The differential cross section for the elastic scattering of unpolarized protons on unpolarized electrons at rest is calculated taking into account two mechanisms: one-photon and scalar-boson exchange. The spin correlation coefficients, when the proton beam and the electron target are both arbitrarily polarized, have also been calculated. These observables are calculated in terms of the proton electromagnetic form factors, namely magnetic and electric ones. Some peculiarities of the inverse kinematics (the mass of the colliding particle is larger than mass of the target particle) have been discussed. It was shown that all the spin correlation coefficients in the elastic proton electron collisions are proportional to the proton magnetic form factor. The same behaviour takes place for the spin correlation coefficients in the elastic electron proton scattering (the electron beam and proton target are both polarized). It was shown that only the interference of the two mechanisms (one-photon and one-boson) gives nonzero contribution to the spin correlation coefficients. If the spin vectors of the proton beam and electron target lie in the reaction plane then the corresponding spin correlation coefficients are zero for the case when scattered electron momentum is in the direction of the proton beam momentum.

KEY WORDS: polarization phenomena, electron, nucleon, form factors, inverse kinematics, scalar boson

EFFECTS OF SCALAR BOSON IN ELASTIC PROTON-ELECTRON SCATTERING

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The differential cross section for the elastic scattering of unpolarized protons on unpolarized electrons at rest is calculated taking into account two mechanisms: one-photon and scalar-boson exchange. The spin correlation coefficients, when the proton beam and the electron target are both arbitrarily polarized, have also been calculated. These observables are calculated in terms of the proton electromagnetic form factors, namely magnetic and electric ones. Some peculiarities of the inverse kinematics (the mass of the colliding particle is larger than mass of the target particle) have been discussed. It was shown that all the spin correlation coefficients in the elastic proton electron collisions are proportional to the proton magnetic form factor. The same behaviour takes place for the spin correlation coefficients in the elastic electron proton scattering (the electron beam and proton target are both polarized). It was shown that only the interference of the two mechanisms (one-photon and one-boson) gives nonzero contribution to the spin correlation coefficients. If the spin vectors of the proton beam and electron target lie in the reaction plane then the corresponding spin correlation coefficients are zero for the case when scattered electron momentum is in the direction of the proton beam momentum.

KEY WORDS: polarization phenomena, electron, nucleon, form factors, inverse kinematics, scalar boson
Some models which introduce new particles, in particular scalar boson, can be motivated by various anomalies: the excess in the muon anomalous magnetic moment, the proton charge radius puzzle [5] and others. The theoretical and experimental consequences of these models are considered in [3]. The production of weakly coupled scalar bosons via nuclear de-excitation of an excited element into the ground state was discussed in [6]. The possibility that a new interaction between muons and protons is responsible for the discrepancy between the CODATA value of the proton radius and the value deduced from the measurement of the Lamb shift in muonic hydrogen was explored in [7]. The cross section and some polarization observables of elastic lepton-nucleon scattering caused by one-photon and one-scalar-boson exchange have been calculated in [8]. In the paper [9] it was shown that spin-0 Dark Matter particles annihilating into electron positron pair could be responsible for the bright 511 keV gamma ray observed by INTEGRAL [10] from the galactic bulge. A recent suggestion proposes that the observed lack of the asymptotic behavior of the pion-photon transition form factor might be due to the production of new particles or states. Two classes of models are considered. In the first, scalar or pseudoscalar particles are introduced with a mass within 10 MeV [11]. The authors of the paper [12] propose to perform the spectroscopy of the mass structure of the rich and complex dark sectors via mono-photon searches at low-energy lepton colliders.

The unpolarized and polarized observables for the elastic scattering of a proton projectile on an electron target at rest were derived in [13]. The authors of the paper [14] suggested that proton elastic scattering on atomic electrons may allow a precise measurement of the proton charge radius. The main advantage of this proposal is that inverse kinematics allows one to access very small values of the transferred momenta, up to four orders of magnitude smaller than the ones presently achieved, where the cross section is huge. The model-independent QED radiative corrections to the differential cross section of the elastic scattering of the protons on electrons at rest have been calculated in [15]. The radiative corrections due to the emission of virtual and real (soft and hard) photons in the electron vertex as well the vacuum polarization are taken into account. The possibility to build beam polarimeters for high-energy polarized proton beams on the basis of the elastic scattering of the protons on electrons at rest have been discussed in [16]. It was shown that polarimeter based on the elastic proton electron scattering gives a good opportunity to reliably measure the longitudinal proton beam polarization as transverse. The inverse kinematics was proposed to measure neutron capture cross section of unstable isotopes [17]. For proton and alpha-induced reactions it was suggested to employ a radioactive ion beam hitting a proton or helium target at rest.

