THEORY OF NEUTRON SCATTERING IN THE COULOMB FIELD OF A NUCLEUS

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The role of certain electrodynamic effects in the scattering of neutrons in the Coulomb field is analyzed. The scattering of the neutron is treated in the first and second approximations of perturbation theory, taking into account the electrical form factor of the neutron and the contact interaction of the neutron with the nucleus. A discussion is given of the possible role of diagrams which are of sixth order in e, and contain the scattering of photons in the Coulomb field of the nucleus. Upper limits are estimated for the polarizability of the proton and neutron, which are related to nonlinear electrodynamic effects. It is shown that the deviations from Schwinger's formulas which are found for the scattering of a moving magnetic moment in the Coulomb field of a nucleus may play an essential role in determining the mesonic polarizability of the neutron from scattering experiments.

1. INTRODUCTION

IN a paper of Aleksandrov and Bondarenko, [1] which was undertaken to confirm the effect of Schwinger scattering of neutrons in the Coulomb field of nuclei, it was mentioned that improvement of the experimental data could make it possible to detect the influence of the polarizability of the meson cloud of the neutron. In fact, in later experiments [2] on scattering of neutrons by nuclei with high Z, deviations from the expected behavior of the differential cross section were observed. But because of the inadequacy of the experimental data, these deviations are still not regarded as definite, particularly since the analysis of another set of experimental data [3] has shown that the deviations are within the limits of error.

In this situation it is of interest to analyze various effects which could cause these deviations. Such an analysis would, in the first place, answer the question whether it is reasonable to attempt to determine the electric polarizability α_n of the neutron from neutron scattering data, if the polarizability is of the order of the mesonic polarizability of the proton $\alpha_p \approx 10^{-42}\ \mathrm{cm}^3$. [4] Secondly, it enables one to evaluate such experiments from the point of view of obtaining information about other effects which occur here, such as nonlinear electrodynamic effects. Most of this type of analysis has been done by various authors. [5-7] In the present paper we consider questions bearing on certain electrodynamic effects. In particular, we discuss the contribution of the first and second Born approximations to the scattering of the neutron magnetic moment, and estimate the role of sixth order diagrams in e, which contain subdiagrams for photon scattering in the nuclear Coulomb field. We also discuss some questions related to scattering of photons by nuclei.

For a phenomenological description of the behavior of a nucleon in an electromagnetic field, one uses the scheme of quantum electrodynamics, where the following expression is taken for the matrix element of the current:

$$\langle p' | j_\mu | p \rangle = i\bar{u}(p') [g_{1n}(q^2)\gamma_\mu + g_{2n}(q^2)\sigma_{\mu\nu}q_\nu] u(p),$$
$$q = p' - p, \qquad \sigma_{\mu\nu} = \tfrac{1}{2} i (\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu),$$
$$g_{1n}(0) = 0, \qquad g_{2n}(0) = \mu_n. \tag{1}$$

Here $\bar{u}(p')$ and $u(p)$ are spinors for the final and initial neutron states, with momenta p' and p; $g_{1n}(q^2)$ and $g_{2n}(q^2)$ are the electric and magnetic form factors of the neutron.

The diagrams describing the process of neutron scattering in the nuclear Coulomb field in the first and second approximations, and the lowest order radiative corrections, are shown in Figs. 1a, b, c, d. Diagram a describes the interaction of the magnetic moment with the electric field of the nucleus in the first order of perturbation theory, and leads to the Schwinger scattering of neutrons [8] which was mentioned earlier. Diagram b shows the second Born approximation for this process. The role of diagram c, which describes the polarization of

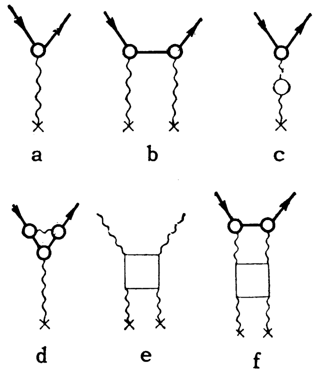

FIG. 1. Diagrams of processes discussed. Solid lines are nucleon lines, the wavy lines are photons and the thin lines are electrons. x is an external field.

the electron-positron vacuum, was estimated in a paper of Breit and Rustgi,[6] where they showed that it gives a contribution not exceeding 1% of the contribution from the polarizability of the meson cloud. The contribution of diagram d cannot be calculated consistently, since the theory using the current (1) is unrenormalizable. But we can take account of it in a certain sense by using for our calculations the experimental value of the anomalous magnetic moment of the neutron $\mu_n = \lambda e\hbar/2Mc$, $\lambda = -1.91$.

