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Muon Ordinary capture for the Nuclear Matrix elemENTs in ββ decays MONUMENT

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Abstract

Search for the neutrinoless double beta decay $(0\nu\beta\beta)$ is one of the priority tasks of the modern physics. Its discovery would play a fundamental role not only for neutrino physics itself, but also for particle physics and cosmology. It would also allow determining the nature of the neutrino (Majorana or Dirac), testing the hierarchy of neutrino masses and possibly finding the effects occurring because of the violation of CP invariance. The discovery of $0\nu\beta\beta$ decay could shed light on the reason for the prevalence of matter over antimatter in our Universe. However, to determine the effective mass of the Majorana neutrino from the measured probabilities of 0nbb decay, it is necessary to know the value of the corresponding nuclear matrix element (NME) with sufficient accuracy. Up to date, theoretical NME calculations give results that vary by a factor of 2–3, depending on the shell model used in evaluation. That is why, in recent APPEC recommendations (Astroparticle Physics European Consortium) [1] it was specially recommended to intensify experimental and theoretical efforts, aimed to improve the calculations of NME.

The purpose of this project is carrying out experimental measurements of muon capture at several daughter candidates for $0\nu\beta\beta$ decay nuclei. Obtained results would be drastically important for checking the accuracy of theoretical calculations of NME. Our group, together with colleagues, already applied for the beam time for measurements of ordinary muon capture (OMC) on several isotopes on a meson-factory of the Paul Scherrer Institute (PSI) in Switzerland. This application was reviewed and approved by the PSI User committee in January 2020. The beam time is officially granted in 2020 for a preliminary study of ¹³⁶Ba (daughter nucleus for ¹³⁶Xe) with a further measurement program for at least three years. This project continues and extends the previous OMC measurement program proposed and implemented under the guidance of JINR employees from 1998 to 2006. Our group has rich experience in the field of high-precision nuclear spectroscopy and its implementation for the study not only rare processes, but also muon capture.

Throughout the period from 2021 to 2023, it is planned to perform OMC measurements for ¹³⁶Ba isotopes, ⁷⁶Se and ⁹⁶Mo. The OMC on ¹³⁶Ba and ⁷⁶Se is of particular importance for the planned leading experimental searches for the $0\nu\beta\beta$ decay of ¹³⁶Xe – nEXO, KamLAND2-Zen, NEXT, DARWIN, and PandaX-III – and of ⁷⁶Ge – LEGEND. In addition, we are going to measure and obtain results for OMC in ³²S, ⁴⁰Ca, ⁵⁶Fe and ¹⁰⁰Mo isotopes. These results are important for the experimental verification of theoretical calculations and may also be useful for astrophysics. JINR will play a leading role in the experiment. With the exception of the experimental infrastructure at the accelerator complex, which will be provided by our collaborators, the rest of the project will be led by us. We plan to purchase isotopes for the enriched targets, buy several germanium detectors and the necessary electronic equipment. We also going to produce the targets and to construct an active muon filtration system for the experimental data. Additionally, the project expenses include cost of travels and work stays at PSI. Overall budget of the project is valued at ~ 378,000 USD for 3 years.

1. Introduction

Nowadays, one of the main theoretical problems associated with the search for neutrinoless double beta decay ($\mathbf{0}\nu\beta\beta$) is the problem of determination of the Majorana neutrino mass from the obtained probability of the process (or in a case of limit on period of $\mathbf{0}\nu\beta\beta$, the corresponding limit on the effective neutrino mass)

The probability of the $\mathbf{0}_{\mathbf{V}}\beta\beta$ decay could be written as follows:

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2,$$

where G^{ov} – phase space factor, $m_{\beta\beta}$ – effective Majorana neutrino mass, and M^{ov} – nuclear matrix element (**NME** – the integral of the overlap of wave functions of the initial and final state). Unfortunately, the NME cannot be calculated with sufficient accuracy up to now.

In case of double beta decay (**DBD**), the transition is occurred with a change of Z by two, via the virtual states of the intermediate nucleus (see Fig. 1). Lack of knowledge about those states creates additional difficulties for the calculations. However, one can try to populate the excited states of the intermediate nucleus in some other process which is complementary to the one being studied. Among processes that can be considered are, for example, charge-exchange reactions or ordinary muon capture (**OMC**) in a nucleus that is a daughter for the DBD nucleus (see Fig. 1). In the second case, an additional advantage could be the following one. Being a massive particle, muon transfers almost all its energy to the nucleus, feeding its excited levels up to a giant dipole resonance state. For this case the capture probabilities can be calculated using the same models as in the case of DBD and can be verified from results of experimental measurements.



Figure 1: Schematic representation of $\beta\beta$ decay of an (even, even) nucleus as two consequent virtual transitions via excited states of an intermediate (odd, odd) nucleus. OMC on a target consisting of the (A,Z+2) daughter nucleus provides information about the right virtual transition. Any admixture of the heavier (A+1,Z+2) isotope would cause intensive population of the same intermediate states, and would thus be a background to the measurement.

Thus, **OMC** is a unique way to study the wave functions of the excited states of the intermediate nucleus related to $0\nu\beta\beta$ decay.

The purpose of the project **MONUMENT** (<u>M</u>uon <u>O</u>rdinary Capture for the Study of <u>Nu</u>clear <u>M</u>atrix <u>Elements</u>) is to study **OMC** in isotopically enriched ¹³⁶Ba, ¹⁰⁰Mo and ⁹⁶Mo, as well as to update the previously obtained ⁷⁶Se results. The main method used in the

experiment is high-precision on-beam spectroscopy by means of high-purity germanium (**HPGe**) semiconductor detectors.

In addition, we consider measuring the total and partial OMC rates in light elements, namely ⁴⁰Ca, ⁵⁶Fe and ³²S, as well as determining the yields of the products of the muon capture reaction in these nuclei. It is also planned to obtain muonic X-rays spectra from the studied nuclei and implement them to the existing electronic catalogue of such spectra (<u>http://muxrays.jinr.ru/</u>).

To achieve these goals, we propose the experimental program intended for the three years of research with measurements are being held at the PSI meson factory (PSI, Switzerland).

2. State-of-the-art of the science case

2.1. State of research, justification of the necessity for research.

Currently, there are not so many places in the world suitable for muon capture studies (especially on extremely thin isotopically enriched targets). For years (1998-2006), our group was the only one in the world that worked on this topic on μ E4 and μ E1 muon beamlines at the Paul Scherrer Institute (PSI, Switzerland).

