Parity nonconservation effects in the photodesintegration of polarized deuterons

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Abstract

P-odd correlations in the deuteron photodesintegration are considered. The \(\pi\)-meson exchange is not operative in the case of unpolarized deuterons. For polarized deuterons a P-odd correlation due to the \(\pi\)-meson exchange is about \(3 \times 10^{-9}\). Short-distance P-odd contributions exceed essentially than the contribution of the \(\pi\)-meson exchange.

\textit{PACS:} 11.30.Er; 13.40.-f

\textit{Keywords:} Deuteron; Weak nuclear forces
1 Introduction

In the past few years discussions about measuring of cross-section asymmetry in the deuteron photodisintegration with polarized photons becomes very popular according to the experimental progress: creating intense sources of polarized photons, electrons, and neutrons. On the other side, theoretical treatments of deuteron are relatively reliable due to the small bound energy. One may hope that they will resolve a contradiction between experiments with $^{133}$Cs and other nuclear experiments which exists at present [1..6].

The theoretical studies parity nonconservation effects in the deuteron were started in [7-11]. The electron-deuteron scattering was investigated in [11-13]. However in this process the effect of the nuclear parity violation is masked by neutral currents. Numerical estimates of this effect were made in [14-16]. Desintegration of deuterons by polarized photons were considered in [16-21]. The point is that the nuclear anapole moment (AM) of $^{133}$Cs was recently discovered and measured with good accuracy in atomic experiment [1]. The result of this experiment is in a reasonable quantitative agreement with the theoretical predictions, starting with [2, 3], if the so-called “best values” [4] are chosen for the parameters of P-odd nuclear forces. But as it is shown in the paper [6], the contribution to the total cross-section asymmetry due to the $\pi$-meson exchange vanishes. The contribution of vector meson exchange is essential, and gives the maximal magnitude for asymmetry $10^{-7}$. However the vector meson ($\rho, \omega$) exchange has the typical range $r_V \sim 1/m_V \sim 0.25 \text{fm}$, that is less than the nucleon size $0.86 \text{fm}$. So because of unreliable theoretical estimates this contribution is not so interesting. Thus it is interesting to consider polarized deuterons photodisintegration. We make all of calculations in the potential model. It is legitimate since the typical range of interaction $1/m_\pi$ is essential more than the experimental nucleon size.

We use in present paper the deuteron wave function in the zero range approximation.

$$\psi_\sigma^d = \sqrt{\frac{\kappa}{2\pi (1 - \kappa r_t)}} \frac{e^{-\kappa r}}{r} \chi^\sigma, \quad (1)$$

where $\chi^\sigma$ is a spin wave function.

It is, strictly speaking, inconsistent, but this function fails only at the small range and give us the correct behavior if the radius is much more than the effective radius of the triplet state $r >> r_t$. Matrix element of the electric dipole transition does not depend on function behavior at small range and we may use the zero range approximation for its calculation. As to the magnetic dipole transition or for the weak potential matrix element the situation is worse because of a sensitivity to the small range contribution their operators. Let us mention
that this function does not satisfy to the normalization condition with the correction factor \( \sqrt{1 - \kappa r_t} \) and if we wish to make calculations sensitive to the small range with this function we must modify it for the right normalization. It is easy to understand that we must neglect \( \sqrt{1 - \kappa r_t} \). 

## 2 Amplitudes calculation

The operators of electric dipole and magnetic dipole transitions are \[ [22] \]

\[
H_{E1} = -i e \sqrt{2 \pi} \omega ne \frac{r}{2},
\]

\[
H_{M1} = -i \frac{e}{2m} \sqrt{2 \pi} \omega (\mu_p \sigma_p + \mu_n \sigma_n + \frac{1}{2}) \left( \frac{k \times e}{k} \right).
\]  (2)

Where \( r_p \) and \( l_p \) are proton coordinate and momentum, \( e \) and \( k \) are polarization and momentum of photon. Now we may calculate the amplitude of the regular electric dipole transition in the deuteron photodesintegration. The initial state is the deuteron wave function \( \psi_d \). It is obviously that final state is continuous \( p \)-wave. Further, we may write in amplitude a plane wave instead of \( p \)-wave, since \( E1 \)-transition selects by itself only \( p \)-state from the plane wave.