Since diagram b shows an effect which is of lower order in e than diagrams c and d, it is not obvious before hand that it plays a negligible role in the scattering of neutrons at small angles. A computation of the contribution of diagram b will be given in Sec. 2. The contribution of this diagram turns out to be small.

Among the higher order diagrams, the sixth order diagrams which contain the diagram for photon scattering in the nuclear Coulomb field (Fig. 1e) may be important for the electromagnetic scattering of neutrons. To illustrate this claim, we recall that the interpretation of these deviations in terms of a polarization interaction

$$U(R) = -\tfrac{1}{2}\,\alpha_n \mathbf{E}^2(R) \tag{2}$$

led to[2,7] an anomalously high value of the neutron polarizability $\alpha_n \approx 10^{-40}$ cm^3. On the other hand, this interaction gives an additional term $\alpha_n k^2(\mathbf{e}\cdot\mathbf{e}')$ in the amplitude for scattering of photons by nucleons (where **k**, **e**, and **e**′ are the wave number of the photon and its polarization before and after scattering). The dispersion relation for the photon-nucleon scattering amplitude at zero angle enables one to express the total coefficient γ_t for terms which are quadratic in the frequency in terms of the total cross section σ_t for inelastic interaction of photons with nucleons:

$$\gamma_t = \frac{1}{2\pi^2}\int_{k_{th}}^{\infty} \frac{\sigma_t(k')}{k'^2}\,dk', \qquad \gamma_t = \gamma_m + \gamma_e. \tag{3}$$

Here k_{th} is the threshold for the first inelastic reaction, while γ_m and γ_e are the contributions of mesonic and electrodynamic processes, respectively. An estimate of γ_m for the proton on the basis of data on photoproduction of mesons gives $\gamma_{pm} \approx \alpha_{pm} \approx 10^{-42}$ cm^3,[4] which agrees with the experimental data on scattering of photons by protons.[9] Such an estimate is valid if we are interested in scattering of photons with energies of 50–60 MeV at large angles, since then, because of the peculiarities of the angular distribution of γ-n scattering, only the part which is related to mesonic effects will play an important role. This is not true in the low energy limit, and we must include the effect of creation of electron-positron pairs, which gives for γ_{pe} a value $\sim 7\times 10^{-40}$ cm^3. Such a large value for γ_{pe} indicates the possibly important role of diagram e in proton scattering. As for neutrons, the mesonic part of the polarizability α_{nm} is of the same order as $\alpha_{pm} \approx 10^{-42}$ cm^3; to compute γ_{ne} one must know the cross section for photoproduction of electron-positron pairs on the neutron. This cross section is computed in Sec. 3. The value found for γ_{ne} was $\sim 10^{-44}$ cm^3. In Sec. 4 the problem of the polarizability of the neutron is treated from the point of view of nonlinear phenomenological electrodynamics. In the concluding section, we discuss the results.

2. CALCULATION OF SCATTERING IN FIRST AND SECOND APPROXIMATIONS

The matrix elements corresponding to diagrams a and b of Fig. 1 are equal to:

$$S^{(1)} = \langle p_2 | j_4 | p_1\rangle A_4(p_2 - p_1),$$

$$S^{(2)} = -\frac{ie^2}{(2\pi^4)}\bar{u}(p_2)\left\{\int d^4p\,\sigma_{4\nu}(p_2 - p)_\nu A_4(p_2 - p)\frac{i\hat{p} - M}{p^2 + M^2}\right.$$
$$\left.\times\,\sigma_{4\mu}(p - p_1)_\mu A_4(p - p_1)\right\} u(p_1);$$

$$A_4(q) = 2\pi i\delta(q_0)F_n(q)/(q^2 + \eta^2), \qquad \hat{p} = \gamma_\mu p_\mu,$$

$$F_{1n}(q) = 3Ze\,(qR)^{-3}(\sin qR - qR\cos qR),$$

$$F_{2n} = Ze\sin qR/qR. \tag{4}$$

We have neglected the neutron form factor in $S^{(2)}$. We use the usual notation for the momenta. The function $A_4(q)$ is the Fourier transform of the nuclear potential. The quantity η characterizes the screening effect, and $F_{1,2n}(q)$ are the form factors describing the distribution of charge over the volume and the surface of the nucleus.

