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Study of NMR signals of rubidium in aqueous solutions and determination of the magnetic moments of Rb-85 and Rb-87 nuclei

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The problem of increasing the accuracy of determining the magnetic moments of rubidium-85 and rubidium-87 nuclei based on the study of NMR signals of RbNO₃ and RbCl solutions in water is considered. The spectral linewidth of the NMR signals from the ⁸⁵Rb and ⁸⁷Rb nuclei is a hundred times greater than the similar width of the signals from the nuclei for other neighboring alkaline elements of the periodic table, and such a broadening limits the possibilities for precision registration of nuclear resonance frequencies. Simultaneous registration of nuclear magnetic resonance signals from water protons and from rubidium nuclei was used in the work, which makes it possible to minimize the spread of data for the resonance frequency ratio. The ratios of the resonance frequencies of water protons and ⁸⁵Rb, ⁸⁷Rb nuclei were determined for aqueous solutions of RbCl and RbNO₃ with concentrations from 0.5 to 2.0 mol/kg H₂O. As a result, the ratios of magnetic moments $\mu(^{87}\text{Rb})/\mu(^{85}\text{Rb}) = 2.0333981(2)$ were calculated with a relative uncertainty $\delta \approx 10^{-7}$. The data on the resonance frequency ratio $f(^1\text{H})/f(^{87}\text{Rb})$ for the content of rubidium salts in water were extrapolated to zero concentrations and $f(^1\text{H})/f(^{87}\text{Rb}) = 3.0561795(2)$ was determined for rubidium ions surrounded by water molecules. As a result, the magnetic moments are determined $\mu(^{85}\text{Rb}) = 1.353067(37)$, $\mu(^{87}\text{Rb}) = 2.751324(74)$. The obtained results are compared with the data of previous works. Keywords: precision determination of nuclear magnetic moments, simultaneous registration of NMR signals from two types of nuclei, quantum radiophysics.

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Introduction

Rubidium is one of the active elements of the alkaline group of the periodic table and is used in magnetometry, in frequency standards and in electronics. In medicine, rubidium medications are used as painkillers and in the treatment of epilepsy, however, the complex effect of rubidium on the tissues of a living organism due to its radioactivity requires further study, since its use is accompanied by radiation burden.

Data on the rubidium nuclear magnetic moments were previously obtained: by optical excitation method with radio frequency detection [1] (OP/RD method); by the nuclear magnetic resonance method [2] (NMR–H₂O method); recording of frequency resonance on rubidium nuclei in an atomic beam [3] (method AB/D); methods of laser spectroscopy in atomic beams [4] (method ABLs) and NMR method at dissolution of rubidium in heavy water [5] (method NMR–D₂O). However, after the required corrections for the electron screening of the nuclei [6,7], it turned out that the data [1–5] diverge in units of the fifth or quadruple sign, and when calculating the nuclear magnetic moment of rubidium isotopes $\mu(^{85}\text{Rb})$ and $\mu(^{87}\text{Rb})$ not all components of the uncertainty were correctly taken into account.

Recording of frequencies of NMR responses from the nuclei of rubidium ions in an aqueous liquid of $f(^{85}\text{Rb}^+)$ and $f(^{87}\text{Rb}^+)$ allows determine the nuclear magnetic moments $\mu(^{85}\text{Rb})$ and $\mu(^{87}\text{Rb})$ on the basis of the relations:

$$f(^{85}\text{Rb}^+) = [\mu(^{85}\text{Rb})/I(^{85}\text{Rb})]B[1 - \sigma(^{85}\text{Rb}^+)], \quad (1)$$

$$f(^{87}\text{Rb}^+) = [\mu(^{87}\text{Rb})/I(^{87}\text{Rb})]B[1 - \sigma(^{87}\text{Rb}^+)], \quad (2)$$

where $I(^{85}\text{Rb}) = 5/2$ and $I(^{87}\text{Rb}) = 3/2$ — spins of rubidium isotopes (strictly quantized values); B — induction of an external magnetic field; $\sigma(^{85}\text{Rb}^+)$ and $\sigma(^{87}\text{Rb}^+)$ — rubidium nucleus screening, which, foremost, is determined by the internal 36 electrons of these ions, and also for the case of study in solutions there is a component from the electrons of the nearest molecular environment of the ions.

