1. INTRODUCTION

Both stable isotopes of silver (\(^{107}\text{Ag}\) and \(^{109}\text{Ag}\)) exhibit low-lying isomer states with mean lifetimes of about one minute. The energies of gamma photons emitted by the excited nuclei are relatively low (93.1 and 88.0 keV for the \(^{107}\text{Ag}\) and \(^{109}\text{Ag}\) isomers, respectively), and the corresponding emission and absorption probabilities in the absence of recoil in metal silver at the liquid-helium temperature are sufficiently large for the observation of their Mössbauer absorption. For the \(^{107}\text{Ag}\) and \(^{109}\text{Ag}\) isomers, these probabilities are 0.0377 and 0.0535, respectively. Interest in Mössbauer experiments with the long-lived silver isotopes is related to the fact that the natural widths of the corresponding gamma lines (about \(10^{-17}\) eV) are narrower than the natural width of the gamma line of the most widely used Mössbauer nuclide \(^{57}\text{Fe}\) by eight orders of magnitude, which enables one to correspondingly increase the resolution of the Mössbauer spectroscopy. Note that, in the vicinity of Earth’s surface, the gravitational interaction shifts the position of gamma resonance by the natural widths of the gamma lines of these isomers when the vertical distance between the emitting and absorbing nuclei is \(10^{-4}\) cm. Owing to the Zeeman effect, Earth’s magnetic field splits the gamma lines of the silver isomers into 14 components, such that the intervals between them are greater than the natural widths of gamma lines by a factor of about \(10^6\). In accordance with a commonly accepted concept, the Mössbauer gamma lines of long-lived isomers must be broadened by several orders of magnitude. It is stated that the Mössbauer gamma line must be broadened due to the so-called dipole–dipole hyperfine interactions between the magnetic moments of neighboring nuclei and between the magnetic moments of nuclei and conduction electrons even in such seemingly ideal Mössbauer substances as the silver single crystals with face-centered cubic lattice, in which silver nuclei are not affected by electric fields and the atoms are diamagnetic. The energies of these interactions can reach \(5 \times 10^{-12}\) eV. Mutual orientations of the nuclear and electron magnetic moments exhibit chaotic variations in time. Hence, the energies of the dipole–dipole interactions must widely range with the above upper bound and, consequently, the Mössbauer gamma lines of silver isomers must be broadened by five to six orders of magnitude.

Early experiments with silver isomers [1–3] seem to prove these inferences. These experiments have demonstrated gamma activity of the initially inactive resonant ultrapure silver absorbers emerging due to irradiation at the liquid-helium temperature by the gamma photons of strong sources created by either proton irradiation of silver plates on a cyclotron (in experiments with \(^{107}\text{Ag}\)) or the neutron irradiation of diamagnetic Ag–Pd samples in a reactor (in experiments with \(^{109}\text{Ag}\)). The activities of the absorbers irradiated by gamma photons were extremely weak and could be
approximated on the order of magnitude using the theoretical estimates of the broadening of gamma lines related to the dipole–dipole interaction. However, the weakness of the effects could be alternatively interpreted. The gamma sources from these experiments were strongly irradiated in the course of manufacturing. Such irradiation leads to a significant number of defects in the crystal structure and, even, a minor variation in the chemical composition. Relatively short half-lives of parent nuclides ($^{108}\text{Cd}$ and $^{109}\text{Pd}$ in experiments with $^{107}\text{Ag}$ and $^{109}\text{Ag}$, respectively) do not allow long-term annealing of the gamma sources. Therefore, after a short-term annealing, one can observe a minor isomer shift between the gamma lines of sources and the absorption lines of unirradiated absorbers. This could be an additional reason for a decrease in the cross section of the resonant absorption of gamma photons in these experiments.