The OMC studies were carried out by JINR team (team leader: V.G. Egorov) and were also supported by the RFBR grants No. 02-02-16800 and No. 06-02-16587, which were successfully implemented in 2002-2003 and 2006, respectively. The project was stopped in 2007 due to the reconstruction of the muon beamline in PSI. However, the issue of theoretical NME calculations in order to correct nuclear models remains very relevant. To interpret the obtained calculations, experimental data (namely OMC results) were again needed. In this regard, the research program was resumed by our group in 2017. At that time only MUSIC beamline at RCNP (Japan, Osaka) have been available. Thanks to our experience in OMC we were asked to join our Japanese colleagues to restart the OMC investigations. However the MUSIC beamline turned out not to be suitable for our purposes because of following reasons: 1) The negative muon beamline at MUSIC is not monochromatic enough to accurately determine the partial OMC probabilities in the bound states in daughter nucleus; 2) The beamtime provided by the committee in RCNP is about 3-4 days, which is clearly not enough to obtain good statistics on OMC. Due to that remarks, we have tried to reconnect with our colleagues at PSI. It was found out that after the reconstruction they have a new negative muon beamline $\pi E1$ (with a moment of 20-28 MeV/c), which is suitable for our purposes. Thus, cooperation with the Paul Scherrer Institute was renewed. As part of this cooperation, in October 2019, the test measurements of the ¹³⁰Xe and ⁸²Kr gas targets, as well as the ²⁴Mg solid target, were carried out in the frame of the muX group collaboration. The data analysis is ongoing.

Due to the continued interest in the study of neutrino properties by $0\nu\beta\beta$, it is proposed to go ahead with our OMC research program. As the result in December 2019 such proposal was submitted at the BVR51 call for Proposals at Paul Scherrer Institute. In addition to the JINR staff, the new collaboration includes colleagues from Germany, Switzerland, Japan, the USA and Finland. The proposal was supported on January 30, 2019 by the PSI Program Committee. Beam time was officially provided for a preliminary study of ¹³⁶Ba (a daughter core for ¹³⁶Xe) in 2020 year with a further measurement program for at least three years.

<u>The relevance of the studies proposed in this project</u> can be found in the following works [1-7].

In order to derive an effective Majorana neutrino mass from the measured $0\nu\beta\beta$ half lives, the corresponding nuclear matrix elements (**NME**) need to be known with sufficient accuracy. Currently, the theoretical calculations of the NMEs differ by a factor of 2-3, depending on the nuclear model applied. Therefore, in the recent report of the **APPEC** (European Consortium for Particle Physics and Astrophysics) [1] neutrinoless double beta decay committee it is explicitly recommended to pursue the dedicated theoretical and experimental efforts in order to achieve a more accurate determination of the NMEs.

In [2-4,7], it is described how muon capture studies could be used to calculate NME, as well as to study the properties of neutrinos.

In [4-6], a review of studies on ¹⁰⁰Mo is presented, which also describes the necessity for research in this area in order to study the astrophysical properties of neutrinos.

The results from our recent OMC measurements [8] have been benchmarked in fresh OMC computations performed by L. Jokiniemi and J. Suhonen [7] using the Morita-Fujii formalism by extending the original formalism beyond the leading order. Table 1 compares our results of the partial OMC strength functions with the theoretical predictions. The correspondence between our experimental results and the theoretical calculations is reasonably good for several J^{π} . Future measurements with higher statistics and improved signal to background ratio will facilitate more complete and accurate determination of OMC strength functions.

J^{π}	OMC rate	(1/s)
	Expt.	pnQRPA
0+	5120	414
1+	218 240	236 595
1-	31 360	28 991
2+	120 960	114 016
2-	$145\ 920 + g.s.$	177 802
3+	60 160	55 355
3-	53 120	34 836
4+	_	2797
4-	30 080	23 897

Table 1: The "most probable" experimental OMC strength distribution below 1.1 MeV in ⁷⁶As [8] compared with the corresponding pnQRPA-computed distribution by L. Jokiniemi and J. Suhonen [7]. `g.s.` means transitions to the ground state that could not be measured.

Finally, works [8–16] illustrate in detail the approaches and methods developed by our group at JINR on the OMC studies, with the attached final results for some nuclei.

Concerning the <u>competing researches</u> in this area, at the moment we do not have any information about their existence. The only potentially competing study could be (p, n) and (n, p) charge-exchange reactions.

It is quite difficult to verify experimentally the excited states of an intermediate nucleus with high energy and multipolarity. To check the "left leg" (virtual transitions from the mother to the $0\nu\beta\beta$ decay to intermediate) in ⁷⁶Ge decay, for example, one could use the charge-exchange (p,n) reaction: ⁷⁶Ge(³He,t)⁷⁶As [17], and the (n,p) reaction for testing the "right leg" (virtual transitions from the intermediate to the daughter nucleus for $0\nu\beta\beta$ decay): ⁷⁶Se($d,^{2}He$)⁷⁶As [18]. Due to strong interaction and the difficulty of selecting the

angular momentum during the experiment, charge-exchange reactions cannot provide sufficient experimental information on the population of excited states with a high multipolarity. Comparing the experimental data with theoretical calculations on the $0\nu\beta\beta$ channel [19], a certain discrepancy between the applied theoretical models was revealed, which is possibly associated with ambiguous calculations of the wave function during the transition from the ground state of the intermediate nucleus to the daughter. From this point of view, other independent experimental information is needed to verify the applicability of charge-exchange reactions and various models.

In this case the ordinary muon capture (**OMC**) is a good alternative to (p, n) and (n, p) reactions [20] so that it can occur at a high momentum transfer $(q \approx 100 \text{ MeV/c})$, as well as the neutrinoless double beta decay, and the state of an intermediate nucleus with a wide spectrum of energies and multipolarities can be populated, in contrast to $2\nu\beta\beta$ - and β - decays occurring with a low momentum transfer ($q \approx$ several MeV/c). Thus, the $0\nu\beta\beta$ decay and muon capture are analogical in practice: both processes, for example, are capable of exciting high-lying nuclear states with a multipolarity J^p above 1. OMC can proceed through similar transitions for $0\nu\beta\beta$ decay or from the daughter nucleus ($0\nu\beta\beta$ -decay with the emission of an electron), or into the parent nucleus (positron emission / electron capture).

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3. Description of the measurements

3.1. Measurement principle

The idea of μ -capture experiments is based on a precise measurement of time and energy distributions of γ -rays following the ordinary muon capture (**OMC**). These distributions provide rich experimental information, which serves as a useful input to the calculations of nuclear matrix elements (**NME**) of double beta ($\beta\beta$) decay. The total OMC rates of specific isotopes are extracted by analyzing the time distribution of delayed γ -rays. The measured intensities of the delayed γ -rays give partial OMC rates to the bound states. The yields of the short-lived isotopes are obtained using the beam-off and off-line measurements. The μ X-rays data is an important by-product of the measurements. It helps to identify the type of atoms captured the muons and serves as a normalization for the total number of stopped muons.

