cases in which there are no data for ND_3 the values of the constants for NH_3 are used.

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The analog of Mott scattering of a spin-1 or spin-zero structured particle by a spin-zero target

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The appearance of vector polarization of spin-1 particles, containing two bound particles each of spin 1/2, upon their scattering by spin-zero targets is investigated. A formula is obtained for the polarization under the assumption that in the system of colliding particles there is, in addition to the central field, a relativistic spin-orbit interaction whose operator is proportional to $(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\mathbf{l}$. It is shown that the polarization tensor, characteristic of the spin correlation, is conserved in the collision, this being a consequence of conservation of the system's total spin in the presence of the spin-orbit interaction. Calculation of the polarization in the system $He(2^3S)+He^{++}$ enables us to predict a maximum polarization $P\sim 0.4$ for the metastable states of helium for energies in the range 1 MeV. Possible experiments with regard to the determination of the polarization and the constants of the optical atomic potential are discussed.

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In 1932, N. Mott predicted the appearance of polarization in a beam of electrons scattered by spin-zero targets.[1] The reason for the emergence of polarization is the spin-orbit $\mathbf{l}\cdot\mathbf{s}$ interaction, which leads to the appearance of a preferred direction $\mathbf{n}$ of spin orientation. For an initially unpolarized beam this direction coincides with the normal to the scattering plane.

We shall consider the analogous phenomenon of the emergence of polarization as a consequence of the spin-orbit interaction in more complicated systems, which contain two bound particles each with spin $\frac{1}{2}$. Examples of such systems are helium atoms, the deuteron nucleus, etc. In such systems the initial spin state is characterized by a polarization vector $\mathbf{P}$ and by a polarization tensor $\hat{Q}$. Our goal is the determination of these characteristics after scattering in a system which contains the relativistic $\mathbf{l}\cdot\mathbf{s}$ interaction in addition to a central field. Below we consider the elastic scattering of particles in triplet ($s=1$) and singlet ($s=0$) states and the possibility of singlet-triplet transitions associated with such collisions.

1. GENERAL CONSIDERATIONS

We shall describe the spin state of a system consisting of two spin-$\frac{1}{2}$ particles by the density matrix ρ. The matrices obtained as direct products of the matrices I, $\sigma_{1\alpha}$, and $\sigma_{2\alpha'}$, given in the spin spaces of the individual particles (I is the identity matrix and $\sigma_{1\alpha}$ and $\sigma_{2\alpha'}$ are the two-dimensional Pauli matrices of the two particles), are introduced as basis matrices. Thus introducing the 4×4 matrices

$$I_{(4)}=I\times I,\quad \hat{\sigma}_{1\alpha}=\sigma_{1\alpha}\times I,\quad \hat{\sigma}_{2\alpha'}=I\times\sigma_{2\alpha'},$$
$$\hat{Q}_{\alpha\alpha'}=\sigma_{1\alpha}\times\sigma_{2\alpha'}\equiv\hat{\sigma}_{1\alpha}\hat{\sigma}_{2\alpha'},\qquad (1)$$

we obtain the following representation for the initial density matrix of the complete system:

$$\rho = {}^1/_4[I_{(4)} + \Sigma_\alpha P_\alpha(\hat\sigma_{1\alpha}+\hat\sigma_{2\alpha}) + \Sigma_{\alpha\alpha'} Q_{\alpha\alpha'}\hat\sigma_{1\alpha}\hat\sigma_{2\alpha'}]. \quad (2)$$

Here $P_\alpha = \langle s_\alpha \rangle = \mathrm{Tr}[(\frac{1}{2})(\hat\sigma_{1\alpha}+\hat\sigma_{2\alpha})\rho]$ denotes a component of the polarization vector and $Q_{\alpha\alpha'} = \mathrm{Tr}(\hat\sigma_{1\alpha}\hat\sigma_{2\alpha'}\rho)$ is a component of the polarization tensor $\hat Q$. Since

$$\langle \hat\sigma_1\hat\sigma_2 \rangle = \begin{cases} -3, & s=0 \\ 1, & s=1 \end{cases}, \quad (3)$$

we obtain the following conditions for the sum of the diagonal components:

$$\langle \hat\sigma_1\hat\sigma_2 \rangle = \Sigma Q_{\alpha\alpha} = \begin{cases} -3, & s=0 \\ 1, & s=1 \end{cases}. \quad (4)$$

The remaining (nondiagonal) components $Q_{\alpha\alpha'}$ can be set equal to zero without any loss of generality.

