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NUCLEAR MEASUREMENT TECHNIQUE

The μSR Setup on the Muon Beam of the Synchrocyclotron at the Konstantinov Institute of Nuclear Physics

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Abstract—The μSR setup for investigating the distribution of magnetic fields in solids using the muon spin rotation (μSR) method is described. The setup is characterized by a high degree of homogeneity of the magnetic field at the site of the sample under investigation, compensation of scattered magnetic fields to a level of -10^{-2} G, and a time resolution of 2.5 ns (the full width at half-maximum). The setup is suitable for μSR measurements on samples in the temperature range of 5–300 K with a precision of ±0.1 K.

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INTRODUCTION

The μSR method [1, 2] has been regularly used in experimental investigations of magnetic materials on the muon beam of the synchrotron at the Russian Academy of Sciences' Konstantinov Institute of Nuclear Physics [3]. In particular, the traditional μSR technique is currently being adapted for studies of nanostructured materials. To guarantee high efficiency of future experiments, it is necessary that the general idea behind the experimental setup be clear.

The fact that polarized muons obtained on particle accelerators are used as a singular tool for investigating the properties of solids is explained by the possibility of easily monitoring the polarization of an ensemble of particles over 10–15 μs after they are embedded in the analyzed sample. The point is that decay of these singly charged unstable particles with mass $m_\mu \approx 206 m_e$ and spin $S = 1/2$ is classified as a weak interaction and is followed by violation of the spatial parity conservation law. This leads to anisotropy in escape of a positron produced thereby ($\mu^+ \longrightarrow e^+ + \nu_e + \tilde{\nu}_\mu$) with respect to the direction of the spin of a muon at rest [4].

The idea behind the μSR method is as follows. Observing the asymmetry of the distribution of decay positrons, one can determine the direction of the magnetic moment of a muon at the instant of its decay. Therefore, embedding approximately completely polarized muons in the sample under investigation, we obtain a chance to monitor the behavior of the magnetic moment of a muon in the medium and to study muon spin relaxation processes, spin precession in magnetic fields, and other important characteristics.

EXPERIMENTAL TECHNIQUE

The currently available μSR setup (Fig. 1) consists of a set of Helmholtz rings *HRs* (three pairs of rings) compensating for the magnetic fields produced by the magnetic lenses of the muon channel and the main

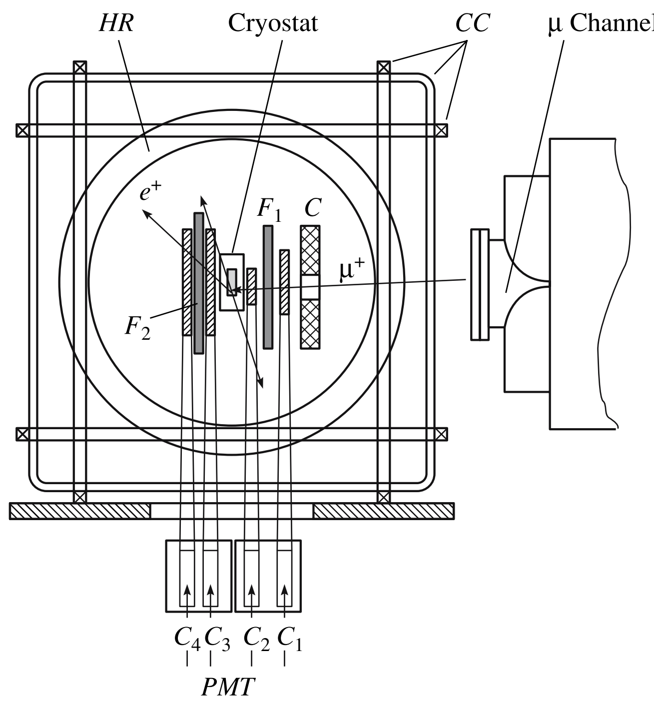

Fig. 1. Setup for the μSR experiments: (*HR*) Helmholtz rings, (*CC*) compensating coils, (*C*) collimator, (F_1, F_2) filters, (*PMT*) photomultiplier tube, and (C_1–C_4) scintillation counters.