In this paper we consider the elastic scattering of protons by electrons at rest. The differential cross section for the elastic scattering of protons on electrons at rest is calculated taking into account the one photon and scalar boson exchange. The spin correlation coefficients, when the proton beam and the electron target are both arbitrarily polarized, have also been calculated. These observables are calculated in terms of the proton electromagnetic form factors.

Purpose of our research is to calculate the differential cross section for the elastic scattering of unpolarized protons on unpolarized electrons at rest taking into account two mechanisms: one-photon and scalar-boson exchange. The spin correlation coefficients, when the proton beam and the electron target are both arbitrarily polarized, have also been calculated.

### GENERAL FORMALISM

Let us consider the reaction (Figure)

\[
p(p_1) + e^-(k_1) \rightarrow p(p_2) + e^-(k_2),
\]

where the particle momenta are indicated in parenthesis, and \( q = k_1 - k_2 = p_2 - p_1 \) is the transferred four momentum. We consider this reaction in the lowest order, i.e., the interaction between electron and proton is described by exchange of a scalar boson or photon.

**Inverse kinematics**

One can show that, for a given energy of the proton beam, the maximum value of the four momentum transfer squared, in the scattering on electrons at rest, is

\[
(-k^2)_{\text{max}} = \frac{4m^2 |\vec{p}|^2}{M^2 + 2mE + m^2},
\]

where \( m \) (\( M \)) is the electron (proton) mass, \( E(\vec{p}) \) is the energy (momentum) of the proton beam.

The four momentum transfer squared is expressed as a function of the energy of the scattered electron, \( \varepsilon_z \), as:

\[
k^2 = (k_1 - k_2)^2 = 2m(m - \varepsilon_z),
\]

where

\[
\varepsilon_z = \frac{m(E + m)^2 + |\vec{p}|^2 \cos^2 \theta_e}{(E + m)^2 - |\vec{p}|^2 \cos^2 \theta_e},
\]

where \( \theta_e \) is the angle between the proton beam and the scattered electron momenta.
From the energy and momentum conservation, one finds the following relation between the angle and the energy of the scattered electron:

$$\cos \theta_{e} = \frac{(E + m)(\varepsilon_{2} - m)}{|\vec{p}||\vec{k}_{2}|},$$ (4)

where $\vec{k}_{2}$ is the momentum of the recoil electron and this formula shows that $\cos \theta_{e} \geq 0$ (the electron can never be scattered backward). One can see from Eq. (3) that, in the inverse kinematics, the available kinematical region is reduced to small values of $\varepsilon_{2}$:

$$\varepsilon_{2,max} = m - \frac{2(E + m) + m^{2} - M^{2}}{M^{2} + 2mE + m^{2}},$$ (5)

which is proportional to the electron mass. From the momentum conservation, one can find the following relation between the energy and the angle of the scattered proton $E_{2}$ and $\theta_{p}$:

$$E_{2}^{\pm} = \frac{(E + m)(M^{2} + mE)\pm M |\vec{p}| \cos \theta_{p} \sqrt{\sin^{2} \theta_{p} - \sin^{2} \theta_{e}}}{(E + m)^{2} - |\vec{p}|^{2} \cos^{2} \theta_{p}},$$ (6)

and this relation shows that, for one proton angle, there may be two values of the proton energies, (and two corresponding values for the recoil-electron energy and angle as well as for the transferred momentum $k^{2}$). This is a typical situation when the center-of-mass velocity is larger than the velocity of the projectile in the center of mass, where all the angles are allowed for the recoil electron. The two solutions coincide when the angle between the initial and final hadron takes its maximum value, which is determined by the ratio of the electron and scattered hadron masses $M_{h}$, $\sin \theta_{h,max} = m / M_{h}$.