The external magnetic field B in such experiments should be determined and maintained with the required high accuracy. According to the recommendation of CODATA [8] experts, the determination of the magnetic field is also associated with recording of the frequency of the NMR response, moreover, from water protons and using fundamental physical constants: the proton magnetic moment μ_p and the proton screening in water $\sigma(\text{H}_2\text{O})$ [9,10]. Therefore, the magnetic moments of rubidium isotopes can

be calculated from the relations:

$$\mu(^{85}\text{Rb}) = \mu_p [f(^{85}\text{Rb}^+)/f(^1\text{H})] [I(^{85}\text{Rb})/I_p] \times \{[1 - \sigma(\text{H}_2\text{O})]/[1 - \sigma(^{85}\text{Rb}^+)]\}, \quad (3)$$

$$\mu(^{87}\text{Rb}) = \mu_p [f(^{87}\text{Rb}^+)/f(^1\text{H})] [I(^{87}\text{Rb})/I_p] \times \{[1 - \sigma(\text{H}_2\text{O})]/[1 - \sigma(^{87}\text{Rb}^+)]\}, \quad (4)$$

where $I_p = 1/2$ — proton spin; $f(^{85}\text{Rb}^+)/f(^1\text{H})$ and $f(^{87}\text{Rb}^+)/f(^1\text{H})$ — the ratio of resonance frequencies of rubidium isotopes and water protons, which should be determined at extremely low concentrations of salts in water, when the effect of dissolved substances on $\sigma(\text{H}_2\text{O})$ can be excluded. Since both frequencies should be recorded strictly in the same magnetic field and at the same temperature (25°C), the best way to minimize experimental uncertainties is to simultaneously induce and accumulate signals from water protons and from nuclei of rubidium ions.

The aim of this paper is to study the opportunities of the method used by the authors for the precise determination of the nuclear magnetic moments $\mu(^{85}\text{Rb})$ and $\mu(^{87}\text{Rb})$.

1. Spectrometers and samples

In this paper, the NMR spectrometer included an electromagnet with an induction of $B = 2.14$ T and a response detection system that allowed to simultaneously induce and digitize nuclear NMR responses of two types [10,11]. Responses from rubidium nuclei were recorded using induction coils, the turn number of which was chosen to be optimal for maximum amplification of responses at frequencies of rubidium isotopes. The response from water protons was recorded by the same common receiving induction coil. For this, in addition to the main receiving induction coil L_1 , an additional small induction coil L_2 with two turns of wire was placed in the matching module of the registration system (Fig. 1). The block diagram of the NMR spectrometer is similar to the one given in the paper [11].

The spectrometer uses an integrated circuit-synthesizer AD9958, which provided the formation of reference frequencies close to the resonant frequencies of the nuclei under study:

$$\begin{aligned} f(\text{H}_2\text{O})_0 &= 90\,974\,379.18 \text{ Hz}, \\ f(^{87}\text{Rb})_0 &= 29\,767\,228.98 \text{ Hz}, \\ f(^{85}\text{Rb})_0 &= 8\,782\,424.93 \text{ Hz}. \end{aligned} \quad (5)$$

The resonant frequencies of the nuclei were calculated from the relations:

$$\begin{aligned} f(\text{H}_2\text{O}) &= f(\text{H}_2\text{O})_0 + \Delta f(\text{H}_2\text{O}), \\ f(^{87}\text{Rb}^+) &= f(^{87}\text{Rb})_0 + \Delta f(^{87}\text{Rb}), \\ f(^{85}\text{Rb}^+) &= f(^{85}\text{Rb})_0 + \Delta f(^{85}\text{Rb}). \end{aligned} \quad (6)$$

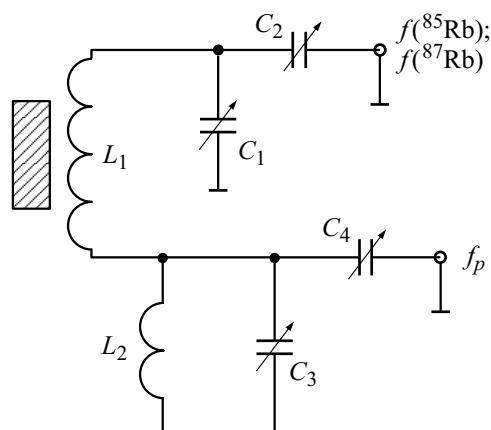


Figure 1. Use of a common receiving induction L_1 for actuation and recording of responses from protons and rubidium nuclei.