Then the amplitude is

\[
A_{E1} = -2 e \sqrt{2 \pi} \omega \sqrt{2 \pi} \sqrt{1 - \kappa r_t} \left( \frac{p e}{\sqrt{1 - \kappa r_t}(\kappa^2 + p^2)^2} \right).
\]  (3)

Due to the weak parity nonconservation interaction, the initial deuteron \( s \)-wave has mixture of the \( p \)-wave, and the final \( p \)-wave has mixture of the \( s \)-wave. Thus mixing \( M1 \) transitions via intermediate states becomes possible.

Parity nonconservation \( \pi \)-meson exchange potential may be written in the following form \[ [23] \]

\[
V = -i \frac{g g}{4 \pi m} (\sigma_p + \sigma_n) \nabla e^{-m \pi r}.
\]  (4)

Then we may write the total amplitude of transition

\[
A = \langle p, \sigma' | H_{E1} | \psi_d, \sigma \rangle + \sum_n \frac{\langle p, \sigma' | H_{M1} | n \rangle \langle n | V | \psi_d, \sigma \rangle}{E_d - E_n}
\]
Let us consider the second expression of the (5) and calculate transition from the deuteron into an intermediate state due to the weak interaction. As it was mentioned above the \( p \) state may be written as a plane wave

\[
\psi(p) = e^{i\mathbf{p}\cdot\mathbf{r}} | \chi^\sigma \rangle.
\]

Then this transition is

\[
\langle \mathbf{p}, \sigma'' | V | \psi_d \rangle = -i \frac{g g'}{4 \pi m} \langle \chi'' | (\sigma_p + \sigma_n) | \chi^\sigma \rangle \sqrt{\frac{\kappa}{2 \pi}} \int e^{-i \mathbf{k} \cdot \mathbf{r}} \frac{e^{-m \pi \mathbf{r}}}{r} e^{-\kappa r} d\mathbf{r}. \tag{6}
\]

Simple calculations leads to the following expression for the weak transition

\[
\sqrt{\frac{\kappa}{2 \pi k m}} \frac{g g'}{2 \pi} \langle \chi'' | \mathbf{p} (\sigma_p - \sigma_n) | \chi^\sigma \rangle f(p). \tag{7}
\]

Here \( f(p) \) is

\[
f(p) = \frac{1}{2} \left[ \frac{m_\pi - \kappa}{p} \left( 1 - \frac{m_\pi + \kappa}{p} \arctan \frac{p}{m_\pi + \kappa} \right) + \arctan \frac{p}{m_\pi + \kappa} \right]. \tag{8}
\]

Now one may consider \( M1 \) transition in the second term (5)

\[
\langle \mathbf{p}, \chi'' | H_{M1} | \mathbf{k}, \chi'' \rangle = -i (2 \pi)^3 \frac{e}{2 m} \sqrt{2 \pi \omega} [\mathbf{n}_k \times \mathbf{e}] \delta(\mathbf{k} - \mathbf{p}). \tag{9}
\]

Then the second term in after summarize over all of intermediate states (momentum and spin) give us the following expression

\[
i \frac{e g g'}{2 p m (\kappa^2 + p^2)} \sqrt{\frac{\kappa}{2 \pi}} [\mathbf{n}_k \times \mathbf{e}] \langle \chi'' | (\mu_p \sigma_p + \mu_n \sigma_n - \frac{i [\mathbf{p} \times \nabla_p]}{2}) | \sigma'' \rangle \delta(\mathbf{k} - \mathbf{p}) \tag{10}
\]

Here we used the known completeness relation

\[
\sum_{\sigma} | \chi^\sigma \rangle \langle \chi^\sigma | = 1
\]
to summarize over all of intermediate spin states.

Because of the orthogonality of radial s-functions in the last term of the formula (5) intermediate state $n$ must be only the deuteron state. That’s why the angular momentum operator is not operative here. After lengthy calculations we obtain the result

\[-i \frac{g}{2} f(p) \sqrt{2 \pi \omega} \frac{\sqrt{\kappa}}{2 \pi} \frac{n_k \times e}{2 p m (\kappa^2 + p^2)} \langle \chi^\sigma | p (\sigma_p + \sigma_n) (\mu_p \sigma_p + \mu_n \sigma_n) | \chi^\sigma \rangle \]  

(11)

