Restrictions on the existence of spin-spin coupling of nonelectromagnetic origin in experiments on the measurement of the gyromagnetic ratios of the proton and deuteron

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Measurements of the ratio of the gyromagnetic factors of the proton and deuteron in a magnetic field produced by a superconducting solenoid and an iron magnet exclude the possibility of the existence of nonmagnetic interaction of oriented spins at the level of $\sim 10^{-10}$ of their magnetic interaction.

The first experimental search for a nonmagnetic interaction between oriented spins of electrons and nuclei led to a negative result.[1] Its purpose was twofold. On one hand, it seemed interesting to verify, in a laboratory experiment, the absence (or presence) of an "arion" long-range interaction due to exchange of massless Goldstone pseudoscalar particles-arions.[2–4] On the other hand, the authors realized that the search for the long-range spin interaction of nonelectromagnetic origin is a task which extends beyond the framework of specific theoretical speculations.[2–4] This is particularly important because the very hypothesis of the existence of the arions encounters serious difficulties connected with the energy loss by the Sun and by red giants (see Refs. 2–4 and references therein).

In this paper we give the results of a new experimental search of nonmagnetic spin interaction. The results contain fewer uncertainties in the theoretical interpretation, while the accuracy remains comparable with that of Ref. 1. We measured the ratio of the gyromagnetic factors of the proton and deuteron in two cases: a) when the magnetic field was produced by a superconducting solenoid and b) when its source was an iron magnet. If there existed a nonelectromagnetic interaction between the oriented spins, then the ratios $(\gamma_p/\gamma_d)_{\rm ss}$ for the superconducting solenoid and $(\gamma_p/\gamma_d)_{\rm im}$ for the iron magnet would be slightly different. It is clear that the hypothetical interaction of the oriented spins must be proportional to their number, i.e., to the magnetization of the ferromagnet, which can be determined from its measured magnetic field. We have then

$$(\gamma_p/\gamma_d)_{\rm cc}=\gamma_p/\gamma_d, \quad (\gamma_p/\gamma_d)_{\rm жм}=(\gamma_p+\gamma_p{}^\alpha)/$$
$$(\gamma_d+\gamma_d{}^\alpha)\approx\gamma_p\gamma_d{}^{-1}(1+\gamma_p{}^\alpha/\gamma_p-\gamma_d{}^\alpha/\gamma_d). \qquad (1)$$

Here γ_p and γ_d are the "true" gyromagnetic factors and γ_p^α and γ_d^α are the "gyroarionic" factors (to keep the designation "arionic" for the general case of nonelectromagnetic spin-spin interaction). The quantities γ_p^α and γ_d^α characterize the strength of the nonelectromagnetic interaction which we are looking for. If it is connected with the exchange of arions then γ_p^α and γ_d^α can be calculated in principle.[2–4]

We present below the measured measurement of the relative spin precession frequencies of the proton (f_p) and deuteron (f_d) for various chemical compounds. We should mention that the determination of the ratio f_p/f_d is itself of considerable metrological interest to ensure uniqueness and correctness of measurements in the spectroscopy of nuclear magnetic resonance where both iron and superconductivity are widely used to produce magnetic fields.

The results shown in Table I were obtained in the following way. The data for the superconducting solenoid were obtained using an NKh-270 NMR spectrometer. The deuteron signal was recorded at a frequency 41, 447, 416, 667 Hz and used to stabilize the resonance conditions. The proton signal was recorded at a frequency $f_p = 270\,005\,000$ Hz + Ω_p, where Ω_p lies in the interval between 32 and 63 Hz for the samples used. The principal error in these measurements was due to inaccuracy of matching the magnetic-field stabilization conditions to the deuteron-signal center. To estimate the magnitude of this error the operator disrupted the stabilization prior to each new proton-signal recording, and after careful symmetrization of the signal he restabilized the system by balancing the phase shift of the reference frequency in the circuit of the lock-in detector. The number of such measurements of f_p used for the averaging is shown in Table I.

The same samples were used next to determine the ratio f_p/f_d in the magnetic field produced by the iron magnet. In this case an RYa-2310 NMR spectrometer was used as the basic instrument. The proton signal was recorded at frequency 60 001 000 Hz and the deuteron signal at 9,210,650 Hz-Ω_d, with Ω_d in the interval between 131 and 133 Hz. The deuteron signals were recorded by frequency scanning. To eliminate transient effects, each reading was the average of the two values obtained as the frequency was increased and decreased in the given interval. The errors were determined to equal degree by the accuracy of the stabilization relative to the proton-signal center and by the accuracy with which the signal center was determined by the paired deuteron signals. Since the magnetic field was 4.5 times weaker in this case than that of the superconducting solenoid we had to obtain and average a larger number of readings to get commeasurate inaccuracy. The number of recorded pairs of signals is shown in Table I. The resolution of the spectrometer was $\Delta H/H \approx 10^{-9}$.