3.1.1 Experimental method

The target arrangement sketched in Fig. 2 consists of an active muon veto-counter system: the C0 counter at the entrance of the target, two thin (0.5 mm) pass-through counters C1 and C2, and the actual target area, surrounded by the cup-like counter C3. The target is able to accommodate both solid and gaseous materials. This arrangement, which was also used during the 2019 measurement campaign, is foreseen for the ¹³⁶Ba and ^{nat}Ba measurements proposed here as the first step in the experimental program.

The C3 counter together with the pass-through counters is used to define a mu-stop trigger as:

$$\mu_{stop} = \overline{C0} \wedge C1 \wedge C2 \wedge \overline{C3}$$

as well as to discriminate against high-energy electrons from muon decay. As it is made of low-Z material, the C3 counter does not affect heavily on the measurement of low energy (20 - 100 keV) gamma rays by the external germanium detectors.



Figure 2: Schematic layout of the μ -beam line and the target arrangement: the aperture defining vetocounter C0, the passing trigger counters C1 and C2, the target area, the veto counter C3 and the HPGe γ -detectors surrounding target.

The beam momentum and position is tuned to maximize the intensity of μ X-rays from the target nucleus, while minimizing the background from the surrounding materials. Under optimal conditions, fraction of muons stopping at target nuclei is usually more than 95%. Typical μ -stop rates during the experiment are between 10⁴ s⁻¹ and 4×10⁴ s⁻¹.

3.1.2 Detection system

The μ X- and γ -rays following OMC will be detected with a set of HPGe detectors placed around the target at a distance of about 10 - 15 cm and integrated into the frame used in previous muX experiments. This already existing frame is supposed to be used in first phase of the project. For further measurements it is planned to create a new holder system, which will be designed by the JINR group. At present, the assembly includes the following types of germanium detectors:

- 1. Four n-type detectors: two low-energy-region (PSI+UZH) detectors with thin beryllium entrance windows intended to detect low-energy photons and two coaxial (PSI+JINR (has to be procured)) detectors;
- 2. Four p-type detectors: two broad energy germanium (BEGe) detectors (provided by TUM and UZH) and one or two inverted-coaxial detectors, which are able to detect photons in a range of several MeV: the TUM group will provide one detector, while the second one will be provided by JINR.
- 3. Additionally, we have two more p-type coaxial detectors as a backup.

3.1.3 Data acquisition system

The data acquisition (DAQ) and software of the muX experiment have been used to collect and analyze the data during the OMC measurements in 2019, in particular energy and time of incoming events (muons and gammas). For the first phase of our project, we will use the same software and DAQ. The DAQ system is based on a Struck SIS3316 digitizer module [http://www.struck.de/sis3316.html]. The module features 16 channels, 14-bit resolution, sampling rate of 250 MHz, and a selectable input range of 2-5 V. The FPGA firmware allows to use the trapezoidal filtering during the pulse shape analysis (PSA) of the HPGe signals. The trigger timestamps, waveforms, and signals' pulse heights are streamed over an optical link to disk at a typical rate of 5 MB/s. The operation and settings

of the module are fully integrated into the MIDAS acquisition system, which expected to provide robust and reliable data taking during first campaign. For the further measurements it is planned to order similar VME module and use the software, which is developing now by TUM group for the LEGEND project. Customization will be made with taking into account the requirements of OMC measurements.

Signals from all detectors (HPGe detectors, plastic scintillators) are directly fed from the corresponding preamplifiers to the digitizer. Signals from some of the small HPGe detectors are anticipates being routed through fast amplifiers in order to better match the dynamic range of the digitizer. In previous campaigns, the energy resolution (FWHM) of 2.1 keV (2.8 keV) at 1.3 MeV was achieved with 20% (75%) detectors when the beam was off. With the beam on, there solution was about 10 to 20% worse.

3.2. Preliminary/proposed measurements

As mentioned before, during the two weeks period in October 2019 we carried out, in collaboration with the muX experiment group, a test measurement that served several purposes. Firstly, it allowed us to check how well one can detect and identify the bound states produced by OMC using the existing setup and DAQ. Secondly, it gave us a chance to assess the steps needed to operate the HPGe detectors optimally. Finally, we made sure that the existing experimental configuration satisfies our requirements to collect enough statistics of good quality for all the relevant types of accumulated data: muonic X-rays, γ -rays following OMC, and γ -rays associated with the decay of short-lived isotopes. Detailed analysis of the collected data is ongoing, but it is already clear that the test was successful. The experimental setup is presented in Fig.3.





Figure 3: Experimental setup in 2019 measurements.

All data from the γ -detectors (on-line measurements) can be divided into two types: events correlated and uncorrelated in time with the incoming muons. If a signal from the γ -detector was not preceded by a stop of the muon in the target within the time window *W*, then the event is considered as Uncorrelated and is written to **U-spectrum**. Otherwise, the event goes to **C-spectrum**. A typical U-spectrum includes γ -lines of natural and technogenic radioactive isotopes (40 K, 60 Co, 137 Cs, U- and Th-chain, etc). These lines are used to calibrate the detectors. The OMC products decay rapidly with the emission of γ rays. The yields of the individual isotopes and isomers produced in OMC are extracted using their γ -rays intensities calculated from U-spectra. C-spectra of 24 Mg, 82 Kr, and 130 Xe were measured in the 2019 campaign at the π E1 beamline of PSI. The preliminary prompt and delayed energy spectra from the enriched 24 Mg target are shown in Fig. 4.



Figure 4. Correlated Prompt (blue) and Delayed (red) spectra measured with the enriched ²⁴Mg target. Some of the identified γ transitions are indicated. The μ X-rays transitions for magnesium (K(np-1s) and L(nd-2p) series), as well as for carbon (mX(C)) are also indicated.

The OMC probability depends on the balance of muon decay versus OMC on a particular target nucleus. As a result, measuring the exponential time evolution of delayed γ -lines of OMC products makes it possible to determine the OMC probability by a dedicated method described in our works presented in [8-11], sec.2.2. Our method is complementary to the commonly used one, which is based on the detection of Michel electrons. The preliminary results of the extracted muon lifetime in ²⁴Mg is shown in Fig. 5.



Figure 5. Time evolution of the spectrum fragment – the 2390.6 keV γ -line following OMC in ²⁴Mg. Violet curve – an integral of the central part of the fragment (the line itself plus the background under it); red curve – an area of the background around the line; blue curve – an integral of the γ -line fitted with a five parameter Gaussian, one for each time slice.

