Proposal for Measurement of Anti-Matter Reaction in Liquid Argon Time Projection Chamber (LArTPC)

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Executive Summary

Antideuterons, which are nuclei composed of one antiproton and one antineutron, may open a very promising window for cosmic dark matter indirect search, in contrast to the signal predictions for positrons, antiprotons, and gamma rays, which typically constitute a small component on the large astrophysical background. This proposal is based on the GRAMS (Gamma-Ray and AntiMatter Survey) project which utilizes LArTPC (Liquid Argon Time Projection Chamber) as tracking-calorimetric-detector, aiming for an indirect dark matter search by Long-Duration Balloon (LDB) flights at Antarctica. We have developed and constructed prototype-LArTPCs at Waseda University and cosmic ray tracking study was successfully performed. The next crucial milestone is to experimentally prove the "exotic atom" scheme for identifying antiparticle in LArTPC. This document proposes the world's first observation of Argon-exotic atom production and its decay by using antimatter beams, *i.e.* antiproton beam from K1.8BR line as a baseline, and possibly antideuteron beam. The primal goal is to collect antiproton data which is the main background in balloon-borne observations against the antideuteron signal event. The momentum range (up to 1.1 GeV/c) and intensity of antiprotons (tunable by the slit adjustment) in the K1.8BR beam line are optimally matched to our physics target (rigidity) and the LArTPC DAQ rate. To achieve our physics goal, more than 10^5 antiproton capture events are desired to be collected and analyzed.

Antideuterons: Antideuteron beam has not been established yet at K1.8BR and dedicated study for beam tuning will be needed before the exposure to the LArTPC[1]. It would be highly desired to obtain antideuteron signal events, even a few capture events, to verify signal efficiency and background rejection power at the same rigidity as antiprotons. Given this situation, we would like to ask the beam experts to study antideuteron beam tuning before (anytime prior to) the LArTPC beam exposure, by using present beam counters.

Antideuteron Beam Study Request

Objective:	Establishment of antideuteron beam at K1.8BR beam line
Beam Line:	K1.8BR in J-PARC Hadron Hall
Beam Particle:	Antideuteron 1100 MeV/c
Detectors:	Present beam counters at K1.8BR beam line (+ ToF counters if necessary)
Beam Time:	8 hours (anytime prior to the LArTPC Beam Request)
Beam Rate:	TBC (*e.g.* 1 antideuteron per spill [1])

As already mentioned, our primal success is given by understanding background with high statistics, while collecting antideuteron signal data is set to be the "maximum" success toward GRAMS realization. Therefore, depending on the outcome from the antideuteron beam study above, the beam time request for the LArTPC exposure is summarized as follows.

Summary of Beam Request (LArTPC beam exposure)

Objective:	Measurement of antimatter reaction in LArTPC
Beam Line:	K1.8BR in J-PARC Hadron Hall
Beam Particle:	**Antiproton 600 MeV/c and 700 MeV/c** **Antideuteron 1100 MeV/c (in case of successful beam study)**
Detectors:	One LArTPC and scintillation counters
Beam Time:	6-hour each (2-hour beam tuning + 4-hour data taking with commissioning)
Beam Rate:	Less than 1 KHz (including background particles)

The detector system will be placed within 4 m×4 m area, arbitrary as far as it is on the beam axis, including 2 layers of plastic scintillation counters, 1.5 m apart each other. From previous experience and current configurations, preparation time without beam at the K1.8BR experimental area will be 3 days, including installation, assembling, pre-cooling, LAr-filling and operation test. After setting up in place, all the system will be ready in queue, flexible for the beam starting time, and even parasitically operated with other experiments. Actual beam exposure time would be 1 day for antiprotons and antideuterons, and additional 1 day will be needed for withdrawal and cleanup. More concrete plan will be flexibly prepared in consultation with J-PARC facility experts. The K1.8BR is the unique facility for this study and we would like to perform this measurement within two-year timescale by the end of 2024 at the latest, limited by secured budget condition and to avoid resource conflict toward prototype balloon flights being proposed to NASA.

