Abstract

Project COMET:

Search for coherent neutrino-less μ -e conversion at J-PARC

(JINR participation)

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The JINR project COMET has been approved by the JINR PAC on nuclear physics in 2014 for the period 2014-2016. In the following we present the results of the past period and propose the extension of the project for 2017-2019.

1. Physics motivation

COMET (COherent Muon to Electron Transition) is the experiment at J-PARC to search for coherent neutrino-less conversion of muons to electrons $\mu^- \to e^-$ in the presence of a nucleus, $\mu^- + N(A,Z) \to e^- + N(A,Z)$, with a single event sensitivity $Br(\mu^- N \to e^- N) \sim 10^{-17}$.

Flavor transitions between the charged leptons (Charged Lepton Flavor Violation, CLFV) have a great potential to reveal new physics phenomena beyond the Standard Model (SM). Many models of such physics require the existence of CLFV at the level that is accessible in future experiments.

Within the SM, the expected branching ratio of μ - e conversion is less than 10^{-50} what is beyond the experiment's reach. Therefore, any observation of $\mu^- \to e^-$ conversion would be a clear signal of a new physics beyond the SM. A measurement at the level of $< 10^{-16}$ for $\mu^- \to e^-$ conversion, which is the COMET goal, is a factor of 10^4 better than the current experimental limit.

Apart from $\mu^- \to e^-$ conversion, there might be two other CLFV processes: muon decays $\mu \to e\gamma$ and $\mu \to eee$. The branching ratio of the $\mu^- \to e^-$ conversion and the $\mu \to eee$ decay is expected to be smaller than that of $\mu^+ \to e^+\gamma$ decay due to electromagnetic interaction of a virtual photon. This implies that the search for $\mu^- \to e^-$ conversion or $\mu \to eee$ decay at the level of 10^{-16} is comparable to that of $\mu^+ \to e^+\gamma$ at the level of 10^{-14}. The diagrams describing these processes are different, therefore all three CLFV processes are differently sensitive to various theoretical models beyond the SM. Hence, the experiments on search for $\mu^- \to e^-$ conversion, $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e$ are complimentary.

Once a negative muon is stopped by some material, it is trapped by an atom, and a muonic atom is formed. The fate of the muon is then to either decay in orbit ($\mu^- \to e^- \nu_\mu \bar{\nu}_e$) or be captured by a nucleus of mass number A and atomic number Z with emission of a neutrino, namely $\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1)$. However, in the context of physics beyond the SM, the exotic process of neutrino-less muon capture, such as $\mu^- + N(A,Z) \to e^- + N(A,Z)$, is also expected. This process violates the conservation of lepton flavor numbers, L_e and L_μ, by one unit, while the total lepton number L is conserved.

The event signature of coherent $\mu^- \to e^-$ conversion in muonic atom is emission of a mono-energetic single electron with an energy $E = m_\mu - B_\mu - E_{rec}$, where m_μ is the muon mass, and B_μ, E_{rec} are the binding energy of the muon and the nuclear recoil energy, respectively. The nuclear recoil energy and the binding energy are very small, therefore the electron energy $E \approx m_\mu$.

From an experimental point of view, $\mu^- \to e^-$ conversion is a very attractive process. First, the e^- energy of about 105 MeV is far above the end-point energy of the muon decay spectrum (~ 52.8 MeV). Second, since the event signature is a mono-energetic electron, no coincidence measurement is required. Potentially this allows of improving sensitivity by using a high muon rate without suffering from accidental background events, which would be serious for other processes, such as $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$ decays.

2. COMET at J-PARC

The COMET experiment will be carried out at the J-PARC accelerator complex. A bunched proton beam slow-extracted from the J-PARC main ring will be used. The experimental setup consists of a dedicated proton beam line section, a muon beam line section and a detector section.