In addition, we obtain 3D (E,t)-spectra (see Fig.6) that allow us to extract maximum information about the OMC. The determination of relative intensities of the delayed lines with respect to the μ X-rays allows the extraction of partial capture rates to the individual excited states of the daughter nucleus. In order to simplify the γ -line identification, the Prompt and Delayed spectra shown in Fig. 4. could be partially separated from each other using different time cuts.



Figure 6. Part of the (E,t) distribution events measured with the ²⁴Mg target.

The partial probabilities and final total capture rates for ¹³⁶Ba and ^{nat}Ba will be obtained using the method described in [8], sec. 2.2. The strength distribution will be determined based on the isotope production rate extracted from the off-line measurements. The theoretical model of the process has been developed by I.H.Hashim, S.A.Hamzah, F.Othman and H.Ejiri (see sec. 2.2. [21-22]).

3.3 Objectives

We propose to carry out a comprehensive three-year research program, which pursues the following scientific objectives:

- 1. The OMC measurements on ¹³⁶Ba, ⁷⁶Se, and ⁹⁶Mo. Results of these measurements will provide significant new input into theoretical models of calculations of nuclear matrix elements (NME) for double beta decay (DBD) of ¹³⁶Xe, ⁷⁶Ge, and ⁹⁶Zr, which are the sources nuclei (primarily ¹³⁶Xe and ⁷⁶Ge) in leading DBD-projects. This will improve the accuracy of NME-calculations, which is a fundamental task for this direction of research. Other important goal is solution of g_A-quenching puzzle, and the OMC data will be also helpful here. Partial OMC rates will be obtained in the first phase of the project. And the total OMC rates will be determined in the next phase.
- 2. The measurement of the OMC on ¹⁰⁰Mo is valuable for studies of properties of astrophysical neutrinos. This isotope is a one of the best candidates for measuring Supernova (SN) explosions (the MOON project), and the results of OMC measurements on ¹⁰⁰Mo will provide vital information for theoretical model calculations of SN-neutrino interaction on ¹⁰⁰Mo.
- 3. Measurement of the total and partial OMC rates on ⁴⁰Ca, ⁵⁶Fe and ³²S will provide essential experimental input in order to test nuclear shell model (SM) calculations. The NME of these relatively light nuclei are well calculated in theoretical models, so a comparison of experimental and theoretical data will help to improve and tune the theoretical models. The results of these studies will also be used in future to improve the NME-calculations of DBD.

- 4. The experimentally determined production rates of isotopes in the OMC will be compared with the theoretical assumption proton and neutron emission model, which derives the OMC strength function and the associated giant resonance (GR) peaks.
- 5. The muonic X-rays spectra measured in OMC will continue to fill and update already existing Mesoroentgen electronic catalogue (muxrays.jinr.ru), which is the international database provided unique information for all projects (both fundamental and applied) used the OMC.
- 6. All results will be published in peer reviewed Russian and international journals, as well as be presented on the Russian and international conferences.

The anticipated results are important and extremely relevant for fundamental science. Applied tasks may arise from the specific tools developed for the data processing of HPGe detectors. Material science will benefit using the muX-rays catalogue.

3.4 Work program including collaborative work and expected expenses

The work program of this proposal would enable us (mainly the JINR, PSI, TUM, and UZH teams) to:

- 1. Prepare and carry out jointly the experimental work to measure the OMC rates, strength functions and branching ratios to excited states on selected targets at the Paul Scherrer Institute,
- 2. Provide comprehensive analysis of the data collected;
- 3. Publish the obtained results in peer reviewed international physics journals.

We will employ state-of-the-art experimental techniques available at the PSI (highintensity muon beam in PiE1 area), novel high-purity germanium detectors (HPGe) detectors developed for GERDA/LEGEND, fully digital recording of the HPGe signal traces, and off-line data analysis techniques developed previously within the framework of the muX/GERDA/LEGEND experiments.

The applied experimental methods are based on successful experience of previous experimental campaigns (JINR). Further main improvements are expected from use of hardware and software techniques developed by the TUM team. An overview of the 3-year work program is shown in Table 2.



Table 2: Overview of the work program and work packages carried out by the JINR-PSI-TUM-UZH teams.

The experimental work program focused on the scheduled beam measurements at the PSI. We will have ~3 weeks of data taking at PSI every year. The whole program consists of six work packages WP1-6. First 3-week beam measurement in the π E1 area at the PSI has been already approved for Oct/Nov 2020 (cf. in Appendix the letter of Prof. K. Kirsch, head of laboratory). Future beam usage will be allocated annually in 2021-2022 by the PSI Scientific Advisory Committee, after approval of project report on the work performed for the previous year.

The program is structured in the following work packages:

<u>WP1</u> - Procurement of target material and production of target cells: Our group will procure isotopically enriched targets of high chemical purities of ^{nat}Ba (2g), ⁷⁶Se (2g), ⁹⁶Mo (2g), ⁴⁰Ca (1g), ⁵⁶Fe (2g), ³²S (2g) and produce suitable solid target sources. The estimated costs for the isotopes correspond to approximately 40 000 USD.

WP2 - Production and characterization of muon trigger and beam profile monitor: To measure the OMC process on the target isotope, each muon that enters the target cell and is captured needs to be identified. For this purpose, the muon trigger and veto counters used to our previous experiments will be refurbished and modernized. To optimize the beam intensity during its tuning the special beam-profile monitor will be constructed.

The modernization of the current muon trigger system and veto counters, as well as beam-profile monitor will be made by the JINR team, which allows to improve trigger and target handling efficiencies. The requested resources correspond to 23 000 USD, including all required materials, PMT's and electronics. Required nanosecond timing accuracy of the trigger system will be worked out together by the JINR-TUM groups during the integration tests at TUM.

WP3 - HPGe detectors (cryostats, detector holders design, constructive production): The µX- and y-rays following OMC will be detected with a set of HPGe detectors placed around the target and integrated into the frame used in previous muX experiments. Seven high-purity germanium (HPGe) detectors will be located close to the target cells. Detectors will be provided by the JINR group (loaned 2 detectors) and by the TUM group (2 detectors). One detector will be provided by the UZN group and two detectors from the PSI. As part of this proposal, we plan to modify the existing cryostats in order to decrease detector distance to the target and, thus, increase the detection efficiency for gamma rays. The cryostats will be redesigned by our JINR engineers in close collaboration with the TUM, and will be machined in the TUM workshop. Integration and testing will be done in the TUM underground clean room. We plan to refurbish the prototype detectors (BEGe and inverted coaxial detectors) which have been developed for the GERDA/LEGEND projects. These detectors demonstrate a superior energy resolution w.r. to standard semicoaxial detectors. And even more important, they are able to separate background double Compton events from signal full energy photopeak single events using topology pulse shape discrimination (PSD on multi-site vs. single-site events) techniques developed by the GERDA/LEGEND projects. For cryostat modifications and support structures, and ordering two detectors we request 130 000 USD.

