A restriction on the existence of a new type of fundamental interaction (the "arion" long-range interaction) in an experiment on spin precession of mercury nuclei

E. B. Aleksandrov, A. A. Ansel'm, Yu. V. Pavlov, and R. M. Umarkhodzhaev

B. P. Konstantinov Leningrad Institute of Nuclear Physics, USSR Academy of Sciences; and Nuclear Physics Institute, M. V. Lomonosov Moscow State University

(Submited 24 May 1983)
Zh. Eksp. Teor. Fiz. **85**, 1899–1906 (December 1983)

For the first time an attempt has been made to detect a new type of fundamental interaction, viz., the nomagnetic spin interaction (the "arion" long-range interaction of A. A. Ansel'm and N. G. Uraltsev, Phys. Lett. **114B**, 39 (1982), Phys. Lett. **116B**, 161 (1982), and A. A. Ansel'm, JETP Lett. **36**, 55 (1982). The arion long-range interaction is similar to the weak magnetic spin interaction, but differs from the latter in particular in that its existence is due only to oriented spins but not to moving electric charges. Within the sensitivity of the experiment the result is negative, which places a restriction on the parameters of the hypothetical arion field. It is established that the arion interaction between nuclear and electron spins is no stronger than 10^{-10}–10^{-11} of their magnetic interaction.

PACS numbers: 14.80.Pb

1. INTRODUCTION

The problem of the possible existence of fundamental long-range interactions other than electromagnetic and gravitational is undoubtedly of exceptional theoretical and experimental interest. The present work is devoted to an attempt to observe a specific spin-dependent long-range interaction: the "arion" long-range interaction of Refs. 1–3, in an experiment on the change in the nuclear spin precession frequency of the isotopes ^{199}Hg and ^{201}Hg in the arion field under conditions in which the magnetic field is reliably monitored. We have established that there is no arion interaction in a certain range of the parameters characterizing it.

In Ref. 2 we noted that the arion interaction can be observed by any methods of detection of a weak magnetic field. The arion field is created by oriented spins (for example, of a ferromagnetic material), and the accompanying magnetic field can be compensated by eddy currents in a conducting shield. In the present work we have used the combination of shielding of the magnetic field with a careful monitoring of its magnitude.

The idea of the experiment is as follows. The spin precession frequencies of nuclei of two types 1 and 2 are measured in a magnetic field H; these frequencies are $\omega_i = \gamma_i H$ ($i = 1, 2$), where γ_i are the gyromagnetic ratios of the nuclei. In the experiment we monitor the quantity $\delta = \omega_2 - (\gamma_2/\gamma_1)\omega_1$, which is by definition zero if the precession is due only to the magnetic field. We surround the working volume, which contains the nuclei and the inductor of the field H, by a ferromagnetic shield located in an external magnetic field H_α which is coaxial with the internal field H. The small part ΔH_α of the external field which penetrates inside the shield as the result of the fact that it is not a perfect shield will lead to some shift of the frequencies ω_i (by an amount $\gamma_i \Delta H_\alpha$), but the equality $\delta = 0$ is of course preserved.

Now consider the hypothetical arion field created by the polarized electron spins of the ferromagnetic material of the shield. We shall take into account that the magnetic field of these spins inside the shield is almost exactly equal to $(-H_\alpha)$, since it compensates the external field H_α to an accuracy $\Delta H_\alpha \ll H_\alpha$ (this is what the shielding mechanism consists of). Since the arion field is created by the same electron spins, the magnetic field $(-H_\alpha)$ can serve as a measure of it. The interaction of the nuclear spins with the arion field leads to a change of their precession frequencies by an amount $\gamma_i^\alpha H_\alpha$, where the "gyroarionic" ratio γ_i^α includes both the characteristics of the nucleus i and the parameters of the arion interaction. Thus, on turning on the external field H_α the precession frequencies of the nuclei, with allowance for the arion interaction, will be