magnet of the synchrotron, as well as the geomagnetic field. One pair of Helmholtz rings is used to create a homogeneous magnetic field (for measurements in external magnetic fields). The required (longitudinal or transversal) orientation of the external magnetic field is provided by rotation of the Helmholtz rings that generate this field. The power supply of the Helmholtz rings ensures stabilization of the current over the range of magnetic field values of 5–1500 G. The current (field) stability is $\sim 10^{-3}$. The degree of homogeneity of the magnetic field is naturally dependent on the size of the Helmholtz ring coils. Experimental results for a copper sample with dimensions of $\varnothing\, 40 \times 5$ mm (the relaxation rate $\lambda = 0.0053 \pm 0.0031 \mu s^{-1}$) showed that this degree of homogeneity is acceptable for μSRexperiments.

The muon channel of the synchrotron at the Russian Academy of Sciences' Konstantinov Institute of Nuclear Physics forms a beam of polarized muons with an intensity of 10^4–10^6 s^{-1} (depending on the momentum selected) in the range of momenta p_μ = 70–130 MeV/c with longitudinal polarization of μ^+ mesons at a level of ~90–95%, which allows samples with an effective thickness along the beam of 4–10 g/cm^2 to be analyzed. The spatial dimensions of the beam at the surface of a sample are set by collimator C (Fig. 1). Varying the thickness of filter F_1, it is possible to optimize the curve of muon stops for each particular sample.

Samples under investigation are inserted in a gas-cooled cryostat [5]. A flow of cooled helium or nitrogen gas is used in it as a coolant. For helium, the attainable temperatures range from 5 to ~300 K and a transfer from one temperature to the other takes 20 min or less. Nitrogen blow of the cryostat sharply increases the time it takes to transfer from one point to the other and reduces the temperature range. The stability of the steady-state temperature of the sample is maintained within the limits of ±0.1 K. The total thickness of the windows in the cryostat is ~0.2 g/cm^2, which is much smaller than the minimum thickness of analyzed samples.

Muons incident on the sample and positrons escaping from it are detected by muon and positron telescopes of scintillation counters, respectively. The arrangement of the counters is presented in Fig. 1. According to this configuration, the positron telescope is located so that the contribution made by the asymmetry of decays of muons with spins aligned with the direction (the momentum) of the muons is maximal. This appears to be very useful in experiments with zero external magnetic fields at high relaxation rates. The dimensions of the plastic scintillators in the positron telescope are $180 \times 180 \times 5$ and $180 \times 180 \times 20$ mm, which guarantees a high detection efficiency for decay positrons ($N_e/N_{st} \approx 0.15$, where N_e is the number of detected positrons produced by decays of stopped muons N_{st}). Filter F_2 located between two positron counters is used to specify the energy threshold in detection of decay positrons, which leads to an increase in the observed asymmetry.

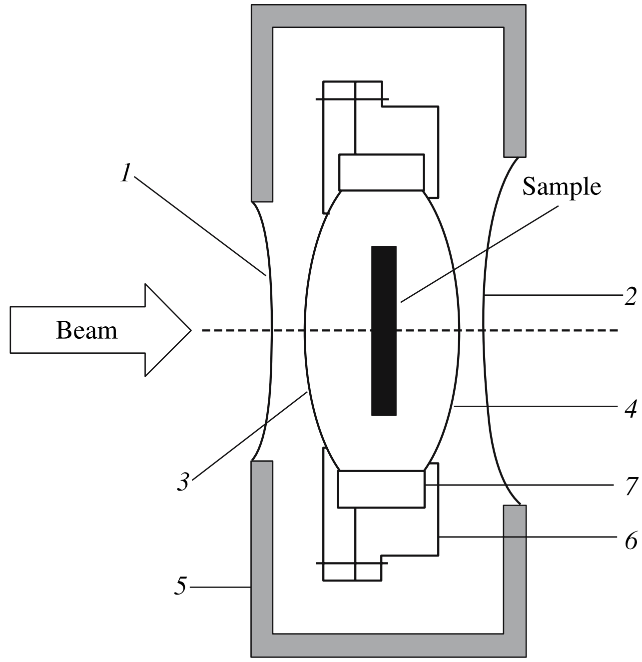

Fig. 2. Cryostat and location of a sample in the cryostat for μSR investigations: (*1*, *2*) entrance and exit hot windows, respectively; (*3, 4*) entrance and exit cold windows, respectively; (*5*) cryostat casing; (*6*) beryllium bronze chamber of the cryostat; and (*7*) sample holder.