The three samples of isotopic mixtures were selected on the basis of following considerations. The absolute screening

TABLE I.

№	Isotope mixture	Width of D-signal Hz	Magnet type	Number of averaged results	Ratio f_p/f_d
1	H_2O-D_2O	0,58	ss	4	6,514 399 585(15)
			ЖМ	18	6,514 399 613(10)
2	$C_6H_{12}-C_6D_{12}$	0,18	CC	6	6,514 400 274(4)
			ЖМ	22	6,514 400 267(5)
3	$(CH_3)_2CO-(CD_3)_2CO$	0,1	CC	9	6,514 400 022(1)
			im	52	6,514 400 021(1)

of protons in water is most accurately known and can be found among the fundamental constants. Samples with water are used for accurate measurement of magnetic fields. However, because of the large width of the signal from the water deuterons it is difficult to obtain for f_p/f_d an inaccuracy of the order of 10^{-10}. Moreover, the position of the proton signal can depend on the presence of active impurities in the sample, which affect the rate of the proton intermolecular exchange. For the more inert bonds, C–D and C–H, the ratio f_p/f_d is not changed by addition of a third component.[5] We therefore studied the mixture C_6H_{12}–C_6D_{12} of inert cyclohexane molecules and also the mixture of acetones $(CH_3)_2CO$–$(CD_3)_2CO$. In the latter we observed the smallest width of the deuteron signal because of the intensive rotation of the CD_3 groups around the C–C bond.

As seen from the results in Table I, the smallest error was reached for the sample with isotopic mixture of acetones. In practice, this measurement run determines the statistical error

$$(f_p/f_d)_{\rm im}-(f_p/f_d)_{\rm ss}=(1\pm1)\cdot10^{-9},$$

$$\frac{(f_p/f_d)_{\rm im}-(f_p/f_d)_{\rm ss}}{(f_p/f_d)_{\rm ss}}=(1{,}5\pm1{,}5)\cdot10^{-10}. \qquad (2)$$

In order to eliminate the systematic error, other measurements are essential. It is therefore interesting to compare earlier measurements of f_p/f_d performed for the same isotopic mixtures about 10 years ago using an iron magnet[5]: for water (I)—6.514399614(20), for cyclohexane (II)—6.514400294(20) and for the mixture of acetones (III)—6.514400040(20).

It can be seen by comparing (1) and (2) that we actually the following limitations on the gyroarionic factors of the proton and deuteron:

$$(\gamma_p{}^\alpha/\gamma_p)-(\gamma_d{}^\alpha/\gamma_d)=(1.5\pm1.5)\cdot10^{-10}. \qquad (3)$$

This estimate is of the same order as that of Ref. 1.

$$|\gamma^\alpha(^{199}\text{Hg})/\gamma(^{199}\text{Hg})-\gamma^\alpha(^{201}\text{Hg})/\gamma(^{201}\text{Hg})|<0{,}5\cdot10^{-10} \quad (4)$$

(Eq. (4) follows directly from the inequality (6) of Ref. 1).

A theoretical interpretation of the results of Ref. 1 was hampered by the difficulty of calculating the matrix elements of the operators of the proton and neutron spins from the wave functions of mercury nuclei. This difficulty is absent in our case. For the arionic interaction described in Refs. 2–4 one can easily find[2]

$$\gamma_p{}^\alpha/\gamma_p=x_ex_q(-g_A)\,(G_Fm_pm_e/2\sqrt{2}\pi\alpha\mu_p)$$
$$=3.86\cdot10^{-8}x_ex_q,\quad \gamma_d{}^\alpha/\gamma_d=0. \qquad (5)$$

Here $(-g_A)=1.25$ is the axial nucleon form factor, G_F is the Fermi constant, m_e and m_p are the electron and proton masses, $\alpha=1/137$, and $\mu_p=2.79$ is the proton magnetic moment. The unknown dimensionless parameters x_e and x_q characterize the strength of the interaction of the arions with electrons and quarks. A zero value of γ_d^α is obtained because $x_p=x_n$ for neutrons and protons and consequently $\gamma_d^\alpha\sim\langle D|\sigma_p-\sigma_n|D\rangle=0$. An upper bound on x_ex_q follows from (3) and (5):

$$|x_ex_q|<10^{-2}. \qquad (6)$$

The somewhat better bound ($|x_ex_q|<2.5\cdot10^{-3}$) obtained in Ref. 1 was based on an unreliable estimate of the nuclear matrix elements σ from the wave functions of mercury nuclei.

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