$$\omega_i=\gamma_i(H+\Delta H_\alpha)-\gamma_i^\alpha H_\alpha,$$

and now the quantity δ is different from zero:

$$\delta=\gamma_1^\alpha H_\alpha(\gamma_2/\gamma_1-\gamma_2^\alpha/\gamma_1^\alpha)=\gamma_1^\alpha H_\alpha\lambda, \tag{1}$$

since in the general case the gyromagnetic and gyroarionic ratios are in no way proportional. In contrast to γ_i^α, the value of which must be established from experiment, the ratio $\gamma_2^\alpha/\gamma_1^\alpha$ can in principle be calculated exactly. In this way it is possible to find the parameter λ, which is of the order of 1. As a result, by measuring δ as a function of H_α it is possible to determine the constants γ_i^α of the arion interaction of the nuclei. In the experiment we obtained a limit $\gamma_i^\alpha/\gamma_i \lesssim 10^{-10} - 10^{-11}$, which means that the magnetic action of the polarized electrons in the mercury nucleus is at least 10^{10}–10^{11} times stronger than the arion interaction.

Before proceeding to a detailed description of the experiment and a discussion of its results, let us recall the theoretical assumptions which underlie the hypothesis of the arion long-range interaction,[1–3] which is accomplished by massless Goldstone particles—arions.

Although in its simplest form the standard model of the electroweak interaction requires existence of only one Higgs doublet and correspondingly of one neutral physically observable Higgs boson, in reality there are no reasons to assume that the Higgs spectrum is so sparse. On the other

0038-5646/83/121103-05$04.00

hand, practically any extension of the standard model (supersymmetry, technicolor, grand unification, inclusion of the generation symmetry group) requires a significant increase of the number of scalar fields. Here one may have Goldstone degrees of freedom—physical Goldstone Higgs bosons not absorbed by gauge bosons by means of the Higgs mechanism. An indication of the possibility of existence of such particles may be, for example, the various technicolor models, in which it is assumed that the Higgs particles are composite. Here the independent chiral rotations of techniquarks, of which Higgs bosons consist, correspond to additional global symmetries which are spontaneously broken as the result of formation of condensates of techniquarks. Here each spontaneously broken global symmetry corresponds to a physical Goldstone boson.

References 1–3 have discussed in various models the properties of the neutral Goldstone boson—the arion, which is a massless analog of the axion of Weinberg and Wilczek[4] in the case in which the corresponding global symmetry is not broken by an anomaly. The following properties of the arion are comparatively model-independent.

1. The arion is a neutral, strictly massless, stable pseudoscalar boson with even charge parity and a semiweak interaction with fermions which is diagonal in flavor and which preserves P and C parity. The interaction of a fermion f has the form

$$\mathscr{L}=x_f(G_F\sqrt{2})^{1/2}m_f(\bar{f}i\gamma_5 f)\alpha, \tag{2}$$

where G_F is the Fermi constant, m_f is the mass of the fermion, α is the arion field, and x_f is an unknown parameter involving the ratio of various vacuum mean fields.

2. There are no more than two arions, of which one interacts with quarks and leptons, and the other only with leptons.

3. The interaction of an arion with u and d quarks differs only in sign:

$$\mathscr{L}=x_q(G_F\sqrt{2})^{1/2}[m_u(\bar{u}i\gamma_5 u)-m_d(\bar{d}i\gamma_5 d)]\alpha, \qquad x_u=-x_d=x_q. \tag{3}$$

4. The interaction of an arion with nucleons can be calculated rigorously in the chiral limit; the coupling constant is proportional to the mass of the nucleon, and not to the current mass of the quark:

$$\mathscr{L}=x_q(G_F\sqrt{2})^{1/2}(-g_A)[(\bar{p}i\gamma_5 p)-(\bar{n}i\gamma_5 n)]\alpha; \tag{4}$$

here $g_A = -1.25$ is the axial form factor of β decay.