The sizes of scintillation counters C_1 and C_2 were selected by recognizing that they must satisfy two requirements: (1) each counter must efficiently detect all muons passing through collimator C, and (2) the number of muons stopped in the material of counter C_2 with dimensions of $60 \times 60 \times 3$ mm must be the smallest possible.

The cryostat chamber (Fig. 2) used in the μSR setup permits analysis of samples smaller than $\varnothing$ 60 × 15 mm. Should the stopping curve for a sample with a thickness downstream of the muon beam of ~4 g/cm^2 be properly adjusted (by selecting momentum p_μ and the thickness of filter F_1), the contribution of the background due to muon stops in counter C_2 and the entrance windows of the cryostat does not exceed 3%.

The μSR method is a universal tool for studying the whole variety of phenomena in disordered magnetic systems. The main source of information in traditional μSR experiments on polarized muon beams is a spectrum of time intervals between muon stops in the sample volume and the instants when a positron produced by decay of a particular muon is detected. Since the spatial distribution of decay positrons in the μ–e decay (which proceeds through weak interactions with parity violation) is anisotropic relative to the muon spin direction at the instant of decay, the time spectrum of decay positrons escaping at an angle 0° to the initial polarization of the muon beam can be described by the expression

$$N(t) = N_0 \exp(-t/\tau_\mu)\,(1 + aG(t)), \quad (1)$$

where $\tau_\mu \approx 2.2$ μs is the muon lifetime; a is the initial asymmetry of decay positrons (at $t = 0$), which is related to the initial muon polarization value, as well as to the detection efficiency and spatial angle for positrons; and $G(t)$ is the function of spin relaxation of a muon stopped in the sample, $G\,(t = 0) = 1$.

The statistical distortions introduced during measurements of the initial time distribution of decay positrons can be attributed to the dead time of the detecting system and are dependent on the muon beam intensity. Note that the finite lifetime of a muon may be responsible for a distortion caused by detection of a false positron due to decay of another muon in the sample volume.

In the special case in which the time distribution of a periodic Poisson flux is being measured, both hardware-based and mathematical algorithms for suppressing statistical distortions are available [6]. However, for the most general case of nonperiodic Poisson flux—in particular, for the μSR method—an analytical expression for complete reconstruction of the initial time distribution does not exist and only some of the distortions can be compensated by selecting events according to certain criteria. To generate the *Start* signal, only those signals due to muon stops in the sample are selected that have not been preceded by an identical signal in time interval t_b (protection *before*). Then, in time interval t_a corresponding to the spectrum measurement range, the *Stop* signal due to a decay positron is expected. If two or more signals from a decay positron or a muon stopping signal (protection *after*) are detected in this time interval, such an event is rejected and not added to the acquired time spectrum.

The durations of protective time intervals t_b and t_a are selected so that admissible distortions of μSR spectra must not exceed 1% at $t_b \approx 5\tau_\mu \approx 10$ μs. The duration of interval t_a (of protection *after*) is equal to the range of the time-interval meter ($t_b = t_a \le 5\,\tau_\mu \approx 10$ μs). Under these conditions of selection, the number of rejected events that governs the data acquisition rate increases with an increase in initial muon beam intensity I_0. The muon beam intensity used to good effect is estimated as

$$I_{eff} = I_0 P(1) = I_0 \exp(-\lambda); \quad \lambda = I_0 (t_b + t_a)\alpha, \quad (2)$$

where I_0 [s^{-1}] is the intensity of the muon beam measured by the muon detector, $P(1)$ is the probability that only one stopped muon will be detected in time interval ($t_b + t_a$), t_b and t_a are the respective time intervals "before" and "after" the stopping time, and α is the coefficient that takes into account the inhomogeneous time structure of the beam ($\alpha \le 1$).