For $P_\alpha = 0$ and $Q_{11} = Q_{22} = Q_{33} \equiv Q$ (a pure state)

$$\rho = {}^1/_4(I_{(4)} + Q\hat\sigma_1\hat\sigma_2). \quad (5)$$

for $s = 0$ we have $Q = -1$, and the density matrix

$$\rho = {}^1/_4(I_{(4)} - \hat\sigma_1\hat\sigma_2) \equiv \Pi_0 \quad (6)$$

coincides with the spin projection operator on the state $s = 0$. For $s = 1$ we have $Q = \frac{1}{3}$ and

$$\rho = {}^1/_4(I_{(4)} + {}^1/_3\hat\sigma_1\hat\sigma_2) = {}^1/_{12}(3I_{(4)} + \hat\sigma_1\hat\sigma_2) \equiv {}^1/_3\Pi_1, \quad (7)$$

where Π_1 is the projection operator on the state $s = 1$.

The density matrix of the final state is given by $\rho' = M\rho M^+$, where M is the transition-amplitude matrix.[2] The algebraic structure of this matrix is determined by the invariants which can be constructed from the axial vectors $\hat\sigma_1$ and $\hat\sigma_2$ and from the vectors that depend on the geometry of the collision. In the absence of the spin-orbit interaction the structure of M is uniquely established and is given by an expression of the form

$$M = A + B\hat\sigma_1\hat\sigma_2, \quad (8)$$

where A and B are complex functions depending on the energy, scattering angle, and type of central interaction. If, then, the $\mathbf{l}\cdot\mathbf{s}$ interaction operator is proportional to $(\frac{1}{2})(\hat\sigma_1+\hat\sigma_2)\cdot\mathbf{l}$, where $\mathbf{l}$ is the orbital angular momentum operator, then the part of the matrix M due to such an interaction is proportional to the invariant $(\hat\sigma_1+\hat\sigma_2)\cdot\mathbf{n}$, where $\mathbf{n}$ denotes the normal to the scattering plane (see, for example, [3]). Therefore, we finally obtain

$$M = A + B\hat\sigma_1\hat\sigma_2 + G(\hat\sigma_1+\hat\sigma_2)\mathbf{n}. \quad (9)$$

We note that in Mott's theory for the scattering of a spin-$\frac{1}{2}$ particle by a spin-zero target, the analog of M is given by the matrix

$$M_{1/2} = a + b\sigma_1\mathbf{n}.$$

For the elastic scattering of a particle with spin 1 or 0 a relationship exists between the functions A and B, and can be established from the following considerations: Let $G = 0$. Then, to the extent that it is assumed that there is no exchange between the incident particle and the target (the total system is a two-particle system), the initial polarization characteristics P_α and $Q_{\alpha\alpha}$ remain without any changes after scattering. Hence it follows that the matrix M must coincide with the projection operator Π_1 for the initial triplet state and with the operator Π_0 for the initial singlet state. Thus, for an elastic collision in a system with total spin $s = 1$ the matrix M is of the form

$$M_1 = {}^1/_4(3I_{(4)} + \hat\sigma_1\hat\sigma_2)F + (\hat\sigma_1+\hat\sigma_2)\mathbf{n}G \quad (10)$$

and for total spin $s = 0$

$$M_0 = {}^1/_4(I_{(4)} - \hat\sigma_1\hat\sigma_2)F + (\hat\sigma_1+\hat\sigma_2)\mathbf{n}G. \quad (11)$$

2. ELASTIC SCATTERING

In the general case the scattering cross section is of the form

$$\sigma = \mathrm{Sp}\, M\rho M^+ = AA^* + BB^*(3 - 2\Sigma Q_{\alpha\alpha}) + (AB^* + A^*B)\Sigma Q_{\alpha\alpha} + 2GG^*(3 + \Sigma Q_{\alpha\alpha}) + 2[(A+B)G^* + (A^*+B^*)G]\mathbf{Pn}. \quad (12)$$