[1] There is an interesting indication for a possibility of antideuteron component (O(Hz)) in K1.8BR beam line [1]

Contents

1 Introduction

Liquid argon (LAr) is dense (40% denser than water), abundant (1% of the atmosphere) and very sensitive active medium for incoming particles (40 photon/keV for scintillation and 1 fc/mm for ionization). LArTPCs (Liquid Argon Time Projection Chambers) have therefore become standard technology in particle physics particularly for neutrino experiments [2] and direct dark matter searches [3]. This proposal is based on the next-generation observation project, called GRAMS (Gamma-Ray and AntiMatter Survey) which utilizes LArTPC as tracking-calorimetric-detector, aiming simultaneously for both astrophysical observations with MeV gamma rays and an indirect dark matter search with antimatter [4]. GRAMS project has carried out by the Japan-US collaboration and long duration balloon-borne experiments are planned at Antarctica within 5-year-timescale and then ultimately evolved to satellite mission in the 2030s. While a scientific importance of MeV gamma-ray observations is extremely high, here we focus on another critical importance of proof-of-principle of cosmic ray antimatter detection in LArTPC, which is a key technique for indirect search for cosmic dark matter by GRAMS. In particular for the identification of cosmic antimatter, such as antiproton and antideuteron, we employ so-called "exotic atom" scheme, which is described in the next section in detail. In order to experimentally prove this detection and identification technique, we propose the world's first observation of Argon-exotic atom production and its decay by using antimatter beams, *i.e.* antiproton beam from K1.8BR line as a baseline, and possibly antideuteron beam (in consulting with J-PARC experts for special tuning) as a full success of this proposal.

We understand the current situation of K1.8BR beam line occupation, where many nuclear physics experiments are waiting for the beam, however, since the realization of antimatter reaction measurement is a critical milestone for our future physics observation, we would like to carry out data taking within two-year timescale by the end of 2024 at the latest.

2 Purpose and Physics Goal

2.1 Cosmic Antideuteron for Dark Matter (DM) Search

Antideuterons have been considered as a promising observable for indirect detection of cosmic dark matter. As shown in Fig. 1, in the range below a few GeV/n (rigidity), the secondary astrophysical background is largely suppressed by kinematical constraint in the process of $p_{\mathrm{CR}} + p_{\mathrm{ISM}} \rightarrow \bar{d} + X$, where cosmic ray protons (p_{CR}) interact with protons of the interstellar medium (p_{ISM}) in outer space. The expected antideuteron flux from DM annihilation (signal) can be more than two orders of magnitude larger than the background around a few hundred MeV/n as in Fig. 1 [5–7]. Therefore, unlike other antiparticles such as positrons or antiprotons, low-energy antideuteron measurements will enable essentially background-free searches, and cleanly exploring the dark matter parameter space. While the current upper limit is only given by the BESS balloon flight [8], GRAMS is aiming for more than two order of magnitude better sensitivity than the current limit, by the 30 days Long-Duration-Balloon (LDB) flight to investigate a detectable flux predicted by the DM relic density. For the LDB flight at Antarctica, the GRAMS instrumentation will be composed of a LArTPC ($\sim$150$\times$150$\times$30 cm^3, not yet finalized) surrounded by two layers of time-of-flight (ToF) plastic scintillators to measure the velocity of incoming charged particles based on timing and position information. Regarding detection technique, BESS utilized a magnetic spectrometer to distinguish antiparticles, while GRAMS uses a novel exotic atom capture and decay technique, the same as the GAPS (General AntiParticle Spectrometer) project which is planned to launch next year [9, 10]. In this sense, GRAMS will be a next generation experiment beyond the current GAPS project dedicated for antimatter survey, in addition to targeting astrophysical observations with MeV gamma rays simultaneously.

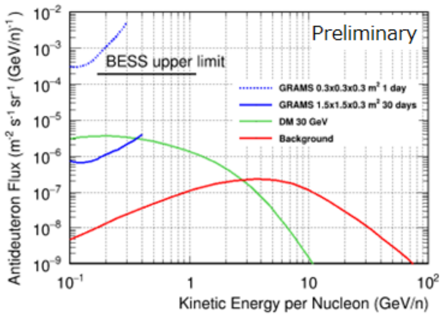

Figure 1: Expected antideuteron fluxes and detection sensitivities (preliminary)

On the other hand, for such rare signal searches, it is essential to validate the detection technique and particle identification power against backgrounds (protons, deuterons, and antiprotons) before the observation flights. We consider antiprotons as the most important background to be understood by high statistics since they also produce exotic atoms in LAr which might mimic the antideuteron signals. As described in the next subsections, track length, energy deposition, and the number of produced hadrons from exotic atoms e.t.c. are all different between antideuteron and antiprotons, this characteristics should be experimentally verified by an accelerator beam line, that is the main purpose of this proposal[2].