Estimates according to Eq. (2) show that the highest possible intensity of the efficiently used muon beam lies in the range (3–6) $\times 10^4$ s^{-1}. Higher-intensity muon beams are used in traditional μSR experiments on the PSI (Switzerland) and TRIUMF (Canada) meson facilities, only with efforts being made to improve the quality of the beam itself (i.e., to decrease momentum resolution $\Delta p_\mu / p_\mu$ and spatial dimensions of the beam) and carry out investigations on samples of a smaller thickness and smaller transversal dimensions. Nevertheless, the resultant data acquisition rate is only slightly greater than the rate achieved on the muon channel of the synchrocyclotron at the Russian Academy of Sciences' Konstantinov Institute of Nuclear Physics.

DATA ACQUISITION SYSTEM OF THE EXPERIMENTAL SETUP

The functional diagram of the data acquisition system of the μSR setup is shown in Fig. 3. Signals *S1–S4* from scintillation counters C_1–C_4 are selected according to their amplitude by respective discriminators D_1–D_4, which generate logic signals. The thresholds of discriminators are selected so as to guarantee high detection efficiency for muons and decay positrons. Signal *S1** from auxiliary discriminator D_1^* with a high threshold suppresses detection of beam positrons. Muon logic unit *ML*, which recognizes a stopped muon, realizes the logic function $S1\&S2\&S1^*\&(\overline{S3})$ with time reference to the signals of counter C_1. Positron logic unit *PL*, which recognizes a decay positron, realizes the logic function $S3\&S4\&(\overline{S1\&S2})$ with time reference to the signals of counter C_3. The use of the logic criteria of event selection in view of the time reference makes it possible to substantially reduce the spurious cross correlations in time between the *Start* and *Stop* channels and to improve thereby the linearity of the whole measuring section.

The start signal generator *SSG* for time-interval meters tests muons for multiplicity of stops in interval t_b, thus performing the function of protection *before*. To do this, one of the output signals of unit *ML* is fed into the start input of the univibrator used in the unit generating protection time intervals t_b (unit of protection *before PB*), which operates in the restart mode (i.e., it extends the interval in response to the signal appearing during the action of signal t_b). The output signal of unit *PB* arrives at the *SSG* and acts as an inhibit signal. The signal from the *ML* unit passes through regulated delay line DL_1 and is fed into the second input of the *SSG*. In this case, a signal will appear at the *SSG* output only in the absence of multiple stops in time interval t_b preceding the stop at hand. The delay time of DL_1 is selected to be as long as possible, so that no self-restraint occurs. Moreover, the *SSG* has additional inputs for enabling production of the *Start* signal for the respective time-to-digital converter TDC_1 or TDC_2 in the absence of their individual busy signals *Bs1* (*Bs2*). To synchronize operation of the system with the synchrocyclotron, acceleration cycle start signal *ACS* arrives at the gate-pulse