The magnetic field of the spectrometer $B = 2.13667$ T was used, at which the resonant frequencies $\Delta f(i)$ recorded after amplification and conversion exceeded the specified reference frequencies (5) by 1–3 kHz (Fig. 2).

In this paper salts with a natural content of rubidium isotopes were used, in which, in addition to the main stable isotope ^{85}Rb with a content of 72.2%, there is a radioactive isotope ^{87}Rb , whose share is 27.8%. Before preparing the studied solutions of the salt RbNO_3 , RbCl and distilled water were weighed, then thoroughly mixed and poured into thin-walled cylindrical ampoules 5 mm in diameter standard for NMR spectroscopy.

The temperature was controlled using a DS18B20 digital sensor (Dallas Semiconductor, USA) calibrated at the VNIIM temperature control laboratory. The sensor was placed in the body of the NMR response sensor at a distance of 0.3 mm under the ampoule with the test solution. Ampoules were rotated to ensure high homogeneity of the magnetic field. The ampoule rotation created a local air vortex, which, after heating for 10–20 min, minimized the temperature difference between the ampoule with the solution and the temperature sensor case, which was recorded by stopping the drift of water proton resonance frequencies.

2. Accumulation of spectral series and data processing

When accumulating a paired numeric array containing the frequencies $\Delta f(i)$, the signals of the free precession of water protons and rubidium nuclei were successively summed. The operator controlled the intensity and form of the Fourier-transformed sum signals on the monitor during the accumulation of digital data (Fig. 2) until an acceptable signal-to-noise ratio was reached (more than 5:1). For this, as a rule, repetitions of $N_i \approx 900$ were sufficient. Meanwhile, the signals from the nuclei both ^{85}Rb and ^{87}Rb decayed to the background noise level in $t \approx 5$ ms, and

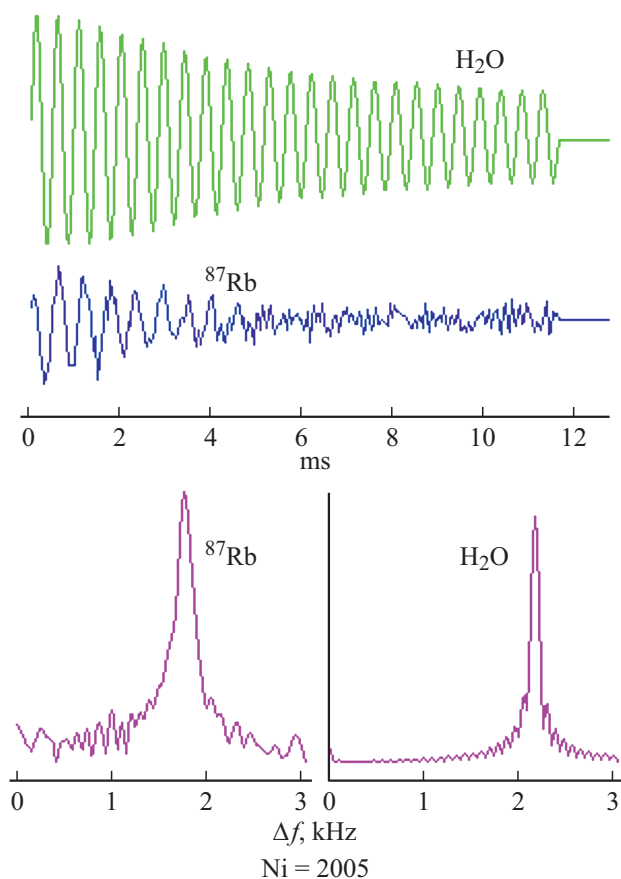


Figure 2. A copy of the screen of the NMR spectrometer monitor, which provides control of the simultaneous accumulation of NMR responses in two frequency ranges. The upper part of the figure — initial responses of the free precession of the magnetization vector of opposite nuclei in the time scale; the lower part — the same responses in the frequency scale after the Fourier conversion; $N_i = 2005$ — number of summed responses.

taking this into account, the rhythmic operation of the NMR spectrometer with repetition of actuation pulses every $t_1 \approx 12$ ms (Fig. 2). An acceptable numeric array, if it was accumulated at a sufficiently low level of external electromagnetic interference, was stored and sent for mathematical processing. The name of each spectral array included both the temperature of the solution and the concentration of the salt RbCl or RbNO₃ in the samples.