For $s = 0$

$$A = B = -{}^1/_4F, \qquad \Sigma Q_{\alpha\alpha} = -3,$$

the cross section $\sigma_0 = FF^*/4$ and does not depend on the amplitude G. This corresponds to the fact that at $s = 0$ the average value of the spin-orbit interaction operator vanishes for any arbitrary function, including the exact function. For $s = 1$

$$A = {}^3/_4F, \quad B = {}^1/_4F, \quad \Sigma Q_{\alpha\alpha} = 1$$

and from Eq. (12) it follows that

$$\sigma_1 = FF^* + 8GG^* + 2(FG^* + F^*G)\mathbf{Pn}. \quad (13)$$

After scattering, the spin polarization of a particle is given by

$$\sigma P_\alpha' = (AA^* + A^*B + AB^* + BB^*)P_\alpha + 4GG^*P_\alpha + 2GG^*\mathbf{Pn}n_\alpha + [(A^*+B^*)G + (A+B)G^*](1 + Q_{\alpha\alpha})n_\alpha - i[(A^*+B^*)G - (A+B)G^*][\mathbf{P}\times\mathbf{n}]_\alpha. \quad (14)$$

For $s = 0$ we obtain $P_\alpha' = 0, j$ as we should. For the triplet state

$$\sigma_1 P_\alpha' = FF^*P_\alpha + 4GG^*P_\alpha + 2GG^*\mathbf{Pn}n_\alpha + {}^4/_3(FG^* + F^*G)n_\alpha - i(F^*G - FG^*)[\mathbf{P}\times\mathbf{n}]_\alpha. \quad (15)$$

If at first no polarization is present, a vector polarization

$$\sigma_1 P_\alpha' = {}^4/_3(FG^* + F^*G)n_\alpha \quad (16)$$

appears after scattering in the system. The polarization is caused by the interference, and in this sense the result is analogous to the expression for the polarization in the Mott theory. After scattering we obtain the following result for the component $Q'_{\alpha\alpha}$

$$\sigma Q_{\alpha\alpha}{}'=AA^*Q_{\alpha\alpha}+BB^*[Q_{\alpha\alpha}-2(1-\Sigma Q_{\alpha\alpha})] + (A^*B+AB^*)(1-\Sigma Q_{\alpha\alpha}+Q_{\alpha\alpha})+2GG^*(1+\Sigma Q_{\alpha\alpha}-2Q_{\alpha\alpha}) + [(A^*+B^*)G+(A+B)G^*]2P_\alpha n_\alpha. \tag{17}$$

For $s=0$

$$\sigma_0 Q_{\alpha\alpha}{}'=-FF^*/4, \quad Q_{\alpha\alpha}{}'=-1,$$

i.e., the quantity $Q_{\alpha\alpha}$ is conserved during a collision. For $s=1$ and $P_\alpha=0$

$$\sigma_1^{(P=0)} Q'_{\alpha\alpha}=FF^*Q_{\alpha\alpha}+2GG^*(2-2Q_{\alpha\alpha}), \tag{18}$$

and hence $Q_{\alpha\alpha'}=\frac{1}{3}$, i.e., $Q_{\alpha\alpha}=\text{const}$. In the case $P\neq 0$

$$\sigma_1 Q'_{\alpha\alpha}={}^1/_3\sigma_1^{(P=0)}+(F^*G+FG^*)2P_\alpha n_\alpha. \tag{19}$$

Setting up the sum of the quantities $Q'_{\alpha\alpha}$, we find $\Sigma Q'_{\alpha\alpha}=1$, i.e., in both cases the initial spin correlation of the particles is conserved.

Let us discuss the results in more detail. The problem concerning polarization in a system of two unbound spin-$\frac{1}{2}$ particles, interacting in a central field, is treated in the article by Burke and Shey.[4] If one sets $G=0$ in the derived formulas, the results agree for scattering in the states with $s=0$ and $s=1$. That is, we obtain $P'_\alpha=P_\alpha$ and $Q'_{\alpha\alpha}=Q_{\alpha\alpha}$ in both spin states in agreement with their results.[4] In the case when the system of two particles is a superposition of singlet and triplet states (for example, the scattering of an electron by a hydrogen atom), a change of the initial values of P_α and $Q_{\alpha\alpha}$ takes place due to the exchange interaction during the collision. In our case, when the two particles are bound in either singlet or triplet states, changes of the vector polarization do not occur in the absence of the spin-orbit interaction. As is shown above, the polarization tensor is also an integral of the motion in the presence of the $\mathbf{l}\cdot\mathbf{s}$ interaction.