WP4 - Data acquisition system (accommodation to setup, software optimization): The proposed DAQ system is based on a Struck SIS3316 digitizer module. The module features 16 channels, 14(16)-bit resolution, sampling rate of 250(125) MHz. For the first phase measurements (2020) it is planned to use already exciting VME module provided

by the muX PSI group. In long-term future the parameters of this hardware/software should be upgraded. So, it was decided to order a new VME module and develop a new suitable and appropriate DAQ for our needs.

A new acquisition software for this module will be developed by the TUM. The online data reduction methods at the FPGA level might be developed in order to accommodate the high trigger rates (~3 kHz per HPGe detector). Signals from all detectors (HPGe detectors, plastic scintillators) are directly fed from the corresponding preamplifiers to the digitizer. Signals from some of the small HPGe detectors are anticipated to be routed through fast amplifiers in order to better match the dynamic range of the digitizer. Usually, signal waveforms are stored only for the HPGe detectors. Trigger timestamps and signal pulse heights will be stored for the muon veto counters. The described DAQ system will allow us to determine the energy peaks with improved energy resolution, which will give us the possibility to make better identification and separation between gamma cascades, which is or special relevance for the ⁷⁶Se measurements. We request funding for a 16-channel SIS3316 desktop digitizer, dedicated server for data acquisition and storage, as well as online monitoring corresponding to 34 000 USD.

WP5 - Detector integration at the TUM (testing of the detectors, setup, DAQ with detectors): Almost all equipment (target, HPGe detectors, and muon-trigger system) must be delivered and mounted at the PSI for a short time before beam measurements. Thus, serious integration efforts are required to make this procedure go as quickly and smoothly as possible to ensure the efficient use of the allocated beam time at PSI. The HPGe and muon-trigger systems will be shipped from Dubna (JINR) to Munich (TUM), where the system integration and testing of all equipment will be carried out. The full system will then be shipped by car to Switzerland, will be assembled and tuned off-line. By the start of beam time allocated for us, the complete system will be fully operational. After completion of the campaign, the detectors will be returned to the TUM and then to the JINR. The integration efforts will also include transportation, logistics and customs and will be jointly carried out by the JINR-TUM. We request 30 000 USD for the shipment of detectors from the JINR to the TUM including the costs for custom clearances, also 15 000 USD for travel allowance, car rental costs for the transportation from the TUM to the PSI and return. The budget is estimated for three transportation cycles and beam times.

WP6 - Data taking at PSI, processing and off-line analysis, publications: The challenge is to record all relevant information for the off-line analysis, without superseding the 700 Mbit/s data rate constraint. In order to derive precision timing for the HPGe detectors, in particular for large inverted coaxial detectors, drift time corrections need to be applied. These algorithms are applied in the off-line analysis. The data processing and off-line analysis will adopt and build on tools developed for the GERDA/LEGEND experiments and follow a TIER structure. The data will be stored and processed at available computing facilities at the JINR-TUM. The mounting, data taking (three weeks for on-line/two for off-line measurements) and shifts will be carried out by the JINR group with support of all other groups. The analysis workshops will be carried out alternating at JINR and at TUM. Funding for travel to TUM for 3 workshops of 5 000 USD each are requested by our group.

For travel costs for the 3-week beam time at the PSI we request totally 85 000 USD for three-year program.

3.5 Scientific background for the project.

The JINR group has accumulated vast experience of OMC studies from the 90s to 2006. The results of these experiments have been published in many refereed journals. We also retained the equipment needed to restart the OMC program in 2017. This project is natural extension of our previous OMC studies at a new higher level together with the search for neutrinoless double beta decay – a fundamental task of modern physics.

The JINR team has a huge experience in nuclear spectroscopy, as well as long-term crucial involvement in a set of DBD experiments (such as, TGV, NEMO/SuperNEMO, GERDA, Majorana, and LEGEND).

It is important to note that most of previous OMC-results were obtained for the first time, and key achievements are listed below:

1. In a series of experiments on a beam of secondary muons of the DLNP JINR phasotron, angular correlations in OMC on various nuclei were studied. On the ²⁸Si silicon target, the correlation characteristics of the allowed μ transition were measured with the best accuracy, and estimated value for the induced pseudoscalar interaction g_P was obtained (Nucl.Phys. A587, (1995) 577; Nucl.Phys. A671, (2000) 647). Two different methods were used to change the polarization of muons: movable HPGe detectors and the μ SR technique with a stationary HPGe detectors.

2. At the PSI muon factory, the correlation parameters of the first forbidden μ transition on the ¹⁶O nucleus were measured and estimated value of the magnitude of the scalar interaction G_s were obtained (Nucl.Phys. A699, (2002) 917).

The techniques of both works were innovative. In these experiments we were studied partial muon capture probabilities (intensities) by detecting γ -rays that discharge certain excited levels of daughter nuclei (²⁸Al and ¹⁶N). The same technique will be used in the present project.

3. The OMC on the enriched ⁴⁸Ti have been studied. The total and partial capture rates on ⁴⁸Sc and ⁴⁷Sc have been extracted for the first time. Based on the results the new NME calculations for the DBD candidate ⁴⁸Ca have been obtained. (Yad.Fiz. 67, 1224 (2004); Phys.Atomic Nuclei 67 (2004) 1202);

4. For the first time, the total muon capture rate in ⁴⁸Ca was measured (1.214 (8)*10⁶ 1/s). Comparison of this value with the OMC rate on ⁴⁰Ca revealed a deviation in the Primakov rule describing the dependence of the OMC rate on the number of nucleons in the nucleus (Nucl.Phys. A724 (2003) 493). In addition, theoretical and experimental OMC rates in ⁴⁸Ca were compared (Europhys.Lett. 58 (2002) 666);

5. A precision analysis of the different type of spectra, accompanying the OMC of argon and neon, measured with good precision (testing the new technique of the measuring gas target) was carried out. The total and partial OMC rates in these nuclei were obtained (Bull. Rus. Acad. Sci. Phys. 67 (2003) 1640).