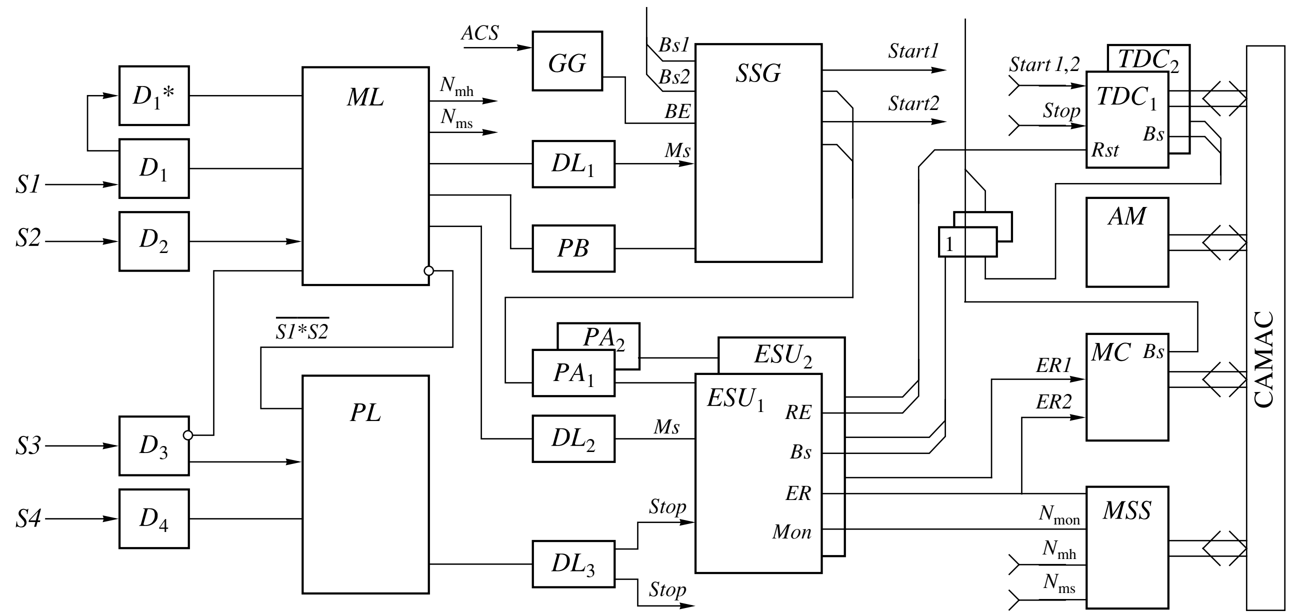

Fig. 3. Functional diagram for generation of a trigger for the μSR setup: (*S1–S4*) signals from counters C_1–C_4, (D_1–D_4, D_1^*) discriminators, (*ML*) muon logic unit, (*PL*) positron logic unit, (*GG*) gate pulse generator, (DL_1–DL_3) delay lines, (*SSG*) start signal generator, (*PB*) unit of protection *before*, (*PA*) unit of protection *after*, (*ESU*) event selection unit, (*TDC*) time-to-digital converter, (*MC*) memory controller, (*AM*) analyzer memory, and (*MSS*) multichannel system of scalers. Signals: (*ACS*) acceleration cycle start, (*Bs*) busy, (*RE*) rejected event, (*Mon*) monitor, (*ER*) event recording, (*BE*) beam extraction, (*Ms*) muon stop, and (*Rst*) reset; (N_{mh}) and (N_{ms}) numbers of muon hits and stops, respectively.

generator (*GG*), which generates beam extraction signal *BE*, which is common for the entire system and enables its operation.

Units *PB* and *PA* that generate protection time intervals t_b and t_a comprise digital univibrators operating in the restart mode (extending the time intervals). The resolving time for multiple events is ≈20 ns; it is governed by the durations of signals (the dead times) of the univibrators used in upstream units D_1–D_4, *ML*, and *PL*. The operating frequency of units *PB* and *PA* is 100 MHz, which guarantees a precision of ±10 ns for the analyzed time interval.

Useful event selection unit *ESU* fulfills the functions of protection *after* by searching for multiple events of both stopped muons and decay positrons in time interval t_a that is produced by unit *PA* and follows the muon stopping, before which no stopped muons were detected in interval t_b. Delay line DL_2 optimizes the signal position in time at input *Ms* (muon stopping), reducing the untestable time interval after the detected muon stopping. Should no multiple events be found in interval t_a, the *ESU* produces signal *ER* that enables recording of the event; otherwise, signal *RE* (rejected event) resets the relevant time-to-digital converter *TDC* to zero. Signal *Mon* at the corresponding output of the *ESU* (monitor) indicates that only one stopped muon has been detected in time interval t_b + t_a. The total counting of *Mon* signals of the *ESU* over the data acquisition time is used to normalize the statistics in the spectrum acquired.

Time intervals are measured by means of two time-to-digital converters *TDC*: TDC_1 used for direct conversion has a range of 10 μs and a channel width of 5 ns/channel, while the expander-type TDC_2 measures time intervals with a length of as great as 1.2 μs at a channel width of 0.8 ns/channel. Both the time-interval meters (TDC_1 and TDC_2) are triggered by the *Start* signals and operate independently of each other, which helps to increase the counting rate. Each time-interval meter uses its own event selection unit (ESU_1 or ESU_2) with interval of protection *after* corresponding to its time range and generated by unit PA_1 or PA_2, respectively.

The system allows for separate interlocking of generation of the *Start* signals for each *TDC* over the time taken to process an event. This interlocking is initiated by arrival of signals *Bs* (busy), which cover the conversion time of the *TDC*, the time of the multiplicity test in the *ESU*, and the time it takes for memory controller *MC* to process the data.