Finally, for comparison one should mention that the problem of the scattering of a spin-1 structureless particle by a spinless particle is solved in the book by Sitenko.[5] An expression of the form

$$M=A+B\mathbf{sn}+\Sigma C_{\alpha\alpha'}S_{\alpha\alpha'},$$

is used for the matrix M, where $S_{\alpha\alpha'}$ are the components of the symmetric tensor composed of three-rowed matrices s_α corresponding to spin 1, and the coefficients $C_{\alpha\alpha'}$ depend on the wave vectors determining the geometry of the collision. As is evident, in this representation of the matrix M the analog of the operator $\hat{\sigma}_1\hat{\sigma}_2$ does not exist, this being the operator whose introduction allows one to take the structure of a spin-1 particle into account. The other difference pertains to the invariants $C_{\alpha\alpha'}S_{\alpha\alpha'}$ which correspond to a type of interaction which is more general than the $\mathbf{l}\cdot\mathbf{s}$ interaction proposed in the present article.

3. INELASTIC SCATTERING

Assuming that the matrix M for an inelastic transition involving a change of the particle's spin is determined by formula (9), we find the following result for the singlet-triplet transition:

$$\sigma_{0-1}=AA^*+9BB^*-3(A^*B+AB^*), \quad \sigma_{0-1}Q_{\alpha\alpha}{}'=-AA^*-9BB^*+3(A^*B+AB^*)=-\sigma_{0-1}, \quad \sigma_{0-1}P_\alpha{}'=0, \quad Q_{\alpha\alpha}{}'=-1. \tag{20}$$

From here it follows that the initial spin correlation, corresponding to the value $s=0$ (the condition $\Sigma Q_{\alpha\alpha}=-3$), is preserved in the collision independently of the form of the amplitudes A, B, and G. In other words, the system's spin is conserved and the transition $0\to 1$ is forbidden. For the triplet-singlet transition, the formulas analogous to (20) have the form

$$\sigma_{1-0}^{(P=0)}=AA^*+BB^*+AB^*+A^*B+8GG^*, \quad \sigma_{1-0}^{(P=0)}Q'_{\alpha\alpha}=\sigma_{1-0}^{(P=0)}\cdot{}^1/_3, \quad Q'_{\alpha\alpha}={}^1/_3, \quad \sigma_{1-0}Q'_{\alpha\alpha}={}^1/_3\sigma_{1-0}^{(P=0)}+2P_\alpha n_\alpha[(A^*+B^*)G+(A+B)G^*], \quad \Sigma_\alpha Q_{\alpha\alpha}{}'=1. \tag{21}$$

Thus, in both cases $\Sigma_\alpha Q'_{\alpha\alpha}=\text{const}$ independently of the form of the amplitudes A, B, and G. This implies conservation of the initial spin in the system in the presence of the spin-orbit interaction. The conclusion that transitions involving a change of the spin are forbidden in the case under consideration follows immediately from general principles. In actual fact, since the spin-orbit interaction $\sim(\hat{\sigma}_1+\hat{\sigma}_2)\cdot\mathbf{l}$ is symmetric with respect to interchange of $\hat{\sigma}_1$ and $\hat{\sigma}_2$, the wave function is symmetric or antisymmetric with respect to the spin variables. Conservation of the wave function's symmetry in time implies forbiddenness of singlet-triplet transitions during a collision. For example, in helium atoms the indicated transitions will not be present during collisions with helium nuclei (of course, to within the accuracy with which the interaction is determined by the operator $(\sigma_1+\sigma_2)\cdot\mathbf{l}$). Inelastic scattering involving a change of the spin may occur thanks to the particle's exchange interaction with the target; however, such a problem is essentially a three-particle problem.

4. POLARIZATION IN THE SYSTEM $He(2^3S)+He^{++}$

For a quantitative estimate of the effect under discussion, let us consider the spin polarization of metastable atoms $He(2^3S)$ originating in elastic collisions with He^{++} nuclei. An experimental technique for the preparation of metastable helium atoms in concentrations sufficient for scattering experiments is described, for example, in[6,7]. In the range of energies corresponding to the maximum value of the polarization, the inelastic channels are energetically open together with the elastic scattering channel. A phenomenological calculation of the influence of the inelastic channels on elastic scattering can be carried out within the framework of the optical model.