5. Exchange of arions leads to a potential energy of interaction of two fermions f_1 and f_2:

$$V(r)=x_{f_1}x_{f_2}\frac{G_F}{8\pi\sqrt{2}}\frac{1}{r^3}[\sigma_1\sigma_2-3(\sigma_1\mathbf{n})(\sigma_2\mathbf{n})], \quad \mathbf{n}=\frac{\mathbf{r}}{r}, \tag{5}$$

which is equivalent to the interaction of two magnetic moments with a "magneton" equal to $(G_F/8\pi\sqrt{2})^{1/2}x_f$. If one of the fermions is a nucleon, then the corresponding parameter is $x_{p,n}=x_{u,d}(-g_A)$.

References 1–3 discussed experimental restrictions on the existence of the arion. From absence of the decays $\psi\to\alpha\gamma$ and $\Upsilon(\Upsilon')\to\alpha\gamma$ we can state that $x_c<0.6$ (Ref. 5) and $x_b<1$,[6] and from the absence of the decay $K\to\pi\alpha$ (Ref. 7) it follows that at least $x_u<1$. (The latter restriction, it is true, may be more rigid. The estimate $x_u<1$ is based on the fact that the arion interacts only with the divergence of the isovector axial current (2) (Ref. 8); in any case the restriction on the corresponding parameter in the case of an axion should be significantly stronger.) The absence of anomalous splitting of the F levels in molecules of orthohydrogen[9] leads to a restriction on the existence of the interaction (4),[10] which in our notation corresponds to $x_u<3.5$. Finally, the interaction (1) between leptons leads to a correction to the anomalous moment of the leptons:

$$\mu=\mu_0(1+x_e^2G_Fm_e^2/8\pi^2\sqrt{2}),$$

which gives a restriction for the interaction of an arion with a μ meson and an electron: $x_\mu<3.6$ and $x_e<100$.

Incomparably stronger restrictions arise from astrophysical considerations if one takes into account the energy loss of the Sun and of red giants as the result of emission of arions.[11] In order that the Sun's energy flux associated with the reaction $\gamma+e\to\alpha+e$ not exceed the photon luminosity, it is required that $x_e^2<10^{-5}$, and if we believe the estimates for red giants, then $x_e^2<10^{-12}$. The same order is obtained also for the restriction on x_q^2 as the result of arion production in a process of the Primakoff type, in which the $\gamma\gamma\alpha$ vertex is determined by quark triangle diagrams. On the other hand, as was mentioned in Refs. 2 and 8, although the absorption of arions as a result of the inverse reaction $\alpha+e\to\gamma+e$ in the Sun is very small (mean free path $\sim 10^{14}$ cm$\cdot x_e^{-2}$), absorption as the result of the three-particle process $\alpha+e+p\to e+p$ leads to a mean free path one thousand times smaller. For $x_e\approx 10$ the arion mean free path becomes $\sim 10^9$ cm, which already is substantially less than the radius of the Sun. Therefore it is not excluded beforehand that arions could be quite efficiently absorbed in the Sun. The thermal conduction then increases greatly, and this leads to a rapid decrease of the size of the hot part of the Sun ($T\sim 1$ keV) and eventually to a considerable decrease of the arionic energy loss. To be sure, this hypothesis requires a radical review of the generally accepted models of the Sun and it is not clear whether it is self-consistent.

Laboratory data on the interaction of the type (4) essentially do not exist. In Ref. 10 an attempt was made to evaluate the possibility of existence of spin-dependent long-range forces by taking into account that in the magnetic field of the Earth a negligible fraction of the nuclear spins must be oriented. This estimate gives an extremely crude restriction which in our notation can be written as $x_u<10^6$, which simply makes no sense since for $x_u\sim 10^6$ the interaction (4) is much stronger than the ordinary magnetic interaction.

Thus, the estimated values for the interaction of the type (4) are extremely varied, which makes it desirable to set up a direct experiment according to the scheme described above.