The scheme of the experiment is the following. Proton beam of 8 GeV energy hits the production target. A dedicated effective pion capture system with superconducting solenoid (5 T magnetic field) directs backward emitted pions to transport system where pions decay to muons. Transport system (of C-shape) including curved and straight superconducting solenoid selects low-energy muons and brings them to a muon-stopping target. Electrons arising in μ-e conversion pass an electron transport section of curved superconducting solenoids and get into the detector consisting of a straw chamber tracker and an electromagnetic calorimeter.

The measurements will be done between the accelerator bunches in a delayed time window in order to remove prompt background.

3. Two-phase realization of the COMET project.

Taking into account the risks of an ambitious goal to increase the sensitivity of measurements to 10000 times, it is necessary to study experimentally all expected background processes and possible obstacles. With this aim, the project is split into two phases. The final declared experiment sensitivity will be reached at Phase-II. At Phase-I the experimental conditions will be estimated and all backgrounds measured, and search for μ-e conversion will be done with an intermediate sensitivity.

The main goals of Phase-I:

1) construction of the proton beam line for COMET;
2) construction of a part of the muon transport line (up to the end of the first 90^o turn);
3) direct measurement of the proton beam extinction and other potential background sources for the full COMET experiment, using the actual COMET beamline;
4) carrying out a search for $\mu^- \to e^-$ conversion with a single-event sensitivity of 3.0×10^{-15} which is a factor of 200 times better than the current limit.

At Phase-I less stringent requirements are applied to the detector performance.

Phase-II stage includes creation of all beam lines and, using experience obtained during Phase-I, carrying out a search for $\mu^- \to e^-$ conversion at the single-event sensitivity $3 \cdot 10^{-17}$.

4. COMET detection system

COMET detector system includes the following main components: electron tracker, electromagnetic calorimeter, cosmic ray veto-system, and at the Phase-I stage also cylindrical detector. All detectors, except for the veto-system, are placed inside a large solenoid providing magnetic field as large as 1 Tesla.

Electron tracker is a straw tube detector. The tracker consists of 5 straw planes, 48cm apart, and placed so that the axial direction of the straws is transverse to the axis of the solenoid. Each of the 5 planes contains a set of 4 straw tube arrays. The tracker system should provide momentum resolution 0.15 MeV/c, and spatial resolution 150 μm.

Electromagnetic calorimeter is made of last generation scintillating crystals LYSO with a high light yield and a short decay time, in total more than 2000 crystals, each of 20x20x120 mm^3 size. The calorimeter should have the energy resolution better than 5% and the space resolution about 1 cm.

The electronic tracker and electromagnetic calorimeter will be employed at the Phase-I stage for the beam line study and direct measurements of backgrounds, and then, at Phase-II, will be the main detectors for search for $\mu^- \to e^-$ conversion with the highest sensitivity. Due to absence of the electron transport system with curved solenoids during Phase-I, high rates are expected in these detectors, therefore their use for $\mu^- \to e^-$ conversion search at the Phase-I stage is possible only at a low beam intensity.

Cosmic ray veto-system will protect the core detectors from cosmic-ray background. It includes a passive shield of concrete and iron, and an active shield of two layers of plastic scintillators.

Cylindrical detector is meant for using only at Phase-I. It will not be hit by beam particles directly, in contrast to the tracker and the calorimeter. Therefore, cylindrical detector is suitable for search for $\mu^- \to e^-$ conversion at Phase-I providing an intermediate sensitivity. The detector consists of a cylindrical drift chamber surrounding the muon stopping target and of trigger hodoscopes.

5. JINR participation in COMET

The main contribution of JINR to COMET consists in participation in creation of two main detector groups – electromagnetic calorimeter and straw tracker, and in different works on simulation.