Defining the scattering potential in the form

$$V(r)=V_0(r)(1+i\zeta)+\eta\frac{1}{r}\frac{\partial V_0(r)}{\partial r}(\hat{\sigma}_1+\hat{\sigma}_2)\mathbf{l} \tag{22}$$

as is the custom in the optical model, and calculating the amplitudes F and G in the Born approximation (it is assumed that the wave vector $k\gg 1$), for the polarization we obtain

$$\mathbf{P}=\frac{4}{3}\mathbf{n}\frac{2\zeta\eta k^2\sin\theta}{1+\zeta^2+8k^4\eta^2\sin^2\theta}. \quad (23)$$

The polarization reaches the maximum value

$$P_{\max}=\frac{\sqrt{2}}{3}\zeta(1+\zeta^2)^{-1/2} \quad (24)$$

at an energy $k_0^2=(1+\zeta^2)^{1/2}/2\sqrt{2}\eta$ and for the scattering angle $\theta=\pi/2$.

Since a rigorous calculation of the imaginary part of the optical potential is hardly realistic, we shall confine our attention to a discussion of a possible experiment for the determination of the polarization and an estimate of the parameter ζ. Let us begin with the estimate. According to the optical theorem $\operatorname{Im}f(0)=k\sigma_t/4\pi$, where σ_t is the total cross section and $f(0)$ is the forward scattering amplitude for elastic scattering. In the Born approximation we obtain the following expression for f

$$\zeta=k\sigma_t/4\pi F(0) \quad (25)$$

($F(0)$ denotes the amplitude for forward scattering by the potential $V_0(r)$). Assuming further that for $k \gg 1$ the cross section σ_t coincides in order of magnitude with the elastic scattering cross section, and calculating σ_{elas} and $F(0)$ by using one-electron wave functions for the 2^3S-state of He, we find that $\zeta\sim 2$ for $k_0^2\sim 3\times 10^8$. According to Eq. (24) we obtain $P\sim 0.4$ for an energy ~ 1 MeV.

Let us now turn to a discussion of a possible experiment. In this connection it is quite clear that experiments aimed at determination of the polarization acquire additional value as a means of reconstructing the imaginary part of the optical atomic potential. Therefore, such experiments would facilitate a description of atomic collisions according to the pattern of the theory of nuclear reactions.

The basic possibility of measuring the polarization P consists in a utilization of the Penning effect. Electrons and excited ions M^+ are formed in the Penning ionization process

$$\text{He}^{\text{met}}+M\rightarrow\text{He}+M^++e$$

with the participation of metastable helium atoms. The spin state of the electrons and certain characteristics of the M^+ emission depend on the vector polarization of He^{met}. For example, in the process

$$\text{He}(2^3S)\uparrow+\text{Cd}\rightarrow\text{He}+\text{Cd}^{+}+e(\uparrow) \quad (26)$$

the emission of the Cd^+ ions for transitions $\lambda J\rightarrow\lambda(J-1)$ is characterized by the asymmetry $A=(I_+-I_-)/(I_++I_-)$, which is related to the initial polarization of He^{met} in the following way[8]:

$$A=DP \quad (27)$$

($I_\pm$ denote the intensities corresponding to right-circular and left-circular polarizations). One can show that for the transition $5^2D_{5/2}-5^2D_{3/2}$ ($\lambda=4416$ Å) in Cd^+, the constant $D=0.7$.[8] Thus, a measurement of the asymmetry A of the radiation in an optical experiment allows us to determine the value of the polarization P and, therefore, the value of the parameter ζ.

A somewhat different possibility for the determination of P is related to the fact that the Penning electrons turn out to be polarized ($P_e=\langle\sigma\rangle\neq 0$) if the excited atom is oriented beforehand. One can indicate several processes in which the initial polarization of the $\text{He}(2^3S)$ is completely transmitted to the ionized electron. Such a situation ($P_e=P$) is realized in the process $\text{He}^{\text{met}}+\text{Cd}$ which has already been discussed, and takes place, for example, in the collision

$$\text{He}(2^3S)\uparrow+\text{Cs}\rightarrow\text{He}+\text{Cs}^++e(\uparrow).$$

An analysis of the polarization of the electrons allows us to determine the value of P for a known energy of the collision $\text{He}(2^3S)+\text{He}^{++}$.

In conclusion let us emphasize that experiments on the determination of the induced spin polarization of particles in the triplet state and the re-establishment of the parameters of the optical atomic potentials would be pioneering achievements in the physics of atomic collisions and would stimulate the development of the theory of atomic collisions in the energy range of order MeV.

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