2. EXPERIMENT

As the object of study we chose the mercury isotopes ^{199}Hg (labeled by the subscript $i=1$) and ^{201}Hg ($i=2$) with respective nuclear spins 1/2 and 3/2 and with gyromagnetic ratios 759.3 and -280.3 Hz/Oe. For mercury atoms in the

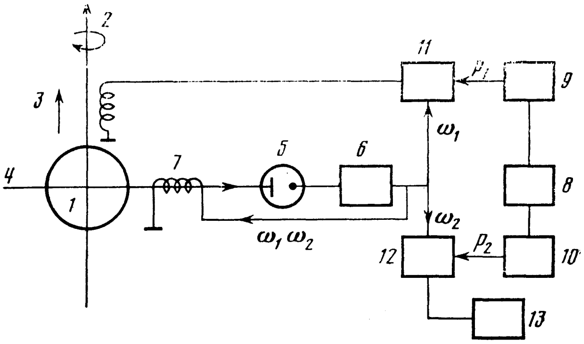

FIG. 1. Block diagram of apparatus: 1—working sample, 2—orientation light beam, 3—field vector H_0, 4—interrogration light beam, 5—photodetector, 6—amplifier, 7—inductor, 8—quartz crystal oscillator, 9 and 10—frequency dividers, 11—synchronous detector, 12—phase meter, 13—recorder.

gas phase there is a well developed technique of optical polarization of the nuclei, which combines a high degree of polarization with an effective optical monitoring system, and this is why these isotopes were chosen.

The figure shows a block diagram of the apparatus in which the experiment was carried out. The working sample 1 is a quartz cell containing a 50% mixture of the vapors of atoms of the mercury isotopes at a pressure 10^{-3} Torr. The sample was placed in a constant magnetic field H_0 of strength ~0.1 Oe. The temperature of the cell was maintained at 150 °C. Here the time of transverse relaxation of the nuclei was 17 sec for ^{199}Hg and 27 sec for ^{201}Hg.

Optical orientation of the atoms of the working material was accomplished by circularly polarized resonance radiation at 2537 Å.[12]

The orienting beam 2 was produced by a spectral lamp with the isotope ^{204}Hg and was transmitted along the direction of the field H_0. The signal of the nuclear magnetic resonance from the oriented atoms was recorded by means of the transverse Faraday effect.[13] A linearly polarized interrogation beam 4 was transmitted at right angles to the field H_0. This beam was provided by a second spectral lamp filled with the isotope ^{202}Hg, in which the 2537 Å spectral line is shifted relative to the absorption lines of the working mercury isotopes as the result of the isotopic shift.

To produce an undamped precession of the magnetization vectors of the mercury nuclei, a spin generator was used. The feedback circuit of the generator included a photodetector 5, an amplifier 6, and an inductor 7. The amplifier 6 was a broadband linear amplifier. Two oscillations were generated simultaneously, with frequencies equal in the first approximation to the Larmor frequencies of precession of the two types of nuclei: $\omega_1 = \gamma_1 H_0$ and $\omega_2 = \gamma_2 H_0$. For the chosen value of the field H_0 and for the relaxation times $^iT_2$ of the mercury nuclei given above, the condition of coexistence of the two frequencies of generation in one linear portion of the feedback circuit $(^iT_2)^{-1} \ll |\gamma_1 - \gamma_2| H_0$ is satisfied.

As the source of the arion field we used the spin system of an eight-layer Permalloy shield, inside which were placed the cell with the mercury vapor and the inductors of the constant field H_0 and the radiofrequency fields. Orientation of the spins of the ferromagnetic material of the shield was accomplished by an external magntic field H_α which was collinear with the field H_0.