6. A series of OMC measurements were carried out with isotopically enriched ⁷⁶Se, ¹⁵⁰Sm, and ¹⁰⁶Cd targets, as well as the corresponding natural targets Se, Sm, and Cd. The total and partial OMC rates in these nuclei were obtained. Preliminary results were published in the Bulletin of the Russian Academy of Sciences (Bull. Rus. Acad. Sci. Phys. 72 (2006) 737-743; Bull. Rus. Acad. Sci. Phys. 74 (2010) 825-828). The main results of the

measurements have been published in Phys.Rev.C : «Ordinary muon capture studies for the matrix elements in $\beta\beta$ decay» / D. Zinatulina, V. Brudanin, V. Egorov et al. // **Phys. Rev. C 99** (2019) 024327.

Based on the results, the **Ph.D. thesis** was defended by Zinatulina D.R., the leader of this project.

7. The OMC on ¹⁰⁰Mo and ¹⁰⁰Ru has been measured in 2018 on the muon beam at the Research Center of Nuclear Problems (Japan, Osaka). The identified muX rays were added to the electronic mesoroentgen catalogue (muxrays.jinr.ru) created in our department. (Bull. Rus. Acad. Sci. Phys. 2019. Vol. 82, no. 3. P. 228.; EPJ Web Conf. --- 2018. --- Vol. 177. --- P. 03006.).

8. A series of OMC measurements on isotopically enriched targets ⁸²Kr, ¹³⁰Xe, and ²⁴Mg was carried out (RFBR grant No. 18-32-00383). Preliminary results were obtained for the total muon capture rates in these nuclei. These results were presented in the annual report to the PSI User committee. And also became one of the key factors of positive decision on the allocation of beam time in 2020, made by the PSI Scientific Advisory Committee. The final results will be published soon.

It should be emphasized once again that most of the previous OMC-studies were supported by the RFBR grants (N93-02-03994-a, N02-02-16800-a, and N06-02-16587-a).

4. Estimation of human resources.

<u>The DLNP JINR participants</u>: development and procuring of the targets, MC simulations, design of the target arrangement and its modernization, purchasing of the HPGe detectors, assembling and testing them at JINR, as well as logistics to TUM – integration with DAQ and testing set-up at TUM, conducting an experiment (mounting, testing of equipment and electronics, beam tuning, running shifts, on-line/off-line data taking, calibration, maintenance), off-line analysis, preparation of publications on the Project.

Name	Catego-ry	Responsibilities	Full Time Equivalent (FTE)
V.V. Belov	junior researcher	MC simulation, data analysis	0.4
V.B. Brudanin	Head of department	Administrative work, coordinator	0.2
K. N. Gusev	senior researcher	HPGe detector's array coordinator, logistics, mounting, testing	0.4
I.V. Zhitnikov	junior researcher	Data analysis	0.3
D. R. Zinatulina	senior researcher	Management and participation in all works	1.0
S.V. Kazarcev	junior researcher	Muon trigger system, mounting, data taking	0.6
N.S. Rumyantseva	junior researcher	Data taking and data analysis	0.6
M. V. Fomina	junior researcher	Preparation, logistics, data analysis	0.3
M.V. Shirchenko	senior researcher	Deputy leader, data analysis coordinator	1.0

Detailed information of the JINR group human resources:

Yu.A. Shitov	Head of sector	Data taking and data analysis	0.3	
E.A. Shevchik	senior	Detector array and holders design,	0.5	
	engineer	muon trigger, beam profile control		
Total FTE (engineers): 0.5, Total FTE (Scientific): 5.1, TOTAL FTE: 5.6				

Paul Sherrer Insitute (PSI), Switzerland:

A.Knecht, S.M. Vogiatzi – mounting, data taking, administrative work at PSI, data analysis;

Technische Universität München (TUM), Germany:

T. Comellato, M. Schwarz, S.Schönert, C. Wiesinger – HPGE detectors, logistics, integration and testing equipment, holders for the detectors, data taking and analysis, software for DAQ;

University of Alabama (ALABAMA), USA:

I.Ostrovskiy – ¹³⁶Ba, data taking, publication preparation;

University of Jyväskylä, Finland:

I.Suhonen, L. Jokiniemi – NME calculations, interpretation experimental data with NME models, publications;

Physik-Institut, University of Zurich (ETH), Switzerland:

L.Baudis – administrative work, HPGe detector;

KU Leuven, Belgium: T. Cocolios – shifts during data taking, mounting;

Research Center on Nuclear Physics (RCNP), Osaka University, Japan:

H. Ejiri – offline analysis, interpretation experimental data to the proton-neutron model, publication preparation;

Universiti Teknologi Malaysia (UTM), Malaysia.:

I.H. Hashim, F. Othman – data taking, offline analysis, calculations with proton-neutron model.

5. Concise SWOT analysis

The major strengths of the project:

- using isotopically enriched elements as targets for muon capture immediately cuts
 off the presence of other nuclei in the target, which can excite the same levels of
 the nucleus during muon capture, which are discharged by gammas with energies
 close to or the same as the one we are interested in;
- using a monochromatic and narrow-collimated negative muon beam, so that the vast majority of muons stop exactly in the target (the piE1 negative muon beam in PSI provides this possibility, having an intensity of 10 kHz at a moment of 28 MeV/c);
- using the beam profile monitoring system simplifies the tuninning of the intensity of the muon beam, and also allows us to make more precise focusing;
- using the active muon trigger makes it possible to determine the moment of incoming muon an accuracy of 5 ns, which, in turn, makes it possible to separate the registered radiation into Prompt (μX-rays) and Delayed (followed in OMC) ones;
- using a data acquisition system (DAQ) on fast flash ADC. This system has a very short data transfer time and excellent timestamp, and with devoted trapezoidal filters, it allows to additionally improve the energy resolution;
- the obtained μX spectra (Prompt) using the new DAQ will contribute to reliable identification of gamma lines and will also provide normalization by the number of

muons stopped in a given chemical element. This will allow us to avoid recalculating the absolute efficiency (taking into account the solid angle);

 precision measurement of time (due to fast scintillator counters) and energy distributions of γ-rays through the use of a set of HPGe detectors of various volumes with high energy resolution. This makes it possible to identify the studied transitions feeding the given states of daughter nuclei.

Weaknesses of the project:

- strong decrease of the detection efficiency in the energy range above 3-4 MeV (this can be improved with use of modern high-volume HPGe detectors);
- large contribution of statistical measurement uncertainty into the final balance of the partial capture rates for the corresponding states of the daughter nucleus (this problem can also be solved by using inverted coaxial detectors with better resolution and the ability to separate signals with a help from pulse-shape analysis);
- imperfection of the calculated NME models for muon capture at the moment, which may cause an incorrect interpretation of the experimental results from the point of view of the calculated models.