When digitizing the responses of each of the nuclei, 1024 points were recorded: 512 points for the real and imaginary components of the response. As a rule, the accumulated numeric array contains the sum of both even and odd components, so subsequent mathematical processing was used to accurately determine the position of the response on the frequency scale.

To increase the number of points in the frequency interval of the recorded responses, the initial numeric arrays were expanded by zeros by a factor of 16 before the Fourier conversion. Mathematical processing of numeric arrays was performed using the software described in the

papers [10,11]. For each of the samples, 15–20 pair spectra were accumulated and the resonance frequency ratios $f(^1\text{H})/f(^{87}\text{Rb}^+)_i$ were calculated. Table 1 shows the ratios of the resonance frequencies of water protons and nuclei of two rubidium isotopes for four ampoules in which either RbNO₃ or RbCl salts were dissolved at different salt concentrations; the responses were accumulated at a temperature of $(25.0 \pm 0.5)^\circ\text{C}$.

Next, the dependence of $f(^1\text{H})/f(^{87}\text{Rb}^+)$ on the concentration of the solution was studied, which in the general case is complex, since the adjustment in the concentration of salts in water adjusts the structure of the solution with an adjustment in the resonance frequency of water protons and the resonance frequency of rubidium nuclei.

To use equations (3), (4), it is required to determine the ratio $f(^1\text{H})/f(^{87}\text{Rb}^+)$ when extrapolating data to zero concentration. In the studied concentration range 0.5–2.0 mol/kg, there is a serial storage of adjustments in the molecular structure of solutions, in which the statistically averaged data recorded by the NMR method are characterized by dependences that are close to linear (Fig. 3).

The inclinations of lines (Fig. 3) reflect the effectiveness of the influence of Cl⁻ or NO₃⁻ ions on the frequency ratio and, therefore, mainly on that part of the rubidium nuclei screening, which depends on the influence of electrons of Cl⁻ ions – or NO₃⁻, located in the nearest environment from rubidium ions. The data extrapolated to zero concentrations

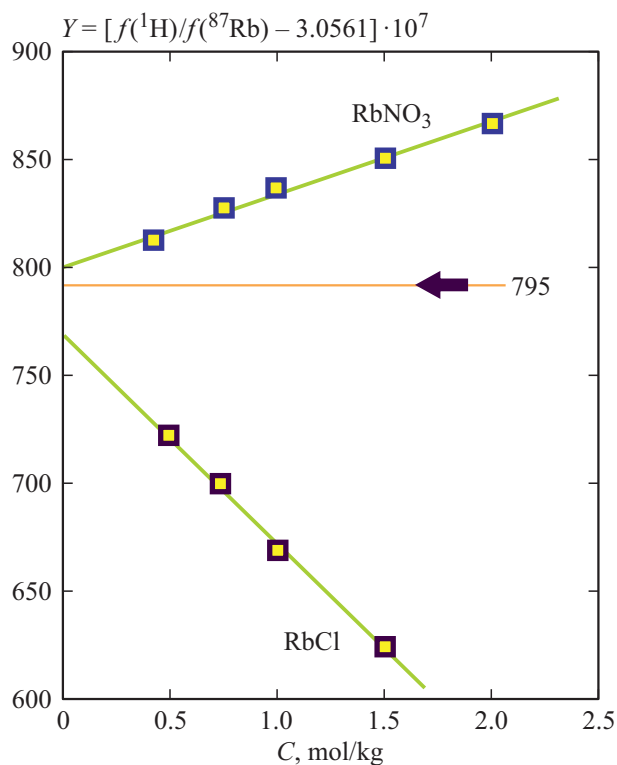


Figure 3. Dependence of the data for the resonance frequency ratio $f(^1\text{H})/f(^{87}\text{Rb}^+)$ on the solution concentration at a temperature of $(25 \pm 0.5)^\circ\text{C}$.