\section*{DIFFERENTIAL CROSS SECTION}

In the considered approximation, the matrix element $\hat{M}$ of the reaction (1) can be written as a sum of two terms

$$\hat{M} = \hat{M}_{\gamma} + \hat{M}_{\phi},$$ (7)

where the first (second) term describes the $\gamma$ ($\phi$) exchange mechanism. Matrix element $\hat{M}_{\gamma}$ can be written as:

$$\hat{M}_{\gamma} = \frac{e^{2}}{k^{2}} j_{\mu} J_{\mu},$$ (8)

where $j_{\mu}(J_{\mu})$ is the leptonic (hadronic) electromagnetic current. The leptonic current is

$$j_{\mu} = \bar{u}(k_{2})\gamma_{\mu} u(k_{1}),$$ (9)

where $u(k_{1,2})$ is the spinor of the incoming (outgoing) electron. The hadronic electromagnetic current can be written as
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\[ J_\mu = \bar{u}(p_2) \left[ F_1(k^2) \gamma_\mu - \frac{1}{2M} F_2(k^2) \sigma_{\mu\nu} k^\nu \right] u(p_1) = \]

\[ \bar{u}(p_2) \left[ G_M(k^2) \gamma_\mu - F_2(k^2) P_\mu \right] u(p_1), \]

where \( F_1(k^2) \) and \( F_2(k^2) \) are the Dirac and Pauli proton electromagnetic form factors, \( G_M(k^2) = F_1(k^2) + F_2(k^2) \) is the Sachs proton magnetic form factor, \( P_\mu = (p_1 + p_2)_\mu / (2M) \), and \( M \) is the proton mass.

Matrix element \( M_\phi \) can be written as:

\[ M_\phi = \frac{g_e g_p}{k^2 - m_\phi^2} \bar{u}(p_2) u(p_1) \bar{u}(k_2) u(k_1), \]

where \( m_\phi \) is the scalar boson mass and the interaction between the scalar boson and electron or proton has the following form: \( g_\phi A_\mu u_\mu \), \( (i=e, p) \), \( g_\phi \) is the corresponding coupling constant, \( \phi \) is the wave function of the scalar boson.

The matrix element squared is written as:

\[ M^2 = 16\pi^2 \frac{\alpha^2}{k^2} (A_\gamma + \lambda A_\phi + \lambda^2 A_{\phi\phi}), \]

where

\[ A_\gamma = L_{\mu\nu} W_{\mu\nu}, L_{\mu\nu} = j_\mu j_\nu^*, W_{\mu\nu} = J_\mu J_\nu^*, \lambda = \frac{k^2}{e^2} \frac{g_e g_p}{k^2 - m_\phi^2}, \]

and \( \alpha = e^2 / (4\pi) = 1/137 \) is the electromagnetic fine structure constant.

The leptonic tensor, \( L_{\mu\nu}^{(0)} \) for unpolarized initial and final electrons has the form:

\[ L_{\mu\nu}^{(0)} = 2k^2 g_{\mu\nu} + 4(k_{1\mu} k_{2\nu} + k_{1\nu} k_{2\mu}). \]

The contribution to the electron tensor corresponding to the polarized electron target is

\[ L_{\mu\nu}^{(p)} = 2ime_{\mu\nu\alpha\beta} k_\alpha S_\beta, \]

where \( S_\beta \) is the initial electron polarization four vector.

The hadronic tensor, \( W_{\mu\nu}^{(0)} \) for unpolarized initial and final protons can be written in the standard form, through two unpolarized structure functions:

\[ W_{\mu\nu}^{(0)} = \left( -g_{\mu\nu} + \frac{k_\mu k_\nu}{k^2} \right) W_1(k^2) + P_\mu P_\nu W_2(k^2). \]

The structure functions \( W_i, i = 1, 2 \), are expressed in terms of the nucleon electromagnetic form factors

\[ W_1(k^2) = -2k^2 G_M^2(k^2), W_2(k^2) = 8M^2 \frac{G_M^2(k^2) + \tau G_E^2(k^2)}{1 + \tau}, \]

where \( G_E(k^2) = F_1(k^2) - \tau F_2(k^2) \) is the proton electric form factor and \( \tau = -k^2 / 4M^2 \).

The second term in Eq. (12) has the following form

\[ A_{\phi\phi} = -2Re \{ S_p[u(k_2) \bar{u}(k_2) \gamma_\mu u(k_1) \bar{u}(k_1)] S_p[u(p_2) \bar{u}(p_2) B_\mu u(p_1) \bar{u}(p_1)] \}, \]

\[ B_\mu = [G_M(k^2) \gamma_\mu - F_2(k^2) P_\mu]. \]