Using the results of Dalitz,[10] who calculated integrals similar to ours, we get the final expression for the differential cross section for neutron scattering:

$$\frac{d\sigma}{d\Omega} = \frac{F_n^2(q)}{4p^2v^2\sin^4(\theta/2)}\, g_{1n}^2(q^2)\left(1 - \frac{v^2}{c^2}\sin^2\frac{\theta}{2}\right) + \frac{F_n^2(q)\, g_{2n}^2(q^2)}{\sin^2(\theta/2)} + \frac{p^2Z^4e^4}{\cos^2(\theta/2)}\left[\pi\left(1 - \sin\frac{\theta}{2}\right)^2 + 4\ln^2\sin\frac{\theta}{2}\right]. \quad (5)$$

The constant η has been set equal to zero. The first two terms in the formula correspond to diagram a, the third to diagram b. In the third term, we have set $F_n(q) = Ze$.

We emphasize the difference between the second term and the result of Schwinger,[8] which was found within the framework of nonrelativistic quantum mechanics, and contains the factor $\cot^2(\theta/2)$ instead of $\sin^{-2}(\theta/2)$. This difference is related to the fact that in our treatment, in addition to the usual interaction $-(\mu_n/Mc)\sigma\cdot\mathbf{E}\times\mathbf{p}$ which was the only one considered by Schwinger, we also automatically include the interaction $i(\mu_n/Mc)(\mathbf{E}\cdot\mathbf{p})$ which was first pointed out by Foldy.[12] The latter interaction gives an additional contribution to the cross section equal to $Z^2e^2\mu_n^2$. Its ratio to the contribution computed from the Schwinger formula is 0.04, 0.12, 0.28, and 0.48% for angles of 2, 4, 6, and 8°. This is of the same order as the contribution from polarization scattering of the neutron, if we take for the polarizability of the neutron a value $\sim 10^{-42}$ cm³.[4]

The difference is especially important for large angles, but there the absolute value of the cross section for Schwinger scattering is small compared to nuclear scattering. Besides, in computing the first approximation we included the electric form factors of the neutron and the nucleus. A numerical estimate of the effect of the form factors shows that they given a contribution which is close to that from polarization scattering of the neutron.

The third term in (5), which represents the correction from the second approximation, depends linearly on the kinetic energy of the neutron. In the energy region below 100 MeV, this correction may give a significant contribution. The numerical values of this correction for a neutron energy of 3 MeV and scattering angles of 2, 6, and 30° are, respectively, 0.003, 0.015, and 0.1% of the Schwinger scattering.

3. PHOTOPRODUCTION OF ELECTRON-POSITRON PAIRS ON A NEUTRON

In this section, we calculate the cross section for photoproduction of pairs on a neutron. For estimates of γ_{ne} and the Delbruck scattering of photons by neutrons, one must know the total cross section for production of pairs in the energy range up to 100 MeV, where the role of the recoil of the nucleons and the nucleon form factors can be neglected. The matrix element for the process $\gamma + n \to n + e^+ + e^-$ has the form

$$\langle\gamma n|S|ne^+e^-\rangle = \frac{ie^3}{(2\pi)^{5/2}}\frac{Mm\delta(k+p_0-p-q_+-q_-)}{\sqrt{2k_0\varepsilon_+\varepsilon_-E_0E}}\frac{1}{\mathbf{Q}^2}\bar{u}(q_-)\left\{\hat{e}\frac{1}{\hat{f}_1-m}\gamma_\mu + \gamma_\mu\frac{1}{\hat{f}_2-m}\hat{e}\right\}v(-q_+)\bar{w}(p)F_\mu w(p_0),$$