2.2 Detection Principle of LArTPC

The LArTPC can achieve high detection and reconstruction efficiency owing to a fully active detector volume, not like embedded or layered semiconductor or scintillation detectors, and thus it works as fully-efficient homogeneous tracking-calorimetric-detector. There are however some technical difficulties in controlling the system as well as maximizing the detection capability. For instance, low operation temperature (about 85 K at 1.4 atm), purification, and high voltage supply systems have to be well controlled and the VUV scintillation light detection and charge readout with good signal to noise ratio have to be established in cryogenic environment.

As illustrated in Fig. 2, a charged particle entering the LArTPC excites and ionizes argon atoms, producing scintillation lights and ionization electrons along the track trajectory. The wavelength of scintillation light peaks at 128 nm, and thus needs to be converted to visible light of 420 nm with a wavelegnth-shifter (TPB) [12] in order to be measured with high-sensitivity cryogenic photosensors (PMTs or SiPMs). As the light collection efficiency strongly depends on the deposition mass and surface conditions of the TPB coating on the detector surface, a dedicated well-controlled TPB evaporation system was built and operated at Waseda. By optimizing the amount of TPB to

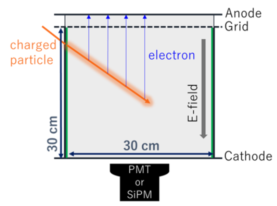

Figure 2: A schematic view of LArTPC for charged particle

[2]The engineering balloon flights have been already proposed to JAXA-TARF [11] and also NASA.

maximize the wavelength-shifting efficiency and transmittance for the converted light,the world's highest light detection efficiency, 12.8 ± 0.3 $p.e.$/keV for 511 keV gamma-ray full-absorption events was achieved for a single-phase LAr detector [13]. Then Photo-sensors finally measure the prompt scintillation light for triggering and timing of any given interaction, and provide a measure of the deposited energy. In parallel, the ionization electrons drift under an applied electric field (typically 200∼500 V/cm) toward anode pad planes with a slightly longer timescale with an order of μs/mm. The signals induced on the charge sensors provide the x-y coordinates of the event, while the drift time of the ionization electrons measured relative to the prompt scintillation time provides the z coordinate. In summary, LArTPC can provide 3D-tracking information with deposited energy along the trajectory (dE/dX) and prompt scintillation light signal for trigger information, resulted in efficient particle detection and strong particle identification (PID) capabilities as homogeneous tracking-calorimetric-detector.

2.3 Antimatter Reaction in LArTPC

In addition to normal tracking and PID capabilities, LArTPC can measure and identify antiparticles produced by dark matter annihilation. When a charged antiparticle stops in LAr through ionization energy loss, it forms an exotic atom with a target argon atom. The exotic atom emits atomic X-rays as it de-excites and at the end of the atomic cascade, the antiparticle subsequently annihilates in the nucleus, resulting in the emission of several hadrons (pions and protons) as in Fig. 3. Identification of incoming antiparticles against particle is based on observing this hard reaction at stopped point by looking at hadronic production and possibly emitted X-rays. A convolution of exotic atom scheme and standard technique based on the stopping range and energy deposition inside the LArTPC can provide antiproton (background) rejection to the negligible level. This reaction mechanism $e.g$ capture rate and hadron multiplicity needs to be investigated by accelerator beams.