The frequencies of oscillation of the spin generator in the absence of the arion interaction are determined by the expression

$$\omega_i=\gamma_i H_0+(^iT_2)^{-1}\,\mathrm{tg}\,\varphi_i+\varepsilon_i+(\gamma_i H_{i'})^2/(\omega_i-\omega_{i'})\equiv\gamma_i H_0+\Delta_i,$$

where φ_i is the phase advance in the feedback circuit at frequency ω_i, which depends in particular on the relative orientation of the interrogation beam and the axis of the inductor coil of the radiofrequency field; ε_i is the total light-induced shift of the precession frequency[12]; $(\gamma_i H_{i'})^2/(\omega_i - \omega_{i'})$ is the Bloch-Siegert shift due to action on nucleus i of oscillations with a foreign frequency $\omega_{i'}$ and amplitude $H_{i'}$.

In the presence of an arion interaction the generation frequencies should change and become equal to $\omega_i = \gamma_i H + \Delta_i + \omega_{i\alpha}$. This change is recorded in the following way. By dividing the reference frequency P_0 of the quartz crystal by k_1 and k_2 times, frequencies $P_1 = P_0/k_1$ and $P_2 = P_0/k_2$ are synthesized. The oscillations of frequency P_1 are used for capture of the oscillations ω_1 of the spin generator. For this purpose the oscillations of the frequencies ω_1 and P_1 are compared in a phase detector. The comparison signal is used to reduce the modulus of the magnetic field inside the shield to the value H determined by the relation $\omega_1 = P_1$, i.e., to the value $H = (P_1 - \Delta_1 - \omega_{1\alpha})/\gamma_1$. In the mode with stabilization of the frequency ω_1 the difference of the frequencies ω_2 and P_2 is

$$\omega_2-P_2=\Omega+\omega_{2\alpha}-\frac{\gamma_2}{\gamma_1}\omega_{1\alpha},$$

$$\Omega=\frac{P_0}{k_1}\left(\frac{\gamma_2}{\gamma_1}-\frac{k_1}{k_2}\right)+\Delta_2-\frac{\gamma_2}{\gamma_1}\Delta_1.$$

The quantity Ω is set equal to zero by choice of the values of the frequency-division coefficients k_1 and k_2. Here the difference of the frequencies $\omega_2 - P_2$ coincides with the previously introduced quantity δ, deviation of which from zero should indicate existence of the arion interaction. In practice the measurement is made by means of a phase meter which the frequencies P_2 and ω_2 are fed to. At the output of the phase meter a difference is observed in the phases of the oscillations, and the dependence of this difference on time is the desired effect $\delta \cdot t$.

Turning on the magnetic field H_α which orients the spins of the shield can lead to violation of the equality $\delta = 0$ and to the absence of the arion interaction as the result of parasitic effects of the following origin.

1. The magnetic field which penetrates through the shields changes the direction of the vector of the working field H, thereby changing the quantities φ_i.[15] To remove this effect the axis of the coils which create the variable field H_i was aligned with the direction of the interrogation beam.

2. The penetrating field changes in addition the gradient of the working field. This produces a broadening of the magnetic resonance line, leading to a shift of frequency, if $\varphi_i \neq 0$. However, in the presence of rapid motion of the mercury atoms there is an effect of averaging of the inhomogene-

ity, which reduces the broadening of the resonance to a negligible amount.[14]

3. The external magnetic field changes the conditions of the discharge in the spectral lamps producing the orientation and interrogation beams. To remove this effect, the spectral lamps were placed in ferromagnetic shields. In addition at the points of location of the lamps the external magnetic field was compensated by additional magnetic systems.

The measurements were made as follows. In the absence of the field H_α an extended record was made of the drift of the phase of the difference of the frequencies $\omega_2 - P_2$, which contains in the general case a component $\delta \cdot t$ linear in time and due to errors in establishing the values of k_1 and k_2, and a random component with an average value equal to zero and with a variance which depends on the time of observation. The desired effect would be a change of the component linear in time of the drift of the phase in response to a change of the polarizing field H_α. The measurements were made in runs of duration 0.5 to 1.0 hours each.