The third term in Eq. (12) is

\[ A_{\phi\phi} = S_p[u(k_2) \bar{u}(k_2) u(k_1) \bar{u}(k_1)] S_p[u(p_2) \bar{u}(p_2) u(p_1) \bar{u}(p_1)]. \]
The differential cross section is related to the matrix element squared by

\[
d\sigma = \frac{(2\pi)^4 |M|^2}{4\sqrt{(k_1 \cdot p_1)^2 - m^2M^2}} \frac{d^3 \vec{k}_2}{(2\pi)^3 2E_2} \frac{d^3 \vec{p}_2}{(2\pi)^3 2E_2} \delta^4(k_1 + p_1 - k_2 - p_2),
\]

where \( p_2(E_2) \) is the momentum (energy) of the final proton, \( \epsilon_2 \) is the energy of the scattered electron and the bar denotes averaging over the spins of the proton beam and electron target. From this point, formulas will differ from the elastic electron-proton scattering, as we introduce a reference system where the electron is at rest. In this system, the differential cross section can be written as:

\[
d\sigma = \frac{1 - |\vec{M}|^2}{32\pi m^2 \vec{p}^2},
\]

where \( \vec{p} \) is the momentum of the proton beam. Using the relation \( k^2 = 2m(m - \epsilon_2) \) one can write

\[
d\sigma = \frac{1 - |\vec{M}|^2}{64\pi m^2 \vec{p}^2}.
\]

The differential cross section over the solid angle can be written as

\[
d\sigma = \frac{1 - \epsilon_2^2}{32\pi^2 m\epsilon_2 (-k^2) E + m},
\]

where \( d\Omega_\epsilon = 2\pi d\cos\theta_\epsilon \) (due to azimuthal symmetry). We used the relation

\[
d\epsilon_2 = \frac{p}{E + m(e_2 - m)} \frac{d\Omega_\epsilon}{2\pi}.
\]

The expression of the differential cross section for unpolarized proton-electron scattering (averaged over the initial electron and proton spins), in the coordinate system where the electron is at rest can be written as:

\[
\frac{d\sigma}{d\epsilon_2} = \frac{\pi \alpha^2 D}{2m^2 \vec{p}^2 k^4}, \quad D = (D_\gamma + \lambda D_\gamma + \lambda^2 D_\phi),
\]

where

\[
D_\gamma = k^2(k^2 + 2m^2)G_M^2(k^2) + 2\left[k^2M^2 + \frac{1}{1 + \tau}\left(2mE + \frac{k^2}{2}\right)^2\right]G_E^2(k^2) + \tau G_M^2(k^2),
\]

\[
D_\gamma = -4mMG_E(k^2)(4mE + k^2), \quad D_\phi = 4M^2(1 + \tau)(2m^2 - k^2).
\]

**POLARIZATION OBSERVABLES**

Let us consider the spin correlation coefficients when both initial particles have arbitrary polarization, \( \vec{p} + \vec{\epsilon} \rightarrow p + e \). These polarization observables were considered in [16], in view of using the polarized proton-electron scattering for the measurement of the longitudinal and transverse polarizations of a high energy proton beams.

Let us calculate the hadronic tensor, when the initial proton is polarized. The contribution of the proton polarization to the hadronic tensor is:

\[
W_{\mu\nu}(\eta_l) = -2iG_M(k^2)\left[MG_M(k^2)\epsilon_{\mu\nu\rho\sigma}k_\sigma \eta_\rho \eta_\beta - F_2(k^2)P_\mu \eta_\nu P_\rho P_\sigma P_\beta\right],
\]

where the four vector \( \eta_l \) stands for initial proton polarization. One can see that all the correlation coefficients in \( \vec{p}\vec{\epsilon} \) collisions are proportional to the proton magnetic form factor. This is a well known fact for \( \vec{e}\vec{p} \) scattering [18]. The dependence of the different polarization observables, namely the spin correlation coefficients, on the polarization four vector of the initial proton is completely determined by the spin dependent part of the hadronic tensor \( W_{\mu\nu}(\eta_l) \).
Let us choose an orthogonal system with the \( z \) axis directed along the proton beam momentum \( \vec{p} \), scattered electron momentum \( \vec{k} \) lies in the \( xz \) plane and the \( y \) axis is directed along the vector \( \vec{p} \times \vec{k} \). Therefore, in this system \( \ell \parallel z, \ t \parallel x \) and \( n \parallel y \).

In the considered frame, where the target electron is at rest, the polarization four vector of the initial proton (electron) has the following components
\[
\eta_i = \left( \frac{\vec{p} \cdot \vec{S}_1}{M}, \frac{\vec{p}(\vec{p} \cdot \vec{S}_1)}{M(E + M)} \right), \quad S = (0, \xi),
\]
where \( \vec{S}_1(\xi) \) is the unit vector describing the polarization of the initial proton (electron) in its rest system.