2. EXPERIMENTAL INDICATIONS OF THE ABSENCE OF SIGNIFICANT BROADENING FOR THE $^{109}\text{m}\text{Ag}$ ISOMER MÖSSBAUER GAMMA LINE

Wildner and Gonser [4] reported on the experimental observation of the resonant absorption of the $^{109}\text{m}\text{Ag}$ isomer gamma rays realized using an alternative approach. The authors studied the temperature dependence of the yield of $^{109}\text{m}\text{Ag}$ gamma rays with an energy of 88 keV for the gamma source that represents a single-crystal silver plate with the thermal-diffusion-introduced parent nuclide ($^{109}\text{Cd}$) whose half-life is 464 days. The transition from room temperature to liquid-nitrogen temperature (77 K) results in a decrease in the intensity of gamma photons emitted by the source owing to the contraction of silver upon cooling. When the source temperature further decreases to the liquid-helium temperature (4.2 K), the contraction of silver and the corresponding attenuation of the gamma yield must continue, but to a lesser extent, since the linear expansion (contraction) coefficient of silver decreases with a decreasing temperature. Using the well-known temperature dependence of the linear expansion coefficient of silver, one can reliably calculate the degree of contraction when the temperature decreases from 77 to 4.2 K and predict a decrease in the measured intensity of gamma photons related to this contraction. The experiments show that, when the source is cooled to a temperature of 4.2 K, the intensity of gamma rays decreases significantly stronger in comparison with the predictions based on the data on the temperature contraction of silver. Wildner and Gonser [4] assign the excess self-absorption of gamma rays in the source to Mössbauer resonant absorption, which is extremely low at 77 K, but increases by a factor of 50 when the source is cooled to 4.2 K. The scale of the excess self-absorption corresponds to a broadening factor of 30 (rather than 10$^5$) for the Mössbauer gamma line. Unfortunately, the authors do not interpret the absence of the effect of dipole–dipole interactions.

Several years later, in experiments from [5–7], the results from [4] were proven and the corresponding broadening factors of gamma lines were determined to be 16, 24, and 100 (the last result was obtained with a relatively large error). However, the authors also did not interpret the absence of the theoretically predicted broadening.

Over several years, our group performed experiments aimed at demonstrating the Mössbauer self-absorption of gamma rays of the $^{109}\text{m}\text{Ag}$ isomer in silver gamma sources using the temperature effect and the effects of gravitational and magnetic action upon the gamma sources [8–12]. In all of the experiments, we observe manifestations of the resonant self-absorption of the gamma rays emitted in the horizontal direction in the absence of such an effect for vertically emitted gamma radiation. In addition, we observed the effect of a variation in the direction of Earth’s magnetic field on the resonant absorption of the horizontally emitted $^{109}\text{m}\text{Ag}$ gamma rays [11, 12]. In accordance with our estimates, the broadening factors of the Mössbauer gamma line of this isomer in the sources under study were no greater than 20–30. The clear absence of a significant contribution of dipole–dipole interactions to the width of the $^{109}\text{m}\text{Ag}$ Mössbauer gamma line indicates that the duration of the gamma photon emission must be significantly longer than the characteristic time of a variation in the energy of these interactions. In the opposite scenario, the energy of emitted photon is represented as a sum of the nuclear transition energy and the instantaneous energy of the dipole–dipole interaction. In this case, a significant broadening of the gamma line must be realized. A relatively long emission of the gamma photon makes it possible to formulate the problem of the averaging of the dipole–dipole interaction energy that exhibits variations in magnitude and sign to a relatively small value. Note that the conclusion regarding the relatively long emission and absorption of gamma photons by nuclei has been drawn based on alternative reasons [13]. A relatively small broadening factor of the Mössbauer gamma line enables one to directly experimentally study the shape of the $^{109}\text{m}\text{Ag}$ gamma resonance using the effect of gravitation.

3. GRAVITATIONAL GAMMA SPECTROMETER

We have developed and created an experimental setup called a gravitational gamma spectrometer. The first variant of this setup can be found in [14]. The spectrometer represents a platform mounted on a horizontal axis around which it can be rotated with an electric drive by an angle of up to 30° on both sides (Fig. 1). A cryostat with the main and auxiliary gamma sources is placed on the platform. Inside the cryostat, the gamma sources can be in direct contact with liquid helium. The main gamma source represents a single-crystal silver plate with a size of $25 \times 16 \times 0.74$ mm$^3$. The $^{109}\text{Cd}$ par-