The result. No effect was observed within the accuracy limited by certain residual systematic errors of a hysteresis nature, which significantly exceed the random phase drift. Thus, for successive values of the field H_α equal to 0, + 72, 0, and − 72 Oe the average value of δ took on respective values 10^{-4}, $7.5 \cdot 10^{-4}$, $8 \cdot 10^{-4}$, and $0.5 \cdot 10^{-4} \pm 0.5 \cdot 10^{-4}$ deg/sec. These results permit us to assume that a change of the polarizing field $\Delta (H_\alpha) = 144$ Oe in any case does not lead to a change of δ by more than $7.5 \cdot 10^{-4}$ deg/sec:

$$\delta/\Delta(H_\alpha) < 1.5 \cdot 10^{-8} \text{ H}_2/\text{Oe}.$$

3. DISCUSSION OF THE RESULT

The restriction obtained in the experiment on the value of $\delta / \Delta (H_\alpha)$ corresponds to a restriction on the product $\varepsilon = \lambda \gamma_1{}^\alpha / \gamma_1$:

$$\varepsilon < 2 \cdot 10^{-11}. \tag{6}$$

Finding the parameter λ for a known ratio γ_2/γ_1 reduces to calculation of the ratio of the matrix elements

$$\langle i \,\mathrm{Hg}| \sum_n \sigma_n - \sum_p \sigma_p |{}^i\mathrm{Hg}\rangle,$$

where summation over the neutrons and protons of the given mercury isotope is understood. Although there are no fundamental difficulties in calculation of this ratio, nevertheless in the case of the mercury isotopes 199 and 201 technical difficulties arise: use of the standard programs for calculation of nuclear constants, which have been well checked in other nuclei, turns out to be unsuccessful in the case of these mercury isotopes. We shall therefore restrict ourselves to giving the result obtained for the quantity λ in the simplest approximation, in which a) we took into account only mixing of single-particle states with states in which the total moment is made up of the single-particle moment and the rotational moment ($R = 2$) and b) we estimated the renormalization of the gyromagnetic and gyroarionic factors as the result of polarization of the nuclear core. The value of λ turned out to be − 0.1, but in view of the remarks made above it obviously does not follow that we should place too much confidence in this estimate. We should rather consider it to be a lower-bound estimate. Indeed, we can suppose that the deviation of λ from unity in a series of nuclei is subject to approximately the same spread as the deviation of the magnetic moments of the nuclei from the nuclear magneton (the average value of the modulus for stable nuclei is 1.5 with a spread from 0.1 to 6). As a result of the remarks made above, we shall rewrite the value obtained above for the restriction on the quantity $\varepsilon = \lambda \gamma_1{}^\alpha / \gamma_1$ in the form $\gamma_1{}^\alpha / \gamma_1 < 10^{-10}$–$10^{-11}$. This smallness of the arion interaction in comparison with the magnetic interaction is also given in the abstract of this work.

We shall now express the result in terms of the parameters of the arion interaction. For interaction of the nuclear spin with the electron spin we obtain from (5) an expression for the quantity ε of (6):

$$\varepsilon = \frac{G_F m_e m_p}{2\pi \sqrt{2}\, \alpha} (-g_A) x_e x_q \frac{\gamma_2}{\gamma_1} (R_1 - R_2), \tag{7}$$

where

$$R_i = \langle {}^i\mathrm{Hg}| \sum_p \sigma_p - \sum_n \sigma_n |{}^i\mathrm{Hg}\rangle / \langle {}^i\mathrm{Hg}| \sum_p (\mu_p \sigma_p + l_p) + \sum_n \mu_n \sigma_n |{}^i\mathrm{Hg}\rangle. \tag{8}$$

In this formula $\mu_p = 2.79$ and $\mu_n = -1.91$ are the magnetic moments of the proton and neutron in nuclear magnetons, l_p is the orbital angular momentum of the proton, and summation is understood over all protons and neutrons of the corresponding mercury isotope.