Potential competitors to our project in the coming years could be only previously conducted measurements of the (n,p) and (p,n) charge-exchange reactions. But, as mentioned above (see sec. 2.1), at the moment there is no reliable information about the existence of such experiments as (n,p) reactions (checking the "right leg", as in the case with OMC). In addition, the actual contribution of charge-exchange reactions to the NME calculations, at least for the neutrinoless mode of DBD, has not been justified to date.

APPENDIX

Schedule proposal and resources required for the prolongation of the Project Muon ordinary capture for the nuclear matrix elements in ββ decays MONUMENT

Expenditures, resources, financing sources		Costs (k\$) Resource Require- ments	Proposals of the Labora- tory on the distribution of finances and resources			
				1 st yr	2 nd yr	3 rd yr
Expenditures		Target materials (enriched stable isotopes, holders for the target, target itself)	40	16	8	16
		Materials for the muon veto counters (scintillators, PMTs,WLS fibers, adapters, SiPMs, mechanics)	18	15	3	0
		Components and materials for R&D (optic glue, cables, connectors, instruments, etc.)	5	2	3	0
		HPGe detectors	130	75	55	0
		Electronics for the DAQ (VME- and NIM-crates and devices, PC and additional hard disks for data)	34	20	12	2
		Total	227	128	81	18
uired	ndard our	Resources of – Laboratory design bureau – Laboratory experimental	300	100	100	100
Reg	Stal	workshop	600	200	200	200
Financing sources	Budgetary resources	Budget expenditures including foreign-currency resources.	227	128	81	18
	External resources	Contributions by collaborators.	20	10	5	5
		Grants (these funds are not currently guaranteed)	15	5	5	5

PROJECT LEADER

- Auch

Form No. 26

Estimated expenditures for the Project

Muon ordinary capture for the nuclear matrix elements in $\beta\beta$ decays

MONUMENT

NN	Expenditure items	Full cost	1 st yr	2 nd yr	3 rd yr
1. 2. 3. 4. 5. 6. 7. 8.	Direct expenses for the Project Computer connection Design bureau Experimental Workshop Materials Equipment Transportation of equipment Collaboration meetings and workshops Travel allowance, including: a) non-rouble zone countries b) rouble zone countries c) protocol-based	\$ 6 k 300 std hours 600 std hours \$ 63 k \$ 164 k \$ 30 k \$ 15 k \$ 100 k \$ 100 k - -	2 100 200 33 95 10 5 35 35 35 -	2 100 200 14 67 10 5 35 35 35 - -	2 100 200 16 2 10 5 30 30 30
	Total direct expenses:	\$ 378 k	180	133	65

PROJECT LEADER

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Daniya Zinatulina JINR 141980 Dubna Russia

Villigen PSI, 25 February 2020



Approval of beam time for OMC4BDB

Dear Dr. Zinatulina

It is our pleasure to confirm that your proposal R-20-01.1 at our laboratory for the OMC4BDB experiment has been positively assessed and was approved by our scientific advisory committee. The committee acknowledges the unique experience of the collaboration in the field and the experiment is seen as a great opportunity to gather new data of critical importance for nuclear and particle physics.

Beam time can therefore be granted for three weeks in Nov./Dec. 2020 in our PiE1 area. Future beam time will be granted on a yearly basis based on the scientific advisory committee's review of the progress of your experiment, which will typically happen in January of each year.

Yours sincerely

Paul Scherrer Institut

Dr. Stefan Ritt Beam Time Coordinator

Prof. Dr. Klaus Kirch Head of Laboratory LTP



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Evaluation of proposal for support of the project with title

MONUMENT: "Muon Ordinary capture for the Nuclear Matrix elemENTs in double beta decays"

proposed under the JINR research theme 03-2-1100 2019/2020 "Non accelerator neutrino physics and astrophysics"

The project MONUMENT is an integrating activity that aims to measure total and partial ordinary muon capture (OMC) rates on ¹³⁶Ba (and later on ⁷⁶Se, ¹⁰⁰Ru and other nuclei) needed to improve an accuracy of calculated neutrinoless double beta decay nuclear matrix elements ($0\nu\beta\beta$ NMEs) and to establish the value of effective axial-vector coupling constant g_A. The scientific goals of the project are planned to be achieved by the JINR team at home institute in Dubna in a collaboration with prominent institutes in Europe and other countries. The measurements itself will be conducted at meson factory at Paul Sherrer Institute in Switzerland (PSI Villingen).

The total lepton number violating $0\nu\beta\beta$ decay is the most powerful tool to clarify if the neutrino is a Dirac or a Majorana particle. The search for the $0\nu\beta\beta$ -decay represents the new frontiers of neutrino physics, allowing in principle to fix the neutrino mass scale, the neutrino nature and possible CP violation effects. Interpreting existing results as a measurement of effective Majorana mass and planning new experiments depends crucially on the knowledge of the corresponding NMEs that govern the decay rate. The NMEs for $0\nu\beta\beta$ -decay must be evaluated using tools of nuclear structure theory. There are no observables that could be directly linked to the magnitude of $0\nu\beta\beta$ -decay NMEs and, thus, could be used to determine them in an essentially model independent way. A reliable calculation of NMEs will be of help in predicting which are the most favorable nuclides to be employed for $0\nu\beta\beta$ -decay searches. The problem of so-called quenching of the axial weak current is of particular importance as well because effective g_A appears to the fourth power in the $0\nu\beta\beta$ -decay rate. There is not a consensus on its origin yet.

The improvement of the calculation of the $0\nu\beta\beta$ -decay NMEs and fixing of the value of effective g_A is a very important and challenging problem. The uncertainty associated with the calculation of the $0\nu\beta\beta$ -decay NMEs can be diminished by suitably chosen nuclear probes. Complementary experimental information from related processes such as charge-exchange and particle transfer reactions, OMC and charged-current (anti)neutrino nucleus reactions is very relevant. A direct confrontation of nuclear structure models with data from these processes improves the quality of nuclear structure models. The constrained parameter space of nuclear models is a promising way to reduce uncertainty in the calculated $0\nu\beta\beta$ -decay NMEs.

Recall that APPEC strongly supports the present range of searches for neutrino-less double-beta decay. Guided by the results of experiments currently in operation and in consultation with its global partners, APPEC intends to converge on a roadmap for the next generation of experiments into neutrino mass and nature by 2020 (see Double Beta Decay APPEC Committee Report: arXiv:1910.04688 and <u>https://www.appec.org/news/neutrinoless-double-beta-decay-report-from-the-appec-committee</u>). In recommendation 6 it is stated that a dedicated theoretical and experimental effort, in collaboration with the nuclear physics community, is needed to achieve a more accurate determination of the NMEs.