5.1. Electromagnetic calorimeter.

At the beginning of COMET the JINR group has proposed two types of scintillating crystals, GSO and LYSO, which became considered in the collaboration as the real candidates. In order to evaluate their adequacy for COMET, a lot of laboratory studies have been done in DLNP JINR. These studies have shown the advantages of the LYSO type which, however, is more expensive compared to GSO. Therefore, the final decision about selection of the LYSO crystals has been done after the test of the calorimeter prototypes (both GSO and LYSO) with an electron beam and takes into account the cost/performance ratio. The crystals to be used in the LYSO prototype (50 pieces) first have been thoroughly investigated in JINR, including light yield, light absorption, homogeneity etc. Later on the JINR physicists participated in assembling of the prototype, beam measurements and fulfilled independent analysis of the beam test results. Following these investigation, the collaboration has selected the LYSO type to be used in the calorimeter.

A dedicated test bench for measuring the crystal parameters has been arranged in DLNP. The test bench includes mechanical arrangement for remote-controlled movement of the crystal, photomultipliers for light readout, plastic veto-counters, corresponding electronics and software. All crystals of the calorimeter will be tested with this test bench in JINR. JINR takes full responsibility for testing of the LYSO crystals to be used in COMET Phase-I and Phase-II. At Phase-1 only about ¼ of the total number of crystals will be used.

We continue also the study of the crystal properties, light readout options, different wrapping materials etc.

At the later stage the JINR physicists will take part in assembling, calibration and tests of the calorimeter.

5.2. Straw tracker

The DLNP JINR group is fully responsible for manufacturing of all straw tubes for Phase-I and R&D work for Phase-II as well.

In order to produce thin wall tubes, an ultrasonic welding method is used. The previously developed in VBLHEP technology of welding tubes of 36 μ wall thickness was updated in order to produce 20 μ thick tubes what is the must in COMET where the multiple scattering has to be minimized. Different procedures of the straw tube tests on pressure, gas leakage and elongation have also been updated in accordance with the COMET requirements and new test standards have been established.
As a result, a full set of straw tubes for Phase-I, more than 2500 tubes of 120 and 160 cm length, 9.8 mm diameter and 20 μ wall thickness, has been produced, tested and delivered to Japan.

The next step in this direction is preparation and carrying out of R&D works of straw tubes for Phase-II of COMET. At Phase-II we need even thinner and less diameter tubes: 12 μ wall thickness and 5 mm diameter. For this purpose within the framework of R&D works we are planning to arranging a new straw line in our Laboratory of Nuclear Problems. The method of manufacturing will be the same, the ultrasonic welding, but the extensive R&D works have to be done in order to deal with such a delicate material. The technology of the production process and the procedures of testing have to be updated for new conditions.

The JINR physicists will be involved in assembling and tests of the full scale straw tracker, first for Phase-I and then R&D works for straw tracker for Phase-II of COMET.
Another JINR activity related to the straw tracker is participation in engineering design of the detector including design of the supermodules, development of the optimal joining of the electronics etc.

5.3. Simulation and Data Analysis

Development of the straw tracker and calorimeter required a lot of simulation work, its results are reflected in the Technical Design Report for Phase-I of COMET. In particular, for the straw tracker there were obtained the values of efficiency and space resolution in different conditions: for tubes of different diameter, wall thickness and a gap between tubes. For calorimeter the simulation has been done for two types of crystals, GSO and LYSO, using real optical parameters. Among others, there were simulated the light output and light collection with different reflecting materials. The simulated energy resolution was found to be better for the LYSO type what has been confirmed later experimentally.

A dedicated simulation has been done aiming to optimize the operation of the J-PARC Main Ring in order to achieve very low extinction factor, below 10^{-9}, what is the must for COMET.

The data from the beam test of the calorimeter prototype have been analyzed independently of a similar analysis in Japan. Both analyses have led to the conclusion about a better performance of the LYSO crystals.

In future we are planning to enlarge our scope of works on simulation and analysis in order to be prepared for physic analysis of the COMET data from J-PARC.