Table 1. Experimental ratios of resonance frequencies of water protons and rubidium nuclei for different salt concentrations at 25°C

C, mol/kg H ₂ O	$f(^1\text{H})/f(^{85}\text{Rb})$	$f(^1\text{H})/f(^{87}\text{Rb})$	$f(^{87}\text{Rb})/f(^{85}\text{Rb})$	$\delta[f(^{87}\text{Rb})/f(^{85}\text{Rb})]$
2 mol RbNO ₃	10.3574084(14)	3.05618674(18)	3.38899723(51)	$1.5 \cdot 10^{-7}$
1 mol RbNO ₃	10.3573980(19)	3.05618385(23)	3.38899703(68)	$2.0 \cdot 10^{-7}$
1 mol RbCl	10.3573407(12)	3.05616732(19)	3.38899661(44)	$1.3 \cdot 10^{-7}$
0.75 mol RbCl	10.3573493(23)	3.05617007(16)	3.38899638(75)	$2.2 \cdot 10^{-7}$

Table 2. Ratios of resonance frequencies as a function of salt content and concentration

Salt	C, mol/kg H ₂ O	$f(^1\text{H})/f(^{87}\text{Rb})$
RbNO ₃	2	3.0561865(1)
RbNO ₃	1.5	3.0561850(2)
RbNO ₃	1	3.0561841(2)
RbNO ₃	0.75	3.0561828(2)
RbNO ₃	0.4	3.0561811(2)
RbNO ₃	$C \rightarrow 0$	3.0561800(2)
RbCl	1.5	3.0561625(1)
RbCl	1	3.0561673(2)
RbCl	0.75	3.0561701(2)
RbCl	0.5	3.0561723(4)
RbCl	$C \rightarrow 0$	3.0561769(2)

for the frequency ratio (Fig. 3) do not converge to one result, since the data in this paper were obtained at relatively high concentrations.

For the data extrapolated to zero concentrations (Table 2), the additional screening of rubidium nuclei due to the presence of molecules in the nearest environment, which is included in expressions (1)–(4), can be represented as the sum of two contributions:

$$\Delta\sigma_i(\text{RbNO}_3)_{C=0} = \delta\sigma[\text{NO}_3 + (n-1)\text{H}_2\text{O}] + \delta\sigma(n\text{H}_2\text{O}), \quad (7)$$

$$\Delta\sigma_i(\text{RbCl}_3)_{C=0} = \delta\sigma[\text{Cl}^- + (n-1)\text{H}_2\text{O}] + \delta\sigma(n\text{H}_2\text{O}), \quad (8)$$

where the first terms – are the contributions to the screening of Rb⁺ ions from the presence of negative ions NO₃[−] or Cl[−] in the close environment; $\delta\sigma(n\text{H}_2\text{O})$ — a term common for two solutions, which takes into account the influence of the environment of n molecules on the screening of Rb⁺ ions water.

The contributions of negative ions to screening are proportional to the slopes of the dependences, which can

be measured (Fig. 3) and the following ratio: can be derived

$$\begin{aligned} \delta\sigma[\text{NO}_3^- + (n-1)\text{H}_2\text{O}] : \delta\sigma[\text{Cl}^- + (n-1)\text{H}_2\text{O}] \\ = (+1) : (-2.76). \end{aligned} \quad (9)$$

Dependence (9), in particular, implies that

$$\delta\sigma(\text{Cl}^-) = -\delta\sigma(\text{NO}_3^-) \cdot 2.76.$$

This equality can be substituted into the system of two equations (7), (8). By solving this system of equations and taking into account expressions (1), (2), the frequency ratio for single ions surrounded by water molecules can be calculated:

$$f(^1\text{H})/f(^{87}\text{Rb}^+)_{C=0} = 3.0561795(3), \quad [\delta = 1.0 \cdot 10^{-7}]. \quad (10)$$

The result (10) refers to rubidium ions with the screening $\sigma(\text{Rb}^+ + n\text{H}_2\text{O})$, which was calculated in [12], and where the variation in the number of neighboring water molecules (number n) was used to calculate the uncertainty of the calculations.

3. Peculiarities of spin-spin interaction of rubidium nuclei in water

The width of the spectral responses of rubidium nuclei usually had the following width at half height: $\delta f(^{85}\text{Rb}) \approx \delta f(^{87}\text{Rb}) \approx 130$ Hz. The decay of the NMR response of rubidium (Fig. 1) allows to estimate that the spin-spin relaxation time of rubidium nuclei is approximately equal to $T_2(^{87}\text{Rb}) \approx 2.5$ ms.