Applying the P-invariance of the hadron electromagnetic interaction, one can write the following expression for the dependence of the differential cross section on the polarization of the initial particles:
\[
\frac{d\sigma}{dk^2}(\xi, \vec{S}_1) = \left( \frac{d\sigma}{dk^2} \right)_{un} \left[ 1 + C_{1i} \xi_i S_{1i} + C_{2i} \xi_i S_{1i} + C_{3i} \xi_i S_{1i} + C_{4i} \xi_i S_{1i} + C_{5i} \xi_i S_{1i} \right],
\]
where \( C_{ik}, i, k = \ell, t, n \) are the corresponding spin correlation coefficients which characterize elastic proton-electron scattering in the case when the proton beam and electron target are both arbitrarily polarized.

The spin correlation coefficients can be written as follows
\[
C_{ij} = C_{ij}^{(\gamma)} + \lambda C_{ij}^{(\varphi)} + \lambda^2 C_{ij}^{(\phi\phi)},
\]
where \( i, j = \ell, t, n \).

The expressions of the spin correlation coefficients due to the \( \gamma \) exchange mechanism are
\[
DC_{nn}^{(\gamma)} = 4mMk^2G_M(k^2)G_M(k^2),
\]
\[
DC_{nt}^{(\gamma)} = 4mM\tau k^2 \frac{G_M(k^2)}{1 + \tau} \left[ (1 - \frac{4M^2}{k_{max}^2})G_E(k^2) + (\frac{k^2}{k_{max}^2} - 1)G_M(k^2) \right],
\]
\[
DC_{tt}^{(\gamma)} = 8mMp \left[ -k^2 \left( 1 - \frac{k^2}{k_{max}^2} \right) \right]^{1/2} \frac{G_M(k^2)}{1 + \tau} \left[ \tau G_M(k^2) - G_E(k^2) \right] - \frac{k^2}{k_{max}^2} m(E + m) \left[ \tau G_M(k^2) + G_E(k^2) \right],
\]
\[
DC_{tu}^{(\gamma)} = -2mMk^2 \left( \frac{E - M}{M - m} \right) \left[ -k^2 \left( 1 - \frac{k^2}{k_{max}^2} \right) \right]^{1/2} \frac{G_M(k^2)}{1 + \tau} \left[ \tau G_M(k^2) + G_E(k^2) \right],
\]
\[
DC_{ti}^{(\gamma)} = 4k^2 \frac{G_M(k^2)}{1 + \tau} \left( mE - \tau M^2 \right) G_M(k^2) + \tau (M^2 + mE) G_M(k^2) - \frac{(M^2 + mE) k^2}{k_{max}^2} m(E + m) \left[ \tau G_M(k^2) + G_E(k^2) \right],
\]
where \( s = M^2 + m^2 + 2Em \).

The expressions of the spin correlation coefficients due to the interference of the \( \gamma \) and scalar boson exchange mechanisms are
\[ DC_{nm}^{(\gamma)} = -4G_M(k^2)\left[ E^2k_z^2 + (E + m)\frac{k^2}{m}\left[ E\varepsilon_z + \frac{k^2}{4m}(E + m) \right] \right], \tag{32} \]
\[ DC_{ii}^{(\gamma)} = -4(E + m)G_M(k^2)\left[ E\varepsilon_z + E\varepsilon_z + (E + m)(1 - \frac{mE}{p^2})\frac{k^4}{4m^2} \right], \]
\[ DC_{ii}^{(\phi)} = 2G_M(k^2)\frac{M}{p}k_zk_\perp(E + m)\sin\theta, \]
\[ DC_{ii}^{(\theta)} = 4k_zG_M(k^2)\sin\theta\left[ pE(m + \varepsilon_z) + \frac{k^2}{2m}(E + m)(p + m\frac{E}{p}) \right], \]
\[ DC_{ii}^{(\phi)} = -\frac{1}{M}G_M(k^2)\left[ 4E(M^2k_z^2 + 2p^2\varepsilon_z^2) + 2\frac{k^2}{m}(E + m)[4E^2\varepsilon_z + mE(k_z - \varepsilon_z)\frac{k^2}{2m}M^2] + \frac{1}{p^2m^2}(E + m)^2(mM^2 + 2Ep^2) \right]. \]

And at last we have
\[ DC_{ii}^{(\psi)} = 0, \quad i, j = \ell, t, n. \tag{33} \]

**CONCLUSION**

The elastic scattering of protons from electrons at rest was investigated in a relativistic approach in the one photon and scalar boson exchange approximation.

The differential cross section and the spin correlation coefficients, when the proton beam and the electron target are both arbitrarily polarized, have been calculated in terms of the proton electromagnetic form factors.

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