6. Financing

A major part of the COMET expenses is borne by the Japanese side. Substantial budget has been approved for creation of the proton beam line, an experimental zone and the magnetic system needed for Phase-I. Production of the detectors is also financed mainly by the Japanese side and other collaborating participants. Expenses of JINR are necessary for a new straw tube production facility, R&D on thin straw tubes, purchasing of necessary equipment and different materials including a part of crystals. Apart from the resources of the JINR theme 03-2-1101-2010/2016, we expect to have support from the Grant of Plenipotentiary of Georgia and from the Program of the JINR-Belarus Cooperation.

7. Conclusion

Experiment COMET at J-PARC is focused at search for coherent neutrino-less conversion $\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}$ in a muonic atom of aluminum at the level of a single-event sensitivity $3{\cdot}10^{-17}$, corresponding to a 90% confidence level $< 10^{-16}$.

Two-fold goal of Phase-I of COMET includes i) study of experimental conditions and different sources of background, and ii) search for the $\mu^- \rightarrow e^-$ conversion with intermediate sensitivity about $3{\cdot}10^{-15}$, which is 200 times better than the current limit.

The role of JINR in the COMET experiment is quite visible and recognized by the COMET Collaboration.

Concluding, we apply for extension of the current JINR project "Search for coherent neutrino-less μ-e conversion at J-PARC (project COMET)" for 2017-2019. This period well fits to the beginning of physics measurement at Phase-I, which is planned for 2018-2019, and preparation and carrying out of R&D work for straw tracker for Phase-II, which is scheduled to start in 2021.

Schedule of works on the project

1.	Participation in assembling and tests of the straw detector for Phase-I	**2017- 2018**
2.	R&D for production of the straw tubes of 12 μ wall thickness and 5 mm diameter for Phase-II:	**2017-2018**
3.	Test of the crystals in JINR to be used in the calorimeter:	**2017-2019**
4.	Participation in the calorimeter designing, assembling and tests:	**2017-2019**
5.	Participation in the beam tests of the detector components:	**2017-2019**
6.	Creation of the COMET computer farm in LIT-JINR	**2017**
7.	Complex detector system (tracker, calorimeter, etc.) simulation to define the acceptance, expected uncertainties, sources of systematics, reconstruction algorithm development, etc.	**2017-2019**
8.	Participation in assembling, installation and testing of the whole detector	**2017-2019**
9.	Participation in the engineering and physical run:	**2018-2019**
10.	Participation in the data acquisition and analysis:	**2019**

Estimation of costs and resources

Proposal for resources necessary for realization of the project ″Search for coherent neutrino-less *μ -e* conversion at J-PARC (COMET) ″, 2017-2019

Form №26

Units and systems of The setup, resources, Sources of financing			Cost of units (k$). Required resources	Laboratory proposal for schedule of financing and re-sources		
				1 year	2 year	3 year
Main items	Computers Electronic devices Materials		15 96 320	5 50 110	5 27 110	5 19 100
Resources	Hours	Design bureau DLNP Workshop	800 hours 1200 hours	300 500	300 500	200 200
Source of financing	Budget	Budget expenses (without salary)	587	217	194	176
	Non-budget	Grant of Georgian plenipotentiary	30	10	10	10
		Program of the JINR-Belarus Cooperation.	15	5	5	5

Project leader **Z.Tsamalaidze**

Estimate of expenses for the project ″Search for coherent neutrino-less μ -e conversion at J-PARC (COMET) ″, 2017-2019

Form №29

NN	**Purpose of expenses from DLNP**	**Full cost**	**1st year**	**2nd year**	**3rd year**
	Direct expenses				
1.	Accelerator	-	-	-	-
2.	Computing	-	-	-	-
3.	Design bureau	800 hours	300	300	200
4.	Workshop LNP	1200 hours	500	500	200
5.	Materials	320$	110	110	100
6.	Equipment	111k$	55	32	24
7.	Contracts for R&D	-	-	-	-
8.	Busyness trips:				
	a) To the non-rouble zone countries	150k$	50	50	50
	b) To the cities of rouble zone countries	6	2	2	2
	c) By protocols	-	-	-	-

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