$$F_\mu = (\mu_n\hbar/2Mc)\sigma^{\mu\nu}(q-q_0)_\nu, \quad (6)$$

where $q_+(\epsilon_+, \mathbf{q}_+)$ and $q_-(\epsilon_-, \mathbf{q}_-)$ are the 4-momenta of electrons and positrons; $k(k_0, \mathbf{k})$ and $\hat{e}$ are the 4-momentum and polarization of the photon; $\bar{w}$ and w are nucleon spinors; $\mathbf{Q} = \mathbf{k} - \mathbf{q}_+ - \mathbf{q}_-$ is the momentum transfer. In the laboratory coordinate system, after averaging over initial and summing over final states, we get the following expression for the differential cross section[11] (θ_+, θ_- are the angles of emergence of e^+ and e^-, φ is the angle between the vectors $\mathbf{k}\times\mathbf{q}_+$ and $\mathbf{k}\times\mathbf{q}_-$:[1])

$$\frac{d\sigma}{d\Omega_-d\Omega_+d\varepsilon_+} = -\frac{e^4}{8(2\pi)^5}\frac{1}{k_0^3}\left(\frac{e\mu_n}{M}\right)^2|\mathbf{q}_+||\mathbf{q}_-|\left\{\frac{\mathbf{q}_+^2\sin^2\theta_+(4\varepsilon_-^2-1)}{(\varepsilon_+-|\mathbf{q}_+|\cos\theta_+)^2\mathbf{Q}^2} + \frac{\mathbf{q}_-^2\sin^2\theta_-(4\varepsilon_+^2-1)}{(\varepsilon_--|\mathbf{q}_-|\cos\theta_-)^2\mathbf{Q}^2} + \frac{2|\mathbf{q}_+||\mathbf{q}_-|\sin\theta_+\sin\theta_-\cos\varphi\,[1-(\varepsilon_--\varepsilon_+)^2-k_0^2]}{(\varepsilon_--|\mathbf{q}_-|\cos\theta_-)(\varepsilon_+-|\mathbf{q}_+|\cos\theta_+)\mathbf{Q}^2} - \frac{k_0^2}{\mathbf{Q}^2}\left[\frac{\varepsilon_+-|\mathbf{q}_+|\cos\theta_+}{\varepsilon_--|\mathbf{q}_-|\cos\theta_-} + \frac{\varepsilon_--|\mathbf{q}_-|\cos\theta_-}{\varepsilon_+-|\mathbf{q}_+|\cos\theta_+} + 2\frac{\mathbf{q}_+^2\sin^2\theta_++\mathbf{q}_-^2\sin^2\theta_-}{(\varepsilon_+-|\mathbf{q}_+|\cos\theta_+)(\varepsilon_--|\mathbf{q}_-|\cos\theta_-)}\right] - \frac{1}{2}\frac{\mathbf{q}_+^2\sin^2\theta_+}{(\varepsilon_+-|\mathbf{q}_+|\cos\theta_+)^2} - \frac{1}{2}\frac{\mathbf{q}_-^2\sin^2\theta_-}{(\varepsilon_--|\mathbf{q}_-|\cos\theta_-)^2} - \frac{3}{2}\frac{2|\mathbf{q}_+||\mathbf{q}_-|\sin\theta_+\sin\theta_-\cos\varphi(\varepsilon_--\varepsilon_+)^2}{(\varepsilon_+-|\mathbf{q}_+|\cos\theta_+)(\varepsilon_--|\mathbf{q}_-|\cos\theta_-)}\right\}. \quad (7)$$

Integrating this formula over θ_+, θ_- and φ, we get an expression for the positron spectrum:

$$\frac{d\sigma}{d\varepsilon_+} = 8e^6\frac{\mu_n^2}{(2M)^2}\frac{1}{k_0^3}\left\{-12 - \frac{3}{\mathbf{q}_-^2} - \frac{3}{\mathbf{q}_+^2} + 3\left(\frac{\varepsilon_-^3}{|\mathbf{q}_-|^3} + \frac{\varepsilon_-}{|\mathbf{q}_-|}\right)L\right.$$

[1]From now on in this section we use the units $\hbar = c = m = 1$.