The data acquisition system with analyzer memory *AM* is used to reduce the data readout time. Operation of this subsystem is controlled by memory controller *MC*. In response to signals *ER*, data are read out of the appropriate *TDC*, tested for compliance with the admitted region, and added to analyzer-type memory *AM* to the address equal to the *TDC* data with a shift toward

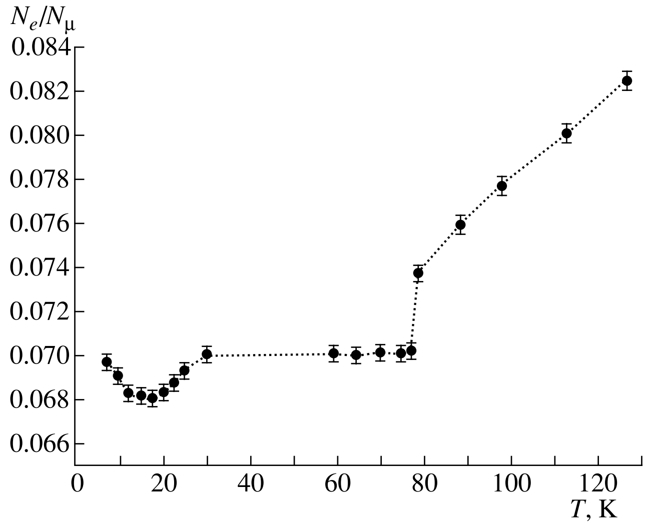

Fig. 4. Ratio of the integrated yield of positrons to the total muon number N_e/N_μ as a function of temperature T for alloy $Fe_{0.54}Ni_{0.28}Cr_{0.18}$.

the memory space assigned for the corresponding spectrum. In view of the conversion time of the *TDC*, the data readout time in this special-purpose system does not exceed 15 μs. Therefore, it is possible to reduce the total dead time of the measuring system by a factor of 4 and over in comparison to the traditional method of data readout into an external computer. Acquired spectra are transmitted to the computer on the operator's request or in response to the *AM* overflow alarm. Such an approach has made it possible to set the computer processor free from the routine procedure of data readout and allocate the liberated processor resources to control the system of thermal stabilization of the analyzed sample in the cryostat.

Multichannel system of pulse scalers *MSS*, which is used for monitoring and normalization of μSR spectra during data acquisition, provides a means for relative measurements of the muon spin relaxation rate by employing the total count method [7]. The use of the total count method is illustrated in Fig. 4, which presents temperature dependence of the ratio of the integrated positron yield to the total number of muons $N_e/N_\mu(T)$ for alloy $Fe_{0.54}Ni_{0.28}Cr_{0.18}$ suffering two phase transitions. One of these is the paramagnet–disordered ferromagnet transition at $T = T_C \approx 80$ K (T_C is the Curie temperature), and the other is the disordered ferromagnet–spin glass transition at $T = T_g \approx 18$ K [8]. As compared to the traditional technique, the total count