The same value for one of the rubidium isotopes $T_2(^{87}\text{Rb}) \approx 1.2$ ms was determined in a recent paper [13], and without specifying their results uncertainty limits both at a higher magnetic field (4.2 T) and at a higher temperature (30°C). The authors of the paper note an anomalously low value of spin-spin relaxation relative to other ions of the alkali group, but the reason for the small value of $T_2(^{87}\text{Rb})$ is not discussed [13].

Note that in a similar paper of ours [14] the frequency ratios of lithium isotope resonances were defined as $f(^7\text{Li})/f(^6\text{Li}) = 2.6409061846(13)$ with an error of $4.9 \cdot 10^{-10}$, since the spectral NMR responses of lithium

Table 3. Amount of relative uncertainties for calculating $\mu(^{85}\text{Rb})$ and $\mu(^{87}\text{Rb})$

Source of Uncertainty	Value	Reference, year
$\mu(^{87}\text{Rb})/\mu(^{85}\text{Rb}) = 2.033\,3981(2)$	$\delta_1 = 1.0 \cdot 10^{-7}$	This paper
$f(^1\text{H})/f(^{87}\text{Rb}^+)_{c-o} = 3.0561795(3)$, [$t = 25.0^\circ\text{C}$]	$\delta_2 = 1.0 \cdot 10^{-7}$	This paper
$\mu_p = 2.792847348(7)\mu_N$	$\delta_3 = 2.5 \cdot 10^{-9}$	[8,9], 2014
$\sigma(\text{H}_2\text{O}) = 25680(2.5) \cdot 10^{-9}$, [$t = 25.0^\circ\text{C}$]	$\delta_4 = 2.5 \cdot 10^{-9}$	[8,10], 2014
$\sigma(^{87}\text{Rb}^+ + n\text{H}_2\text{O}) = (3593 \pm 27) \cdot 10^{-6}$	$\delta_5 = 2.7 \cdot 10^{-5}$	[12], 2012
Combined uncertainty $\Sigma(\delta_{1-5}) = 2.7 \cdot 10^{-5}$		

Table 4. Data on the determination of the nuclear magnetic moments of ^{85}Rb and ^{87}Rb

Method	δ_i	$\Sigma(\delta_i)$	$\mu(^{85}\text{Rb})/\mu_N$	Reference, year	Δi
OP/RD	$1.5 \cdot 10^{-5}$	–	1.35302(2)	[1], 1968, [6,7]	$-3.7 \cdot 10^{-5}$
NMR–H ₂ O	$5.9 \cdot 10^{-7}$	–	1.3533515(8)*	[2], 1976, [6,7]	$+2.1 \cdot 10^{-4}$
AB/D	$2.2 \cdot 10^{-6}$	–	1.353028(3)	[3], 1968, [6,7]	$-3.1 \cdot 10^{-5}$
ABLS	$7.4 \cdot 10^{-5}$	–	1.35298(10)	[4], 1993, [6,7]	$-6.6 \cdot 10^{-5}$
NMR–H ₂ O	$1.4 \cdot 10^{-7}$	$\Sigma(\delta_{1-5}) = 2.7 \cdot 10^{-5}$	1.35307(4)	This paper 1.35307(4)	–

Method	δ_i	$\Sigma(\delta_i)$	$\mu(^{87}\text{Rb})/\mu_N$	Reference, year	Δi
OP/RD	$1.1 \cdot 10^{-6}$	–	2.751235(3)	[1], 1968, [6,7]	$-3.1 \cdot 10^{-5}$
NMR–D ₂ O	$7.3 \cdot 10^{-7}$	–	2.751818(2)*	[5], 1976, [6,7]	$+1.8 \cdot 10^{-4}$
ABLS	$4.4 \cdot 10^{-5}$	–	2.75131(12)	[4], 1993, [6,7]	$-3.6 \cdot 10^{-6}$
NMR–H ₂ O	$1.0 \cdot 10^{-7}$	$\Sigma(\delta_{1-5}) = 2.7 \cdot 10^{-5}$	2.75132(7)	This study	–

Note. * in the papers of [2,5] a number of uncertainty components are taken into account incorrectly.

isotopes were recorded with our device with a width of ≈ 0.3 Hz.