$$+3\left(\frac{\varepsilon_+^3}{|\mathbf{q}_+|^3}+\frac{\varepsilon_+}{|\mathbf{q}_+|}\right)L_+ - \frac{2}{|\mathbf{q}_-||\mathbf{q}_+|}(1-2k_0^2+4\varepsilon_+\varepsilon_-)L_+L_-$$

$$-\frac{L_{+-}}{|\mathbf{q}_+||\mathbf{q}_-|^2}\left[\frac{k_0^2}{|q_+|^2|q_-|^2}(2|q_+|^2|q_-|^2-3\varepsilon_+\varepsilon_-+3)\right.$$

$$+\frac{k_0}{|\mathbf{q}_-|^3}(2\varepsilon_-^2+1)L_-$$

$$\left.+\frac{k_0}{|\mathbf{q}_+|^3}(2\varepsilon_+^2+1)L_-\right]\Bigg\};$$

$$L_+=\ln(\varepsilon_++|\mathbf{q}_+|),\quad L_-=\ln(\varepsilon_-+|\mathbf{q}_-|),$$

$$L_{+-}=\ln\frac{1+\varepsilon_+\varepsilon_-+|\mathbf{q}_+||\mathbf{q}_-|}{k_0}. \qquad (8)$$

The electron-positron pair spectra computed from (8) are similar to the spectra from pair production on a charge.

The dependence of the total cross section for pair production on the photon energy for the ultrarelativistic case of $\epsilon_+ \gg 1$ has the form

$$\sigma_n = 16e^2(\mu_n/2M)^2\left[\tfrac{4}{3}\ln^2 2k_0 - \tfrac{26}{9}\ln 2k_0 + \tfrac{151}{54} - 2\pi^2/9\right]. \quad (9)$$

The energy dependence of the total cross section is shown in Fig. 2; it differs only slightly from the energy dependence in the case of pair production on a charge. Although the matrix elements for the processes $\gamma + n \rightarrow n + e^+ + e^-$ and $\gamma + p \rightarrow p + e^+ + e^-$ differ by a factor $\mathbf{Q}^{-2}$, the integration of the differential cross sections over angle does not give any essential change in the rate of rise of the cross section with k_0. This is connected with the fact that in pair production processes, momentum transfers greater than unity play a minor role.

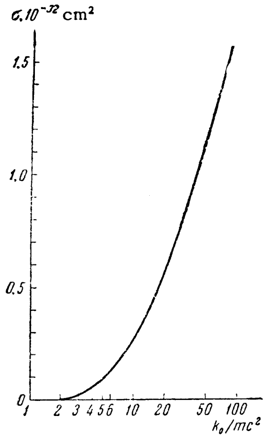

FIG. 2. Total cross section for the process $\gamma + n \rightarrow n + e^+ + e^-$.

From the cross section σ_n we can calculate the real part of the amplitude for Delbruck scattering of the photon at zero angle by the anomalous moment of the neutron, and can also estimate the contribution of electrodynamic corrections associated with nonlinear effects, in the low energy limit of the γ-n scattering. From the dispersion relations it follows that the contribution of pair production to the γ-n scattering amplitude is given by the expression

$$\mathrm{Re}\, f(k_0) = k_0^2\gamma(k_0) = \frac{k_0^2}{2\pi^2}\int_{k_{th}}^{\infty}\frac{\sigma_n(k_0')}{k_0'^2-k_0^2}dk_0'. \qquad (10)$$

The result of a computation of $\gamma(k_0)$ is given in Fig. 3.

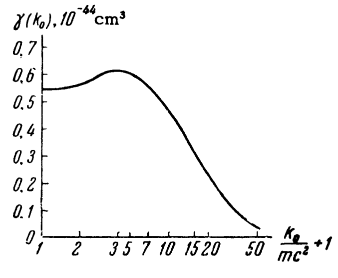

FIG. 3. $\mathrm{Re}\, f(k_0)/k_0^2$, where $f(k_0)$ is the amplitude for forward Delbruck scattering of photons by the anomalous magnetic moment of the neutron.

From Fig. 3 we see that $\gamma(0) = 0.54 \times 10^{-44}$ cm^3. Consequently the contribution from the diagrams shown in Fig. 1e, in the low energy limit of γ-n scattering, is 1% of the contribution from the polarizability of the meson cloud of the neutron. On the other hand, this indicates that the deviations discussed above in experiments on scattering of neutrons by nuclei can hardly be explained in this way.