Then for the total amplitude after summarize of two terms we find

\[A = -2e \sqrt{2 \pi \omega} \sqrt{2 \pi \kappa} \frac{p e}{\sqrt{(1 - \kappa r_t)(\kappa^2 + p^2)^2}} \delta_{\sigma\sigma'} \]

\[+ i \frac{e}{2 p m (\kappa^2 + p^2)} \frac{\sqrt{\kappa}}{2 \pi} [n_k \times e] \langle \chi^\sigma' | (\mu_p \sigma_p + \mu_n \sigma_n) p (\sigma_p + \sigma_n) - p (\sigma_p + \sigma_n) (\mu_p \sigma_p + \mu_n \sigma_n) | \chi^\sigma \rangle \]

\[+ e \sqrt{2 \pi \omega} \sqrt{2 \pi \kappa} \frac{p e}{\sqrt{(1 - \kappa r_t)(\kappa^2 + p^2)^2}} \delta_{\sigma\sigma'} \]

(12)

3 Differential and total cross-sections

The differential cross section depends on amplitude as

\[\frac{d\sigma}{d\Omega} = \frac{p m}{8 \pi^2} |A|^2. \]  

(13)

Then we have

\[\left( \frac{d\sigma}{d\Omega} \right) = \frac{1}{3} \sum_{\sigma} \frac{2 e^2 \kappa p |p e|^2}{(1 - \kappa r_t)(\kappa^2 + p^2)^3} - \]

\[\frac{i}{3} \sum_{\sigma} \frac{eg\kappa f(p) (pe^*) [n \times e]}{2\pi \sqrt{1 - \kappa r_t m (\kappa^2 + p^2)^2}} \langle \chi^\sigma | 2(\mu_p + \mu_n) (I (pI) - (pI)I) - i[p \times I] | \chi^\sigma \rangle. \]

It is obviously, the parity violation contribution to the cross-section is proportional to the average spin of the initial (unpolarized) deuteron. Thus the $\pi$-meson exchange does not operate here. This fact for the total cross-section was mentioned in the present paper [6].
Now we are interesting in polarized deuterons and unpolarized photons. Then after easy treatment one may obtain the total expression for the differential cross-section

$$\left( \frac{d\sigma}{d\Omega} \right)_{\text{tot}} = \left( \frac{d\sigma}{d\Omega} \right)_{E1} + \Delta \frac{d\sigma}{d\Omega}, \quad \text{(14)}$$

where

$$\frac{d\sigma}{d\Omega}_{E1} = e^2 \frac{\kappa p (p^2 - (p_n)^2)}{(1 - \kappa r_t)(\kappa^2 + p^2)^3} \quad \text{(15)}$$

is a ordinary expression for the electric dipole desintegration of the deuteron. And

$$\Delta \frac{d\sigma}{d\Omega} = -\frac{e^2 g \bar{g} \kappa p^2 f(p)}{2\pi m \sqrt{1 - \kappa r_t (\kappa^2 + p^2)^2}} \left( \mu_p + \mu_n - \frac{1}{2} \right) \left( nI - \frac{I_p n_p}{p^2} \right) \quad \text{(16)}$$

is a correction to the regular differential cross section due to the $\pi$-meson exchange.

Now it is easy to integrate this result over angles and find the total cross-section

$$\sigma = \frac{8\pi e^2 \kappa p^3}{3 (1 - \kappa r_t)(\kappa^2 + p^2)^3} - \frac{4 e^2 g \bar{g} \kappa p^2 f(p)}{3 m \sqrt{1 - \kappa r_t (\kappa^2 + p^2)^2}} \left( \mu_p + \mu_n - \frac{1}{2} \right) nI. \quad \text{(17)}$$

## 4 Vector meson exchange

Unfortunately, the $\pi$-meson contribution into the amplitude is not dominating. There are also vector-meson (so called short-distance) contributions of two types. The first of them is dominating near the threshold and the second one has the similar form as the $\pi$-meson exchange.

These contributions may not be reliably calculated with good accuracy as it was mentioned above. But we use the potential model to estimate their magnitudes. It is important to understand the relation between cross-section correction due to the $\pi$-meson exchange and the vector meson one.