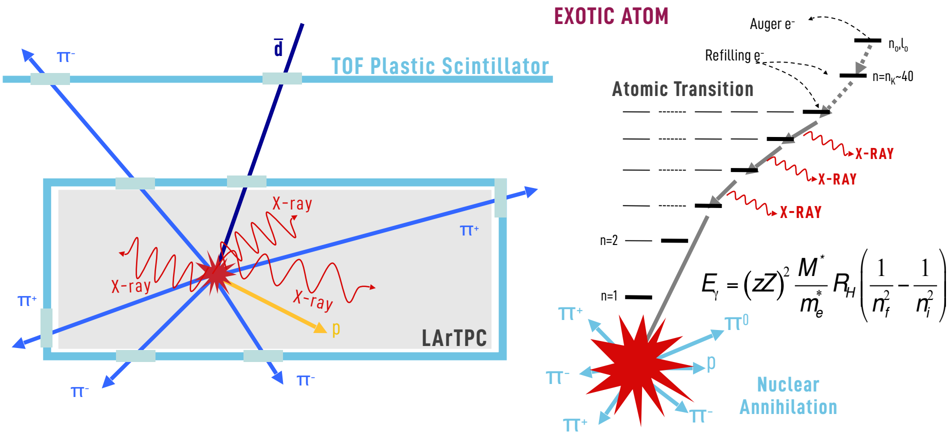

Figure 3: Antimatter detection principle in LArTPC

2.4 Target Rigidity and K1.8BR Beam Line

As shown in Fig. 1, GRAMS's target rigidity ranges from 100 to 300 MeV/n where expected signal to background ratio is greater than 100. In particular, the benchmark rigidity point is around 150 MeV/n, that corresponds to the velocity β of 0.5 independent of the atomic mass, and momentum of 600 MeV/c and 1100 MeV/c for antiproton and antideuteron, respectively. Figure 4 shows Geant4 simulation results on track length (stopping range) in liquid Ar as a function of particle momentum, where 21 cm and 32 cm are expected for antiproton and antideuteron at the benchmark rigidity, respectively. We expect that K1.8BR beam line provides negative charged particles up to 1.1 GeV/c which is well matched to our interest and almost optimal for validating GRAMS sensitivity.

Regarding the required number of events, it should be worth noting that since antiproton flux is higher than the target antideuteron signal flux by 10^4, we need a background rejection power by 10^5 or more to achieve background level as small as < 0.1 event during the LDB flight. It is extremely important for GRAMS to demonstrate this PID capability based on the combination of the ToF, track length, dE/dX energy deposit, and reaction at stopping point (hadrons and X-rays)

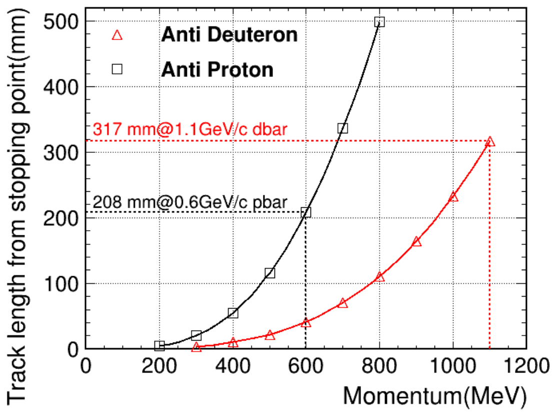

Figure 4: Stopping range (track length) in LAr for antiproton in black and antideuteron in red. Momenta of 600 MeV/c and 1100 MeV/c, giving almost the same rigidity for antiproton and antideuteron, are noted as benchmark points.

Particle	velocity β	Rigidity	Momentum	Range in LATPC
Antiproton	0.43-0.65	100-300 MeV/n	450-800 MeV/c	8-50 cm
Antideuteron	0.43-0.65	100-300 MeV/n	900-1600 MeV/c	16-100 cm

Table 1: GRAMS's target rigidity and corresponding momentum and stopping range in LArTPC for antiproton (background) and antideuteron (signal). The benchmark rigidity is 150 MeV/n which can be reasonably produced by K1.8BR beam line.

in LArTPC. As the PID should work for particles with the same velocity β (the same rigidity), momentum points of 600 MeV/c and 1100 MeV/c for antiproton and antideuteron are the best choice for this study. We would like to collect more than 10^5 antiproton capture events and even a few events for antideuteron is highly desired to achieve full success of this proposal. The details of simulation study and beam time request will be described in Sections 4 and 6.

3 LArTPC Construction and Preparation Status

We have developed LArTPC for more than 10 years at Waseda University in Japan [14]. In this section, the LArTPC test-stand and recent achievement are briefly introduced before discussing detector and beam configurations at J-PARC.