4. ASYMPTOTIC BEHAVIOR OF THE INTERACTION POTENTIAL BETWEEN NEUTRONS AND NUCLEI

The coefficients γ_{pe} and γ_{ne}, calculated using only the cross sections for production of electron-positron pairs, we shall call "polarizability" coefficients, associated with nonlinear electrodynamic effects. The word "polarizability" is enclosed in quotation marks because our definition does not coincide with the usual one (which associates it only with the cross section for electric dipole absorption, σ_{E_1}). In the first section we stated that estimates of γ_{pe} and γ_{ne} can serve only as indications of a possible role of diagram e in processes of scattering of protons and neutrons by nuclei. Exact quantitative estimates can be made by a direct computation of diagram e. Such computations are very tedious.

In this section we shall calculate the asymptotic behavior of the potential for the electromagnetic interaction of a nucleus with a neutron at rest. To do this we use the Lagrangian for the electromagnetic field given by Heisenberg and Euler:[13]

$$L = (\mathbf{E}^2 - \mathbf{H}^2)/8\pi + (\alpha/16\pi^2)\,[(\mathbf{E}^2-\mathbf{H}^2)^2 + 7\,(\mathbf{EH})^2], \quad (11)$$

where $\alpha = 2e^4/45m^4$, **E** and **H** are the electric and magnetic field intensities. This Lagrangian can be used to describe weak, slowly varying fields

$$|\mathbf{E}| \ll E_k, \quad |\mathbf{H}| \ll H_k,$$

$$E_k = H_k = m^2c^3/e\hbar, \quad (\hbar/mc)\,\mathrm{grad}\,|F_i| \ll |F_i|; \quad (12)$$

where F_i are the components of the fields E_i and H_i, and m is the electron mass.

Applying the variational principle, we get the second pair of equations for the electromagnetic field:

$$\mathrm{rot}\,\mathbf{H} = (\alpha/32\pi)\{32(\mathbf{H}^2 - \mathbf{E}^2)\,\mathrm{rot}\,\mathbf{H} - 32\,[\mathbf{H}\nabla](\mathbf{H}^2 - \mathbf{E}^2) - 112\,[\mathbf{E}\nabla](\mathbf{EH})\},$$

$$\mathrm{div}\,\mathbf{E} = (\alpha/32\pi)\,[32\,(\mathbf{E}\nabla)(\mathbf{H}^2 - \mathbf{E}^2) + 32\,(\mathbf{H}^2 - \mathbf{E}^2)\,\mathrm{div}\,\mathbf{E} - 112\,(\mathbf{H}\nabla)(\mathbf{EH}). \quad (13)^*$$

In the variation we have assumed that the fields **E** and **H** are time-independent. Within their region of validity, the nonlinear field equations thus obtained effectively describe processes associated with the virtual production of pairs.

The energy density of the field is

$$w = (\mathbf{E}^2 + \mathbf{H}^2)/8\pi + \alpha\,(\mathbf{E}^2 - \mathbf{H}^2)(3\mathbf{E}^2 + \mathbf{H}^2) + \beta\,(\mathbf{EH})^2, \quad (14)$$

where $\beta = {}^{14}/_{45}\,(e/m)^4$. Subtracting from the energy of the field of **E** and **H** the energy of the field **E′** without **H** and **H′** without **E**, we get the interaction energy of the particles producing **E** and **H**. We give the final expression for the interaction energy:

$$U_{\mathrm{int}}(R) = \frac{1}{2}\int(\varphi_0\rho_1 + \mathbf{A}_0\mathbf{j}_1)\,d\tau - \frac{\alpha}{16\pi^2}\int[2\mathbf{H}_0^2\mathbf{E}_0^2 - 7\,(\mathbf{E}_0\mathbf{H}_0)^2]\,d\tau. \quad (15)$$