The half-live of the $0\nu\beta\beta$ -decay depends strongly on the structure of the intermediate multipole states. In attempts to adjust the related nuclear-structure parameters from the β -decay or electron-capture data one can only probe the virtual transition through the lowest J^{π} intermediate state. Fortunately, the structure of intermediate states of a double-beta decay transition can be probed by the OMC. Due to the heavy mass of the muon (roughly 100 MeV), the final states in the OMC can be (highly) excited and the forbidden transitions are not as suppressed as in the case of beta decays. Experimental work on this process is currently conducted at J-PARC (see e.g., Phys.Rev. C97 (2018) no.1, 014617). Since the axial-vector component dominates the OMC rate (the partial rates are quite sensitive to the value of effective g_A), the OMC can be used to resolve the " g_A quenching" dilemma. Further measurements and computations of the OMC strength functions for final nuclei of double beta decays would enable a systematic anatomy of the OMC strength function to the effective in-medium values of the weak axial couplings. This, in turn, could help in improving the accuracy of calculations of the nuclear matrix elements of the $0\nu\beta\beta$ -decay.

The team leader Victor Brudanin and other members of the team (D. Zinatulina, M. Shirchenko, N. Rumyantseva and others) are outstanding scientists with a longtime experience in the field of experimental neutrino physics and physics of underground laboratories. They have expertise also in the subject of muon capture experiments being involved in their realization and analysis, in particular for Ar, Ti, Se, Kr, Cd, and Sm isotopes, within a period of about 15 years. The team size and its composition are adequate. It is recommended the scientific group to be extended with young and promising scientists from the JINR member states.

In summary, the proposal MONUMENT successfully addresses all relevant aspects of the scientific and technological excellence in question. The concept and objectives are well described. I sincerely recommend the Scientific Council of the Laboratory of Nuclear Problems and the Programmed Advisory Committee (PAC) of the JINR to approve this proposal with highest priority. It will enable the JINR scientists to gain important results in the field of particle and nuclear physics.

Sincerely yours,

Fed Prob

Dubna, 06.04. 2020

Prof. Dr. Fedor Šimkovic

Review of the project **MONUMENT**.

"Muon ordinary capture for the nuclear matrix elements in ββ decays".

The proposed project MONUMENT is aimed at research muon capture on nuclei: ¹³⁶Ba, ⁷⁶Se, ⁹⁶Mo, ¹⁰⁰Mo and natural mixtures that include the nuclei under study, as well as on lighter nuclei (⁴⁰Ca, ⁵⁶Fe, ³²S). The relevance of the topic studied in the project is related to the ability of apply the obtained results by extracting the muon capture rates for solving the fundamental problem of modern particle physics: search for neutrinoless double β -decay (0v $\beta\beta$). This problem is directly related to the questions about the nature of the neutrino and its masses which are beyond the Standard Model.

The main interest in these studies is caused by measurements with ¹³⁶Ba, ⁷⁶Se and ⁹⁶Mo, which are the daughter isotopes for ¹³⁶Xe, ⁷⁶Ge, and ⁹⁶Zr, on which a large number of experiments are being conducted to find neutrinoless double β -decay. Measurements at ⁷⁶Se should be highlighted, in connection with the beginning of an international experiment of a new generation on ⁷⁶Ge, namely LEGEND.

The importance of the results that are to be expected in the considered project is related not only to the solution of the main task of the project – determination of the partial μ -capture rates for the nuclei that have of decisive importance for theoretical calculations of probabilities of neutrinoless double β -decay, but also with extracting an information required for testing nuclear models. So, for example, the results of measurements of the muon capture at ⁴⁰Ca, ⁵⁶Fe, ³²S allow one to estimate quenching of the axial-vector coupling constant g_A, which affects the determination of the decay rate is $0\nu\beta\beta$. From the astrophysical point of view, the results are of interest for the development of the theory of nucleosynthesis, that would take into account the astro-neutrino component (for example, in the case of ¹⁰⁰Mo).

It should also be noted that there is an applied part of the MONUMENT project. It is the possibility of widening an interactive atlas of mesoroentgen radiation spectra created by the authors, which is a unique set of experimental information of such kind in the world.

An important advantage of the project is that a group of authors from DLNP JINR is a pioneer in such muon capture studies and have extensive experience in conducting experiments at the psi meson factory. In these studies, several daughter nuclei for the double beta decay (⁴⁸Ti, ¹⁵⁰Sm, ¹⁰⁶Cd, and ⁸²Kr) have already been studied and priority results have been obtained, published in leading peer-reviewed journals and presented at major international conferences. It also should be noted that the comparison of the experimental results derived by the team of authors on muon capture with the modern theoretical calculations of L. Jokiniemi and J. Suhonen showed a good agreement. All this gives a strong argument to continue the experimental program on a new set of nuclei.

At the same time, I would like to make two critical remarks about the content of the proposed project:

- 1. the need for measurements on a ¹⁰⁰Mo target is not clearly justified, especially given the planned measurements on a natural mixture of molybdenum isotopes, which contains 9.62% ¹⁰⁰Mo.
- 2. the project does not fully describe a comparison of the experimental results with the predictions of various theoretical models used for calculating nuclear matrix elements (NME).

In my opinion, these remarks can be taken into account in the future work of the DLNP JINR group. I believe that the project **MONUMENT** "Muon ordinary capture for the nuclear matrix elements in $\beta\beta$ decays" contains all signs of relevance, allow the group to obtain priority results that are important for fundamental physics, in particular for the search for neutrinoless double beta decay, and deserves support.

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Boris Chernyshev

ВЫПИСКА из протокола заседания 2020-4 Научно-технического совета ЛЯП 16 апреля 2020 г.

ПРИСУТСТВОВАЛО: 29 членов НТС из 38.

- 1. Д.Р. Зинатулина представила проект «Измерение обычного мюонного захвата для проверки ядерных матричных элементов 2β-распадов». Проект MONUMENT.
- 2. Заслушали рецензию на проект, подготовленную Fedor Šimkovic (COMENIUS UNIVERSITY, Bratislava, Slovakia). Отзыв положительный.
- 3. Заслушали рецензию на проект, подготовленную Б.А. Чернышевым (МИФИ). Отзыв положительный.

ПОСТАНОВИЛИ: Одобрить проект «Измерение обычного мюонного захвата для проверки ядерных матричных элементов 2β-распадов». Проект MONUMENT. (ЕДИНОГЛАСНО).

Рекомендовать дирекции ЛЯП подписать проект и направить материалы проекта в Дирекцию ОИЯИ для дальнейшего прохождения процедуры согласования и утверждения проекта.

Председатель НТС ЛЯП 16 апреля 2020

Allenna

Шелков Г.А.