3.1 LArTPC at Waseda Test-stand

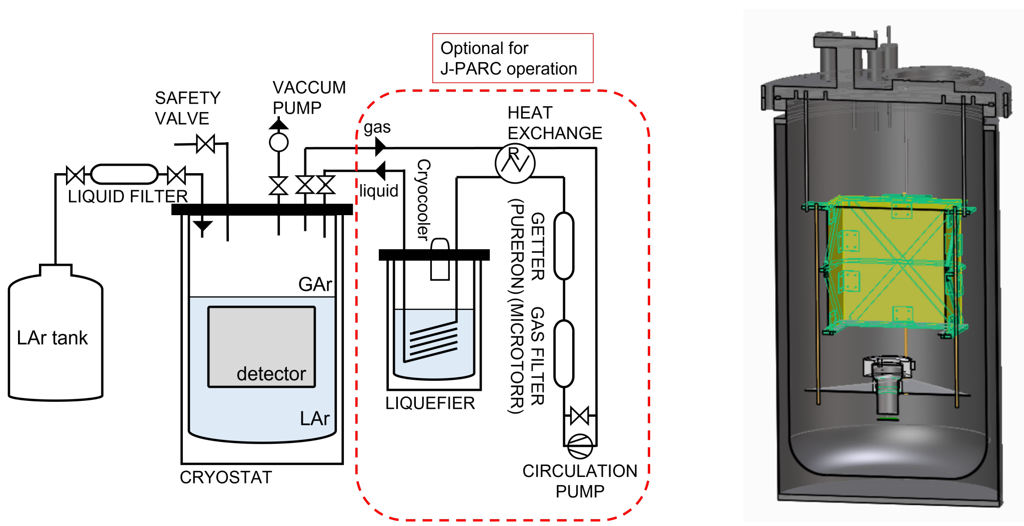

Figure 5: Schematic view of the Waseda LAr test-stand (left) and 30×30×30 cm^3 LArTPC and PMT installed inside the ϕ50 cm (200L) cryostat.

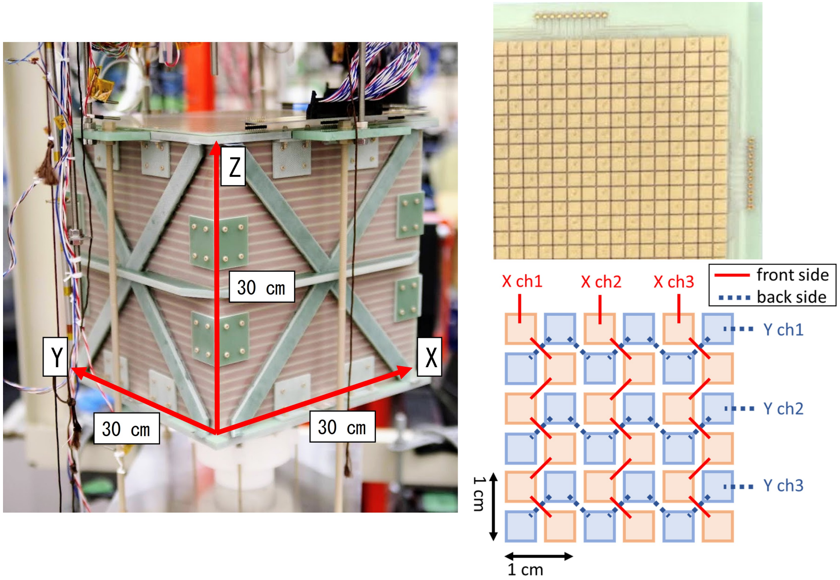

Figure 6: Picture of the 30×30×30 cm^3 LArTPC and the 2D readout scheme of the anode electrode

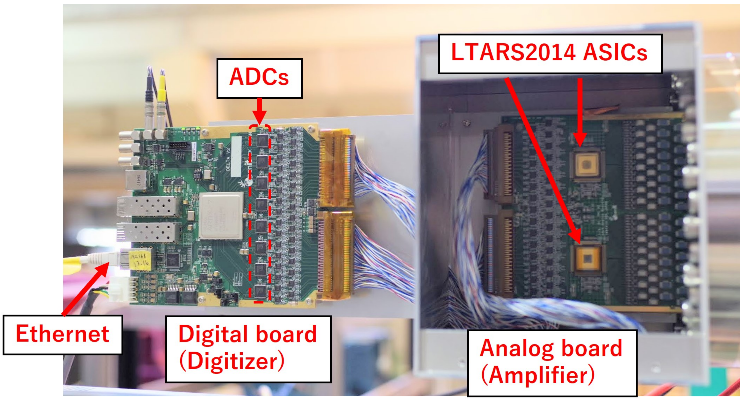

Figure 7: Picture of the LTARS readout system (Digital board(left) and LTARS2014 analog board (right))