In this formula, $\mathbf{E}_0$ and $\mathbf{H}_0$ denote the field of the nuclear charge Ze and the neutron magnetic moment $\mu_n\sigma$; A_0 and φ_0 are, respectively, the potentials of these fields; R is the distance between the neutron and nucleus;

$$\rho_1 = (\alpha/128\pi^2)\,[32\,(\mathbf{E}_0\nabla)\,\mathbf{H}_0^2 - 112\,(\mathbf{H}_0\nabla)(\mathbf{E}_0\mathbf{H}_0)],$$

$$\mathbf{j}_1 = (\alpha/128\pi^2)\,\{32\,[\mathbf{H}_0\nabla]\,\mathbf{E}_0^2 - 112[\mathbf{E}_0\nabla](\mathbf{E}_0\mathbf{H}_0)\}. \quad (16)$$

Formulas (14) and (15) were obtained on the assumption that the true fields **E** and **H** can be represented as series in the small parameter α:

$$\mathbf{E} = \mathbf{E}_0 + \alpha\mathbf{E}_1 + \ldots, \qquad \mathbf{H} = \mathbf{H}_0 + \alpha\mathbf{H}_1 + \ldots. \quad (17)$$

The integration in (15) extends over all space except for the region where the fields E_0 and H_0 cease to satisfy the criterion for applicability of the equations. These regions are the sphere of radius a surrounding the neutron and the region near the nucleus. For $R \to \infty$, the interaction potential can be written as a series in the reciprocal of the radius:

$$U_{\mathrm{int}}(R) = -\tfrac{1}{2}\alpha'_n e^2R^{-4} + \theta(R^{-5}),$$

$$\alpha'_n = \gamma a^{-3}, \quad \gamma = 1{,}8\,\mu_n^2\alpha. \quad (18)$$

If we take for a the value $\sim 0.5\,\hbar/mc$, we get a value close to $\gamma_{ne} = 0.5 \times 10^{-44}\,\mathrm{cm}^3$.

The value $\hbar/mc$ limits the region of validity of the equations and is also a characteristic length. The strong dependence of the interaction on the parameter a is not due to anything fundamental but is the result of this specific computation. The region around the nucleus gives no contribution to the coefficient of R^{-4} and can therefore be disregarded. This is caused by the difference in the dependence of E_0 and H_0 on distance. Thus, for very large R, we have

$$U_{\mathrm{int}} = -\tfrac{1}{2}\alpha'_n\mathbf{E}_0^2.$$

For $R \approx \hbar/mc$, other interaction terms may be important. For such distances it is not at all clear that one can represent U_{int} as a series in 1/R. Klein [14] has shown that all the additional terms, quadratic in the frequency, which appear in the amplitude for photon-nucleon scattering come from an interaction of the form

$$-\tfrac{1}{2}\alpha\mathbf{E}^2 - \tfrac{1}{2}\beta\mathbf{H}^2.$$

Here α and β are constants, while **E** and **H** are the fields of the scattered waves. This is an indication that the expansion (18) may also hold for small distances R.

5. CONCLUSION

The computations which we have made of the first and second approximations including all corrections and the estimates of γ_{pe} and γ_{ne} show that one cannot explain the deviations in the experiments on scattering of neutrons by nuclei [2] by the electrodynamic effects considered here. At the same time we see that in deducing the mesonic polarizability from experimental scattering data, the effects considered earlier [5-7] and in this paper may be very important. We have shown that in addition to the usual interactions of the neutron with the Coulomb field, there is a specific additional interaction described by the expression U(R) $= -\alpha'_n\mathbf{E}^2/2$ as $R \to \infty$, which is related to nonlinear electrodynamic effects. An exact quantitative estimate of its importance is difficult. But

*rot = curl, $[\mathbf{H}\nabla] = \mathbf{H} \times \nabla$.

from our computations it follows that other terms in the expansion in inverse powers of R may also be important in treating the experimental results. This in turn may lead to a strong energy dependence in the region of the threshold for pair production in collisions of neutrons with nuclei.

It is thus not excluded that this kind of effect will be noticeable when the experimental data are improved considerably. The need for such an improvement in accuracy is already indicated by the fact that numerous attempts to explain the observed deviation have had no success. In addition there is a need for measurements at several neutron energies, in order to study the variation of the effect with energy. The last remarks apply even more strongly to the study of the electromagnetic scattering of nuclei by nuclei with large Z. In this case the constant $\gamma_{nuc,e}$ is equal to $Z^2\gamma_{pe}$. It is true that these effects must be seen on the background from ordinary Rutherford scattering. It seems to us that an investigation of this possibility would be of particular interest.

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