The crude theoretical estimate mentioned above led to the values

$$R_1 \approx -\frac{1}{\mu_n} = 0.52;\quad R_2 \approx -\frac{1.4}{\mu_n} = 0.73;\quad \lambda = \frac{\gamma_2}{\gamma_1}\left(1 - \frac{R_1}{R_2}\right) = -0.1, \tag{9}$$

from which we obtain

$$\varepsilon \approx 0.8 \cdot 10^{-8} x_e x_q.$$

Therefore the inequality (6) means that

$$|x_e x_q| < 2.5 \cdot 10^{-3}. \tag{10}$$

We note that the experimental restriction adopted apparently is actually exaggerated. The observed evolution of the phase as a function of the value of the polarizing field H_α does not fit into the logic of the hypothesis of the arion interaction, but is more likely the result of parasitic effects produced by reversal of the magnetization of the inner shells of the shield. At the present time the apparatus is being redesigned for the purpose of obtaining a usable accuracy at a level limited by random drift of the phase.

4. CONCLUSION

In the present work we have carried out the first experiment to search for a nonmagnetic interaction between oriented spins of electrons and nuclei (the arion long-range interaction). We have been able to establish that this interaction does not exist at a very low level in comparison with the "natural" interaction corresponding to a magnitude of the arion moment of the electron and quark $\mu_a = (G_F/8\pi\sqrt{2})^{-1}$, i.e., to values $x_e = x_q = 1$. In a previous letter[3] we emphasized, however, that in some models the values of x_f can turn out to be substantially less than unity. Therefore it appears to us that further search for the arion long-range interaction will not be useful.

Finally, it seems obviously to us that search for a long-range interaction of nonelectromagnetic (and nongravitational) origin presents interest outside the framework of specific theoretical constructions.

We are grateful to N. G. Ural'tsev for helpful discussions and to L. B. Okun' for his constant interest in this work.

[1] A. A. Ansel'm and N. G. Uraltsev, Phys. Lett. **114B**, 39 (1982).

[2] A. A. Ansel'm, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 46 (1982) [JETP Lett. **36**, 55 (1982)].

[3] A. A. Ansel'm and N. G. Uraltsev, Phys. Lett. **116B**, 161 (1982).

[4] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978). F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[5] C. Edwards *et al.*, Phys. Rev. Lett. **48**, 903 (1982).

[6] M. Sivertz, J. Lee-Franzini, J. E. Horstkotte, *et al.*, Phys. Rev. **D26**, 717 (1982).

[7] Y. Asano, E. Kikutani, S. Kurokawa, *et al.*, Phys. Lett. **107B**, 159 (1981).

[8] A. A. Anselm, Preprint LNPI-761, Leningrad, May, 1982.

[9] R. F. Code and N. F. Ramsey, Phys. Rev. **A4**, 1945 (1971).

[10] G. Feinberg and J. Sucher, Phys. Rev. **D20**, 1717 (1979).

[11] M. I. Vysotskiĭ, Ya. B. Zeldovich, M. Yu. Khlopov, and V. M. Chechetkin, Pis'ma Zh. Eksp. Teor. Fiz. **27**, 533 (1978) [JETP Lett. **27**, 502 (1978). D. A. Dicus, E. W. Kolb, V. L. Teplitz, *et al.*, Phys. Rev. **D18**, 1829 (1978); **D22**, 839 (1980).

[12] J. C. Cohen-Tannoudji, Ann. Phys. (Paris) **7**, 469–504 (1962); **7**, 423–460 (1962).

[13] J. Manuel and J.-C. Cohen-Tannoudji, Compt. Rend. **B257**, 413 (1963).

[14] R. M. Umarkhodzhaev, Radiotekh. Élektron. **22**, 597 (1977) [Radio Eng. Electron. Phys. (USSR)].

[15] C. P. Slichter, Principles of Magnetic Resonance, Harper-Row, 1963.

Translated by Clark S. Robinson