A left drawing in Fig. 5 shows a schematic view of the Waseda LAr test-stand. Main cryostat is a stainless-steel vacuum-insulated vessel with the volume of 200 L, the diameter of 50 cm, and the height of 100 cm. This system can stably hold the liquid argon for several weeks and also provide ultra-pure LAr. Impurity (O_2, H_2O) level is $\mathcal{O}$(100 ppt), corresponding to drift electron lifetime of $\mathcal{O}$(ms) [15], which is good enough for charge measurement in 30 cm drift length. We note that the heat inflow of the cryostat is about 30 W, and the LAr inside the cryostat evaporates about 20 L per day without the cryocooler. Thus, the liquefier (area surrounded by dotted line in Fig. 5) is not necessary for only few day's experiment, that is the case for this proposal.

A cubic shape LArTPC with the size of 30×30×30 cm^3 and fiducial mass of 40 kg (GRAMS40) was constructed and tested for tracking performance of cosmic muons at the Waseda LAr test-stand in October 2022. As shown in the right drawings of Fig. 5, GRAMS40 was the almost maximum size of the detector that fits within the ϕ50 cm cryostat. In addition to the LArTPC, a PMT was installed near the bottom of the cryostat for detecting the LAr scintillation light.

A picture of GRAMS40 is shown in Fig. 6. It consists of 6 printed circuit boards (PCB) with the base of FR4 and gold-plated copper electrodes. There is a cathode PCB at the bottom side of the detector and up to 13 kV of high voltage was safely tested to produce uniform electric field inside the TPC. There are 4 side plates PCBs for shaping the electric field inside the fiducial volume. The anode PCB at the top side of the detector has segmented electrodes (5 mm×5 mm pads). Figure 6 shows a picture of the anode PCB and explains the 2-dimensional readout scheme of the anode electrodes (so-called "CHIDORI" readout). The 5 mm×5 mm pads were alternately connected on the front/back side for X/Y-axis readout, respectively, with effective readout pitch of 1 cm and the total number of readout channels of 60.

The charge signals from the LArTPC are amplified and digitized using LTARS readout system [16]. Figure 7 shows picture of the 64-ch readout system with LTARS2014 ASIC. One LTARS ASIC chip amplifies the 32 channels of the LArTPC signal. Two ASICs are mounted on the analog board, thus the number of readout channels per board is 64. ADCs on the digital board digitized the amplified signals, and the digital data is transferred via the Ethernet cable with the SiTCP protocol. The gain of the amplification is 10 mV/fC, the shaping time is 2 μs, and the sampling frequency is 2.5 MHz.

3.2 Cosmic Ray Tracking Study at Waseda

The test run of GRAMS40 was successfully performed for 1 week in early October 2022 at the Waseda LAr test-stand and several million events of the cosmic muon candidates were collected. Since the anode electrodes cover 30×30 cm^2 of area, the expected muon event rate is about 10 Hz. Approximately 2% of the muons which have 150-300 MeV/c of momentum stop inside the LArTPC with expected rate of 0.2 Hz. Figure 8 shows typical cosmic muon candidates. From left to right column, each plot represents scintillation light waveforms, LArTPC waveforms in the X-Z plane, Y-Z plane, and reconstructed 3-dimensional tracks. Plots in the top row have a single straight-line track from the top to the bottom of the LArTPC which corresponds to a muon passing through the TPC. Plots in the middle row have second scintillation light after 1 μs and kink structure which corresponds to a stopped muon inside the TPC and a Michel electron from muon decay (likely $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$). Plots in the bottom row have a single straight line track terminated inside the LArTPC but no other structure, which corresponds to a μ^- captured event ($\mu^- + p \to \nu_\mu + n$). This test run shows preliminary proof of the particle(μ^-)/anti-particle(μ^+) identification capability of the LArTPC.