We mean the Jastrow repulsion between nucleons at small distance \cite{3,24} to obtain wave function mixtures. According to the paper \cite{12} we use perturbative deuteron wave function in the following form

$$\delta \psi_d = -i\lambda t (\Sigma \nabla) \sqrt{\frac{\kappa}{2\pi}} \frac{e^{-\kappa r}}{r}. \quad \text{(18)}$$

Admixtures to the $s$ and $p$-waves of the continuous spectrum are
\[ \delta \psi_s = i \frac{\alpha_s}{1 + i p \alpha_s} \lambda_s \nabla \left( \frac{e^{ipr}}{r} \right), \]

\[ \delta \psi_p = -\lambda_s \frac{\alpha_s}{1 + i p \alpha_s} \Sigma p \frac{e^{ipr}}{r}. \]

Here \( \alpha_s \) is a triplet scattering length, \( \Sigma = \sigma_p - \sigma_n \), \( \lambda_t \) and \( \lambda_s \) are \[ \lambda_s = (0.028h_\rho^0 - 0.023h_\rho^2 + 0.028h_\omega^0) \times 10^{-7} m_\pi^{-1} = -0.16 \times 10^{-7} m_\pi^{-1}, \]

\[ \lambda_t = (0.032h_\rho^0 + 0.001h_\omega^0) \times 10^{-7} m_\pi^{-1} = -0.37 \times 10^{-7} m_\pi^{-1}. \] (20)

Let us now consider the regular \( E1 \)-transition from the deuteron into the \( p \)-wave of the continuous spectrum. Due to wave function admixtures, the nonzero \( M1 \)-transition appears. It’s straightforward calculation using the wave functions (18,19) give us the total amplitude

\[ A = -2 e \sqrt{2 \pi} \sqrt{2 \pi} \kappa \frac{p e}{\sqrt{1 - \kappa r_t (\kappa^2 + p^2)^2}} \delta_{\sigma' \sigma} - i e \frac{2 m}{2 \pi} \sqrt{2 \pi} \sqrt{2 \pi} \left( \lambda_t + \alpha_s \lambda_s \right) \frac{(\chi^{\sigma'} | \Sigma [n \times e] \Sigma p | \chi^{\sigma'})}{(1 - i p \alpha_s)(\kappa + i p)} - \alpha_s \lambda_s \left( \chi^{\sigma'} | \Sigma p \Sigma [n \times e] | \chi^{\sigma'} \right). \] (21)

If we are not interesting in photon’s polarization effects we may average over all of them. Then for the correction to the differential cross-section we have

\[ \Delta \frac{d \sigma}{d \Omega} = \frac{\kappa e^2 (\mu_p - \mu_n) p^3}{m \sqrt{1 - \kappa r_t (\kappa^2 + p^2)^2}} \left[ \left( \lambda_t + \alpha_s \frac{\kappa + \kappa^2 \alpha_s}{1 + \kappa^2 \alpha_s^2} \lambda_s \right) \left( I - \frac{p n p}{p^2} \right) + \lambda_s \frac{\alpha_s}{p} \frac{1 - \kappa \alpha_s}{1 + \kappa^2 \alpha_s^2} \left( p I [n \times p] I + I [n \times p] p I \right) \right] \]

and for the total cross-section

\[ \Delta \sigma = \frac{8 \pi \kappa e^2 (\mu_p - \mu_n) p^3}{3 m \sqrt{1 - \kappa r_t (\kappa^2 + p^2)^2}} \left( \lambda_t + \alpha_s \frac{\kappa + \kappa^2 \alpha_s}{1 + \kappa^2 \alpha_s^2} \lambda_s \right) \text{In.} \] (23)
5 Short-distance contribution near the threshold

Now we consider the photodesintegration near the threshold. Here the magnetic dipole transition \( ^3S_1 \rightarrow ^1S_0 \) is dominating. This transition does not conserved the total spin. However, the total spin is conserved in the admixed \( E1 \)-transition. Therefore only the vector meson exchange (which does not conserve spin too) operates.

All the calculations are very easy and the result for the amplitude is

\[
A = -i \frac{e}{2m} \sqrt{2 \pi \omega} \sqrt{2 \pi} \kappa (\mu_p - \mu_n) \frac{1 - \kappa \alpha_s}{(1 - i p \alpha_s) (\kappa^2 + p^2)} \Sigma [n \times e] + \\
\frac{e \sqrt{2 \pi} \omega \sqrt{2 \pi} \kappa}{3} (\lambda_t I_t + \lambda_s I_s) \Sigma e. \tag{24}
\]

Here \( I_t \) and \( I_s \) are radial integrals

\[
I_t = \frac{3 \kappa^2 + p^2}{(\kappa^2 + p^2)^2} - \frac{\alpha_s (2 \kappa + i p)}{(1 - i p \alpha_s) (\kappa + i p)^2},
\]

\[
I_s = \frac{\kappa + 2 i p}{(1 - i p \alpha_s) (\kappa + i p)^2}. \tag{25}
\]