In this case, the spectral NMR responses of rubidium nuclei have the largest width among other ions of the alkaline group [14–17]. Additional studies are required to find out the cause of small values T_2 of rubidium nuclei in water. Nevertheless, even at spectral response widths of ≈ 130 Hz, the averaged data for the resonance frequency ratio were obtained with a relative uncertainty of $\delta \approx 10^{-7}$ in this paper.

4. Comparison of data on rubidium nuclear magnetic moments

It follows from the data in Table 1 that for the four ampoules under study, the frequency ratios $f(^{87}\text{Rb}^+)/f(^{85}\text{Rb}^+)$ are in good agreement with each other within the experimental uncertainties. This agreement is contingent on the following equality: $\sigma(^{85}\text{Rb}^+)_i \approx \sigma(^{87}\text{Rb}^+)_i$, which is true for each of the four

ampoules ($i = 1-4$), since in each ampule the rubidium nuclei of two isotopes (despite the difference in masses, magnetic and nuclear quadrupole moments of these two isotopes) are in very close conditions of electron screening. Four data averaging (Table 1) gives the result taking into account their weight:

$$f(^{87}\text{Rb}^+)/f(^{85}\text{Rb}^+) = 3.3889968(3) [\delta = 1 \cdot 10^{-7}]. \quad (11)$$

A similar (11) ratio was determined earlier in a [1] study of free rubidium atoms by optical excitation method with the result 3.388985(7) [$\delta = 2.3 \cdot 10^{-6}$], which within two standard deviations does not contradict the more accurate result (11). It follows from equality (11) and relations (1), (2):

$$\mu(^{87}\text{Rb})/\mu(^{85}\text{Rb}) = 2.033\,3981(2) [\delta = 1 \cdot 10^{-7}]. \quad (12)$$

Thus, a characteristic property of this method is the opportunity to determine the ratio of nuclear magnetic moments of rubidium isotopes with the lowest uncertainty. To calculate $\mu(^{85}\text{Rb})$ and $\mu(^{87}\text{Rb})$ in units of the nuclear

magneton using the relations (3), (4) it is required to take into account the uncertainties that are presented in Table 3, where the largest contribution is related to the calculation of screening of rubidium ions in water [12].

Table 4 shows a comparison of the data on determining the rubidium nuclear magnetic moment from the papers [1–5] and the data of the present paper. The results of the papers [1–5] were later included in reference publications [6,7] after being corrected for the nuclear electron screening.

Table 4 shows the value of Δi , which in relative units indicates the deviation of the previous data from the data of the present paper.

Note the coincidence of our new result for $\mu(^{87}\text{Rb})$ with the data of the ABLS method presented by twenty co-authors of the ISOLDE, CERN [4] collaboration. For $\mu(^{85}\text{Rb})$, the data of the ABLS method also agree with our new result, but at the limit of the uncertainty of their result indicated in [4] [$\delta = 7.4 \cdot 10^{-5}$].

And in general, the new result is in good agreement with the data of previous papers, but with the exception of those data where erroneously low results [2,5] were used in estimating the rubidium ions screening in H_2O or D_2O .

For further more accurate determination of the magnetic moments $\mu(^{85}\text{Rb})$ and $\mu(^{87}\text{Rb})$, it is required to perform more accurate calculations of electron screening, and for further use it is reasonable to present the final result of this paper in nuclear magneton units without correction for rubidium ions screening:

$$\mu(^{85}\text{Rb})[1 - \sigma(^{85}\text{Rb}^+)] = 1.34820532(19)_{\mu_N},$$

$$[\Sigma(\delta_{1-4}) = 1.4 \cdot 10^{-7}], \quad (13)$$

$$\mu(^{87}\text{Rb})[1 - \sigma(^{87}\text{Rb}^+)] = 2.74143684(28)_{\mu_N},$$

$$[\Sigma(\delta_{1-4}) = 1.4 \cdot 10^{-7}]. \quad (14)$$

Conclusion

NMR responses from rubidium isotopes in the studied aqueous solutions have a 100 times greater width than, for example, analogous responses from cesium-133 nuclei. This phenomenon is of interest and requires further study. By the results of a comparative analysis of new data for the rubidium nuclear magnetic moment with the data of previous papers, it follows that the use of the method of simultaneous recording of NMR responses of two types of dissimilar nuclei allows one to reduce the experimental uncertainties to the level of $\delta \approx 10^{-7}$. The $\delta \approx 10^{-7}$ uncertainty also applies to the ratio of nuclear magnetic moments of two rubidium isotopes, where the screening correction is small and can be neglected at the achieved level. New results are obtained for the ^{87}Rb and ^{85}Rb nuclear magnetic moments, which do not contradict the previously known data, but have a smaller uncertainty.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

- [1] C.W. White, W.M. Hughes, G.S. Hayne, H. Robinson. *Phys. Rev.*, **174**, 23 (1968). DOI: 10.1103/PhysRev.174.23
- [2] G.H. Fuller. *J. Phys. Chem. Ref. Data*, **5**, 835 (1976). DOI: 10.1063/1.555544
- [3] V.J. Ehlers, T.R. Fowler, H.A. Shugart. *Phys. Rev.*, **167**, 1062 (1968). DOI: 10.1103/PhysRev.167.1062
- [4] ISOLDE Collaboration, H.T. Duong, C. Ekström, M. Gustafsson, T.T. Inamura, P. Juncar, P. Lievens, I. Lindgren, S. Matsuki, T. Murayama, R. Neugart, T. Nilsson, T. Nomura, M. Pellarin, S. Penselin, J. Persson, J. Pinard, I. Ragnarsson, O. Redi, H.H. Stroke, J.L. Vialle. *Nucl. Instrum. Method. Phys. Res.*, **A325**, 465 (1993). DOI: 10.1016/0168-9002(93)90392-U
- [5] O. Lutz. *Z. Naturforsch.*, **23a**, 1202 (1968).
- [6] N.J. Stone. *Atomic Data Nucl. Data Tables*, **90** (1), 75 (2005).
- [7] N.J. Stone. *TABLE OF NUCLEAR MAGNETIC DIPOLE AND ELECTRIC QUADRUPOLE MOMENTS* (Nuclear Data Section International Atomic Energy Agency Vienna International Centre, Vienna, Austria, 2014), <https://www-nds.iaea.org/publications/indc/indc-nds-0658.pdf>
- [8] P.J. Mohr, D.B. Newell, B.N. Taylor. *Rev. Modern Phys.*, **88**, 035009 (2016). DOI: 10.1103/RevModPhys.88.035009
- [9] A. Mooser, S. Ulmer, K. Blaum, K. Franke, H. Kracke, C. Leiteritz, W. Quint, C.C. Rodegheri, C. Smorra, J. Walz. *Nature*, **509**, 596 (2014). DOI: 10.1126/science.aan0207
- [10] Yu.I. Neronov, N.N. Seregin. *Metrologia*, **51** (1), 54 (2014). DOI: 10.1088/00261394/51/1/54
- [11] Yu.I. Neronov, N.N. Seregin. *Measurement Techniques*, **53** (8), 2010, 926 (2010).
- [12] A. Antušek, D. Kedziera, A. Kaczmarek-Kedziera, M. Jaszunski. *Chem. Phys. Lett.*, **532**, 1 (2012). DOI: 10.1016/j.cplett.2012.02.036
- [13] K. Hayamizu, Y. Chiba, T. Haishic. *RSC Adv.*, **11**, 20252 (2021). <https://pubs.rsc.org/en/content/articlepdf/2021/ra/d1ra02301b>
- [14] Yu.I. Neronov. *Izmer. Tekh.*, **9**, 3 (2020) (in Russian). DOI: 10.32446/0368-1025it.2020-9-3-8
- [15] Yu.I. Neronov. *Tech. Phys.*, **66** (1), 93 (2021). DOI: 10.1134/S106378422101014X
- [16] Yu.I. Neronov, A.N. Pronin. *Izmer. Tekh.*, **4**, 3 (2021) (in Russian). DOI: 10.32446/0368-1025it.2021-4-3-8
- [17] Yu.I. Neronov, A.N. Pronin. *Izmer. Tekh.*, **3**, 3 (2021) (in Russian). DOI: 10.32446/0368-1025it.2021-11-3-7