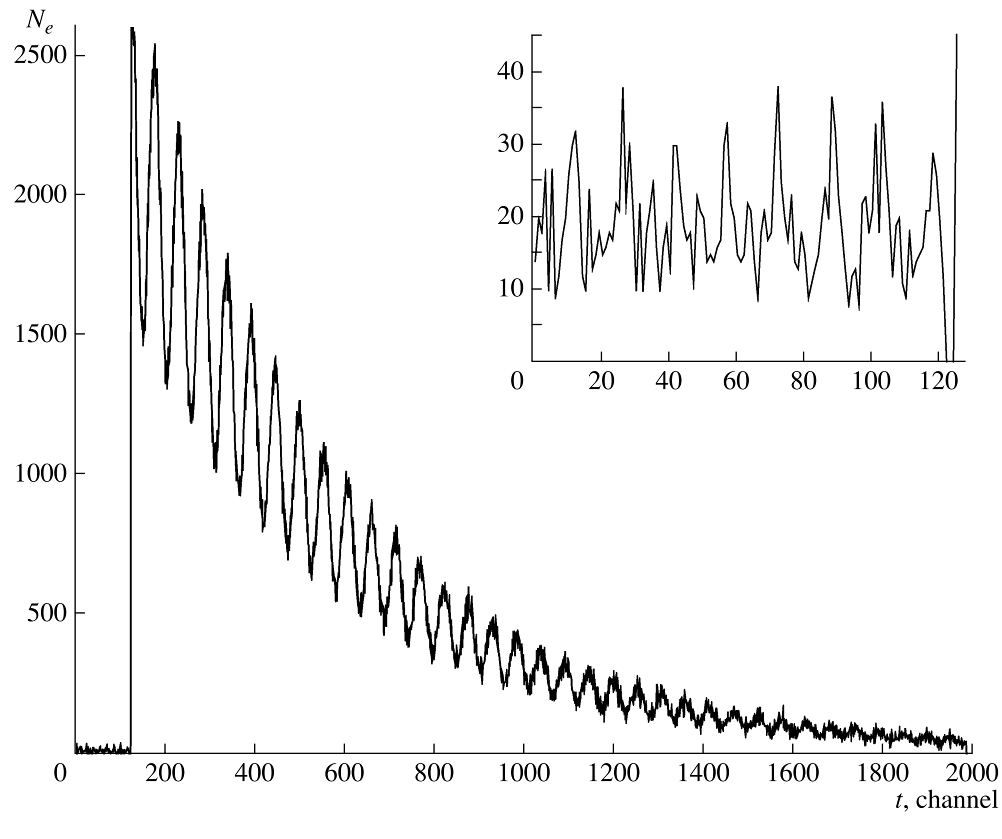

Fig. 5. Example of the original μSR spectrum obtained for the 40-mm-diameter 5-mm-thick copper sample in the transversal (with respect to the spin direction) external magnetic field with induction $B = 278$ G at temperature $T = 300$ K. The background distribution in the interval from the origin of the converter scale to the time zero is shown in the inset. One channel on the horizontal scale (time t) corresponds to 5 ns, and the time zero is in the 126th channel.

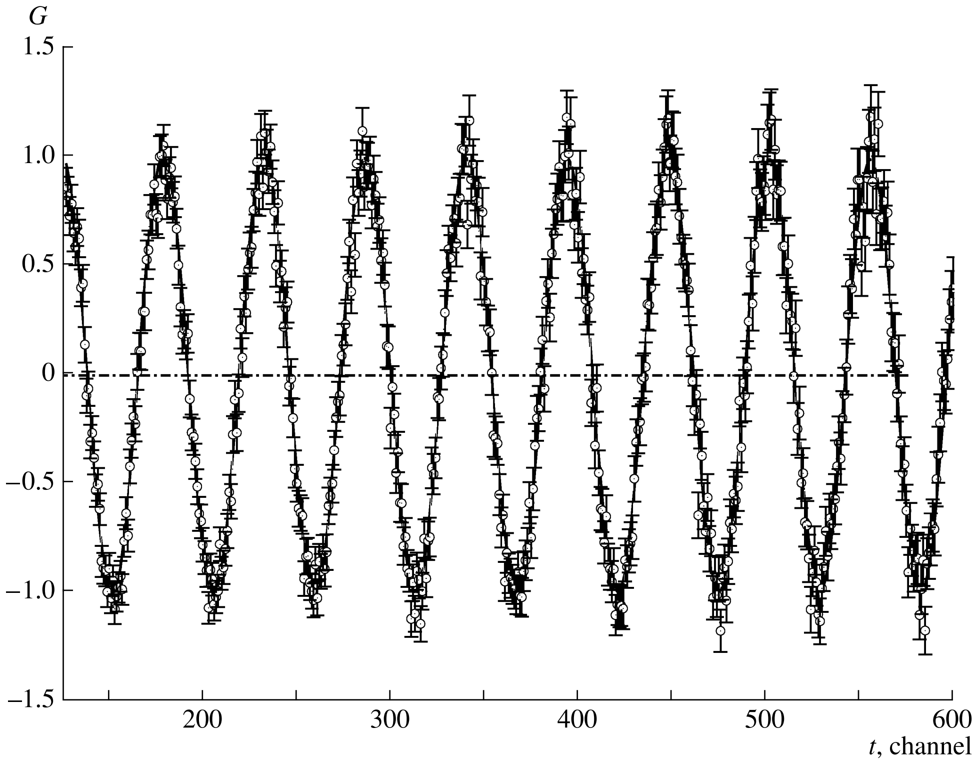

Fig. 6. Function of spin relaxation in the transversal (with respect to the muon spin direction) external magnetic field with induction B = 278 G for the 40-mm-diameter 5-mm-thick copper sample at temperature T = 300 K. One channel on the horizontal scale (time t) corresponds to 5 ns, the time zero is in the 126th channel, $\lambda = 0.0053 \pm 0.0031$ μs, $a = 0.2718 \pm 0.0022$, and $F = 3.7647 \pm 0.0005$ MHz.