One may obtain the differential cross-section after a simple algebra

\[
\frac{d\sigma}{d\Omega} = \frac{\kappa e^2 (\mu_p - \mu_n)^2 (1 - \kappa \alpha_s)^2 p}{4 m^2 (1 + p^2 \alpha_s^2) (\kappa^2 + p^2)^2} (In)^2 + \\
\frac{\kappa e^2 (\mu_p - \mu_n) (1 - \kappa \alpha_s) p}{3 m (1 + p^2 \alpha_s^2)} \frac{3 \kappa^2 + p^2}{(\kappa^2 + p^2)^2} \times \\
(\lambda_t (1 - \frac{2 \alpha_s \kappa^3}{3 \kappa^2 + p^2}) + \kappa \alpha_s \lambda_s \frac{\kappa^2 + 3 p^2}{3 \kappa^2 + p^2} nI. \tag{26}
\]

The total cross-section is

\[
\sigma = \frac{\pi \kappa e^2 (\mu_p - \mu_n)^2 (1 - \kappa \alpha_s)^2 p}{m^2 (1 + p^2 \alpha_s^2) (\kappa^2 + p^2)^2} (In)^2 + \\
\frac{4 \pi \kappa e^2 (\mu_p - \mu_n) (1 - \kappa \alpha_s) p}{3 m (1 + p^2 \alpha_s^2)} \frac{3 \kappa^2 + p^2}{(\kappa^2 + p^2)^2} \times \\
(\lambda_t (1 - \frac{2 \alpha_s \kappa^3}{3 \kappa^2 + p^2}) + \kappa \alpha_s \lambda_s \frac{\kappa^2 + 3 p^2}{3 \kappa^2 + p^2} nI. \tag{27}
\]
6 Conclusion

We write the total cross-section as

\[ \sigma = \sigma_{E1} + \sigma_{M1} + \Delta\sigma_{\pi} + \Delta\sigma_{V1} + \Delta\sigma_{V2}, \]

\[ \sigma_{E1} = \frac{8 \pi e^2 \kappa p^3}{3 (1 - \kappa r_t)(\kappa^2 + p^2)^3}, \]

\[ \sigma_{M1} = \frac{\pi \kappa e^2 (\mu_p - \mu_n)^2 (1 - \kappa \alpha_s)^2 p}{m^2 (1 + p^2 \alpha_s^2)(\kappa^2 + p^2)} (\ln)^2, \]

\[ \Delta\sigma_{\pi} = \frac{4 \pi e^2 g \gamma \kappa p^2 f(p)}{3 m \sqrt{1 - \kappa r_t}(\kappa^2 + p^2)^2} (\mu_p + \mu_n - \frac{1}{2}) \ln, \]

\[ \Delta\sigma_{V1} = \frac{8 \pi \kappa e^2 (\mu_p - \mu_n)p^3}{3 m \sqrt{1 - \kappa r_t}(\kappa^2 + p^2)^2} \left( \frac{\lambda_t}{1 + p^2 \alpha_s^2} - \lambda_s \right) \ln, \]

\[ \Delta\sigma_{V2} = \frac{4 \pi \kappa e^2 (\mu_p - \mu_n)(1 - \kappa \alpha_s)p}{3 m (1 + p^2 \alpha_s^2)} \frac{3 \kappa^2 + p^2}{(\kappa^2 + p^2)^2} \left( \lambda_t \left( 1 - \frac{2 \alpha_s \kappa^3}{3 \kappa^2 + p^2} \right) + \kappa \alpha_s \lambda_s \frac{\kappa^2 + 3 p^2}{3 \kappa^2 + p^2} \right) \ln. \]
Figure 2: $E1$ regular transition. The vector-meson contribution into $\Delta \sigma$.