In principle, the whole system in the Waseda LAr test-stand is ready to move to the J-PARC hadron facility and to be exposed to the anti-proton/anti-deuteron beams. Although, there is still ongoing preparation to further improve the detector performance as follows: (1) Current anode readout pitch is 1 cm and efforts are ongoing to improve the segmentation to at least 5 mm or less. (2) GRAMS40 is the maximum size of the detector inside the ϕ50 cm cryostat. Although GRAMS40 works properly in the current cryostat, we are discussing the use of larger size of the cryostat to have more flexibility as an upgrade option. (3) Preparation of secondary particle counter outside the LArTPC to detect outgoing hadrons generated at capture point. Details of these efforts will be discussed in Section 5.

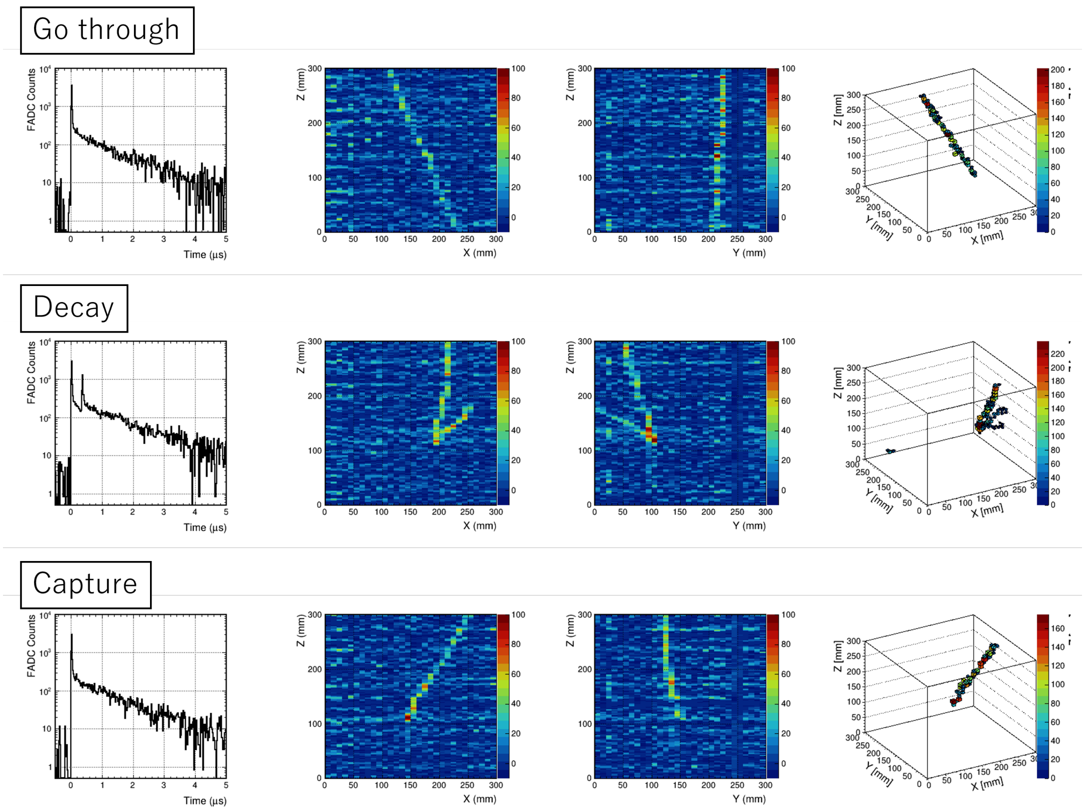

Figure 8: Typical cosmic muon events taken with the 30×30×30 cm^3 LArTPC at the Waseda LAr test-stand in October 2022.

4 Experimental Setup and Sensitivity Estimation at K1.8BR

4.1 Experimental Setup

As stated above, the detector system in the Waseda LAr test-stand shown in Fig. 5 is ready to move to the J-PARC K1.8BR beam line. Figure 9 shows a bird's-eye view of the K1.8BR experimental area and a 3-dimensional view of the detectors. The detector system will be placed within 4 m×4 m area shown as a red frame in Fig. 9. It is noted that the location of the red frame is arbitrary as far as it is on the center of the beam line. From upstream, the beam will pass through 2 layers of plastic scintillation counters, 5 mm in thickness and 1.5 m apart each other. The two scintillation counters will form a ToF counter with 300 ps of the time resolution which is sufficient for separating the antiprotons/antideuterons from other particles. Then, the GRAMS40 detector inside the ϕ50 cm cryostat will be placed downstream of the ToF counters.