method makes it possible to significantly reduce the time of measurements aimed at determining the phase transitions, which is very important for saving the beam time.

The original μSR spectrum obtained for a 40-mm-diameter 5-mm-thick copper sample in the transversal (with respect to the spin direction) external magnetic field with induction B = 278 G is shown in Fig. 5. The background distribution in the interval from the origin of the converter scale to the time zero is presented in the inset of Fig. 5. Figure 6 displays relaxation function G after processing of the time spectrum in Fig. 5. The background is composed both of positrons from decays of muons stopped in the collimator material and beam positrons from decay $\pi^0 \longrightarrow e^+ + e^-$ in the region near the meson-producing target. In approximately 85% of events, a positron due to a decay of a muon stopped in the sample does not hit the positron detector (i.e., the geometrical acceptance is ~15%) and is substituted in the time interval either by a beam positron or by a positron escaping from the collimator material. Several channels of the time-interval meters are allocated for estimating the contribution of this background. Delay line DL_3 (Fig. 3) shifts the origin of the decay spectrum to the right of the *TDC* time scale origin at a time interval of ≈600 ns, which corresponds to background events only. During selection of spectrum events satisfying the conditions of protection *before* and *after*, the background contributions under the spectrum (to the right of the time zero) and on the left of the spectrum have equal values and identical time structures. As a rule, the background consists of isotropic and bunched fractions, the relation between which is dependent on the size of the collimator limiting the dimensions of the muon beam at the sample surface. The collimator size and the muon beam momentum are selected for each particular sample prior to starting the measurement cycle; the conditions selected are invariable in the course of the whole experiment, and identical background conditions are retained. This approach offers a chance to correctly take into account the contribution of the background component to the total spectrum as it is processed.

CONCLUSIONS

The key parameters of the μSR setup are as follows.

(1) The setup permits the carrying out of μSR investigations on samples with transverse dimensions fitting into a circle 3–6 cm in diameter, a thickness of ≥4 g/cm^2 downstream of the beam, and a temperature of 5–300 K, maintained with a precision of ±0.1 K.

(2) The setup is suitable for experiments both in a zero magnetic field (i.e., the external scattered fields are

suppressed by the compensating Helmholtz rings to a level of ~0.05 G) and in an external transverse or longitudinal magnetic field with an induction ranging from 5 G to 1.5 kG. The homogeneity of the external magnetic fields in a volume of 200 cm^3 being 10^{-4} or better allows the making of measurements at relaxation rates of >0.005 μs^{-1}. Measurements on a copper sample (Figs. 5 and 6) showed that muon spin relaxation rate λ was 0.0053(31) μs^{-1}.

The μSR setup can be used to perform the following tasks:

(i) testing and investigating the distribution of local magnetic fields of different magnetic materials (spin glasses, ferromagnetics, antiferromagnetics, and asperomagnetics) and controlling the quality of commercial-grade steels;

(ii) examining the relationship between the magnetic and electric properties of materials, which in turn is of great significance for understanding how, e.g., the magnetic properties of a material can be controlled by electricity and vice versa;

(iii) investigating the magnetic properties of nanostructured materials (in particular, ferrofluids are currently being studied); it is expected that experiments will be carried out with different concentrations and sizes of Fe_3O_4 grains, which is very important for obtaining information on interactions of these grains placed in a surface-active substance, as well as on the occurrence of superparamagnetism in the intergrain space and the value of it; and

(iv) measuring the characteristics of muonium behavior in time (if muonium is formed in the sample under investigation), which will allow the purity of semiconductor materials to be determined up to an impurity content level of ~10^{-8}–10^{-9}.

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