Figure 3: $M1$ regular transition. The vector-meson contribution into $\Delta \sigma$. 
Let us estimate now results and their precisions. We accord to the "so called" best values of weak constants (supported by the experimental result for the $^{133}$Cs anapole moment [1]). Then the weak $\pi N N$ constant is

$$\bar{g} = 3.3 \times 10^{-7}.$$ 

Correction to the total cross-sections (there $nI = 1$) are plotted in figures. Let us talk now about the $\pi$-meson (Fig.1) and the vector-meson (Fig.2) contributions to the regular $E1$-transition. Unfortunately, the vector meson contribution is dominating here and it is more than the $\pi$-meson one of a factor 2 in the main region of energies. The accuracy of the vector meson exchange is too bad as it was mentioned above because of the unreliable calculations at the small range. But the main error we have in a calculation of $\lambda_t$, $\lambda_s$ constants. Our calculations of these constants with and without Jastrow repulsion discrepancies of the factor less than 1.7. So, we may expect that the accuracy of this result is about 40% for given parameters of weak constants. The precision of the $\pi$-meson one is 20%. The last estimate one may obtain via comparison of two results of the $\pi$-meson contribution with the zero range approximation function and with model function [23]. We obtain that the magnitude of $\Delta \sigma_\pi / \sigma$ is about $0.3 \times 10^{-9}$ that is essentially less than the maximal magnitude due to the vector meson exchange.

The maximal magnitude has the vector meson contribution to the magnetic dipole regular transition (Fig.3), which relative magnitude $\Delta \sigma / \sigma$ is about $4 \times 10^{-8}$. The accuracy is again 40%.

7 Acknowledgements

I very much appreciate to Khriplovich I.B. for helpful discussions and useful notices and to Krupnikov E.D. for careful reading the paper. The work was supported by the Russian Foundation for basic Research through Grant No. 01-02-16898, No. 00-15-96811 and by Ministry of Education through Grant No. 00-3.3-148.
References

[1] C.S. Woods et al, Science 275, 1759 (1997)

[2] V.V. Flambaum and I.B. Khriplovich, Zh.Eksp.Teor.Fiz. 79, 1656 (1980)
   [Sov.Phys.JETP 52, 835 (1980)].

[3] V.V. Flambaum, I.B. Khriplovich and O.P. Sushkov, Phys.Lett. B 146, 367 (1984).

[4] B. Desplanques, J.F. Donoghue and B.R. Holstein, Ann.Phys.(N.Y.) 124, 449 (1980).

[5] E. Adelberger and W. Haxton, Ann.Rev.Part.Nucl.Sci. 35, 501 (1985).

[6] I.B. Khriplovich, R.V. Korkin, Nucl.Phys. A 690, 610 (2001).

[7] F. Partovi, Ann.Phys. (N.Y.) 27, 114 (1964).

[8] G.S. Danilov, Phys.Lett. 18, 40 (1965).

[9] G.S. Danilov, Phys.Lett. B 35, 579 (1971); Yad.Fiz. 14, 788 (1972)
   [Sov.Nucl.Phys. 14, 443 (1972)].

[10] D. Tadić, Phys.Rev. 174, 1694 (1968).

[11] R.J. Blin-Stoyle and F. Feshbach, Nucl.Phys. 27, 395 (1961).

[12] A.I. Mikhailov, A.N. Moskalev, R.M. Ryndin, and G.V. Frolov, Yad.Fiz. 35, 887 (1982)
   [Sov.Nucl.Phys. 35 (1982)].

[13] M. Porrmann and M. Gari, Phys.Rev.Lett. 38, 947 (1977).

[14] W.Y.P. Hwang and E.M. Henley, Ann.Phys.(N.Y.) 129, 47 (1980).

[15] W.Y.P. Hwang, E.M. Henley and G.A. Miller, Ann.Phys. (N.Y.) 137, 378 (1981).

[16] H.C. Lee, Phys.Rev.Lett. 41, 843 (1978).

[17] B. Desplanques, Nucl.Phys. A 242, 423 (1974).

[18] K.R. Lassey and B.H.J. McKellar, Phys.Rev. C 11, 349 (1975); C 12, 721 (E) (1975).

[19] M. Gari and J. Schlitter, Phys.Lett. B 59, 118 (1975).

[20] J.P. Leroy, J. Micheli and D. Pignon, Nucl.Phys. A 280, 377 (1977).
[21] T. Oka, Phys.Rev. D 27, 523 (1983).

[22] V.B. Berestetskii, E.M. Lifshitz, and L.P. Pitaevskii, 
    Quantum Electrodynamics (Pergamon Press, 1994).

[23] I.B. Khriplovich and R.V. Korkin, Nucl.Phys. A 665, 365 (2000).

[24] V.V. Flambaum, V.B. Telitsin and O.P. Sushkov, Nucl.Phys. A 444, 611 (1985).