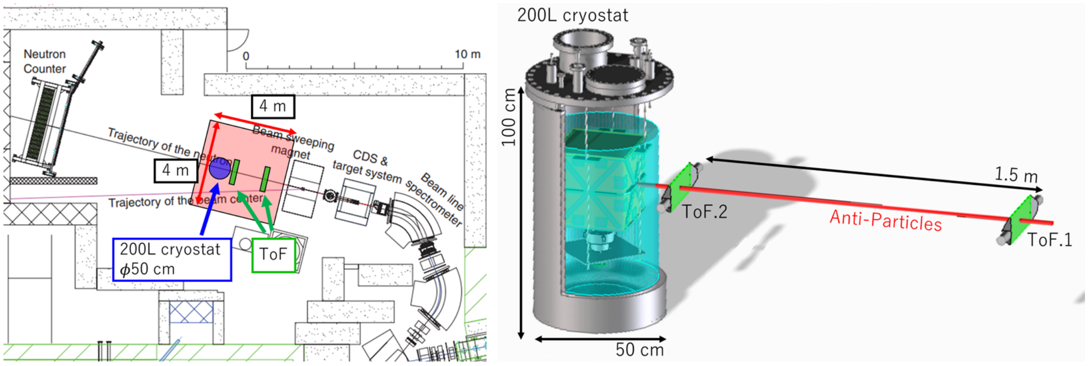

Figure 9: A bird's-eye view of the K1.8BR beam line and drawing of the detector system.

4.2 Geant4 Simulation

Geant4 (Ver.4.10.07.p01) software [17] has been used for simulating the response of the LArTPC for the antiparticles. The setup shown in Fig. 9, where the two ToF plastic scintillators are placed in the upstream and the cryostat placed in the downstream of the beam was set up in Geant4. The volume inside the cryostat was filled with LAr.

Figure 10 shows top views (left) and side views (right) of typical simulated events for the 600 MeV/c antiproton (top) and the 1100 MeV/c antideuteron (bottom) which are approximately the same rigidity (150 MeV/n). The grey box represents the fiducial area of the TPC placed in the middle of the ϕ50 cm cryostat. The beam particles are injected from the negative beam axis direction and the purple and red lines correspond to the antiproton and antideuterons, respectively. The antiparticles lose their energy by the ionization and stop after 10 cm and 20 cm inside the TPC, respectively for the antiproton and antideuteron. The green lines correspond to the charged pions from the annihilation of the argon exotic atoms. The blue lines correspond to the electrons and positrons mainly from the EM shower of the neutral pions. It is noted that these displays show just generator-level energy deposition with the 0.1 mm step and no detector effects are included. However, the LArTPC is capable to reconstruct all these charged tracks in 3D with better than 1 cm of resolution depending on the anode segmentation.

Figure 11 shows the distribution of the stopping points of the captured antiparticles with different initial momenta up to 1100 MeV/c (maximum beam momentum from K1.8BR). The horizontal axis represents the coordinate of the stopping point along the beam axis, and the vertical axis represents the capture rate which is normalized to the number of generated events. The variations of the stopping points are relatively small (a few cm) compared to the size of the TPC. The stopping points are contained inside the TPC for the antiprotons with a momentum of 600 MeV/c and 700 MeV/c, and the antideuterons with a momentum above 900 MeV/c. Some fraction of the antiparticles are lost before stopping by the inelastic scattering, and the fraction increases for the higher initial momentum. Thus the fraction of captured events decreases for the higher initial momentum, and the capture rates are 58%/44% and 35% respectively for the 600/700 MeV/c antiprotons and 1100 MeV/c antideuterons.

From the above, it follows that multiple momentum ranges for both antiproton and antideuteron can be captured inside the LArTPC, enabling to study the capture process of antimatter in LAr. Moreover, the corresponding momentum values are well matched to the signal ranges for GRAMS.

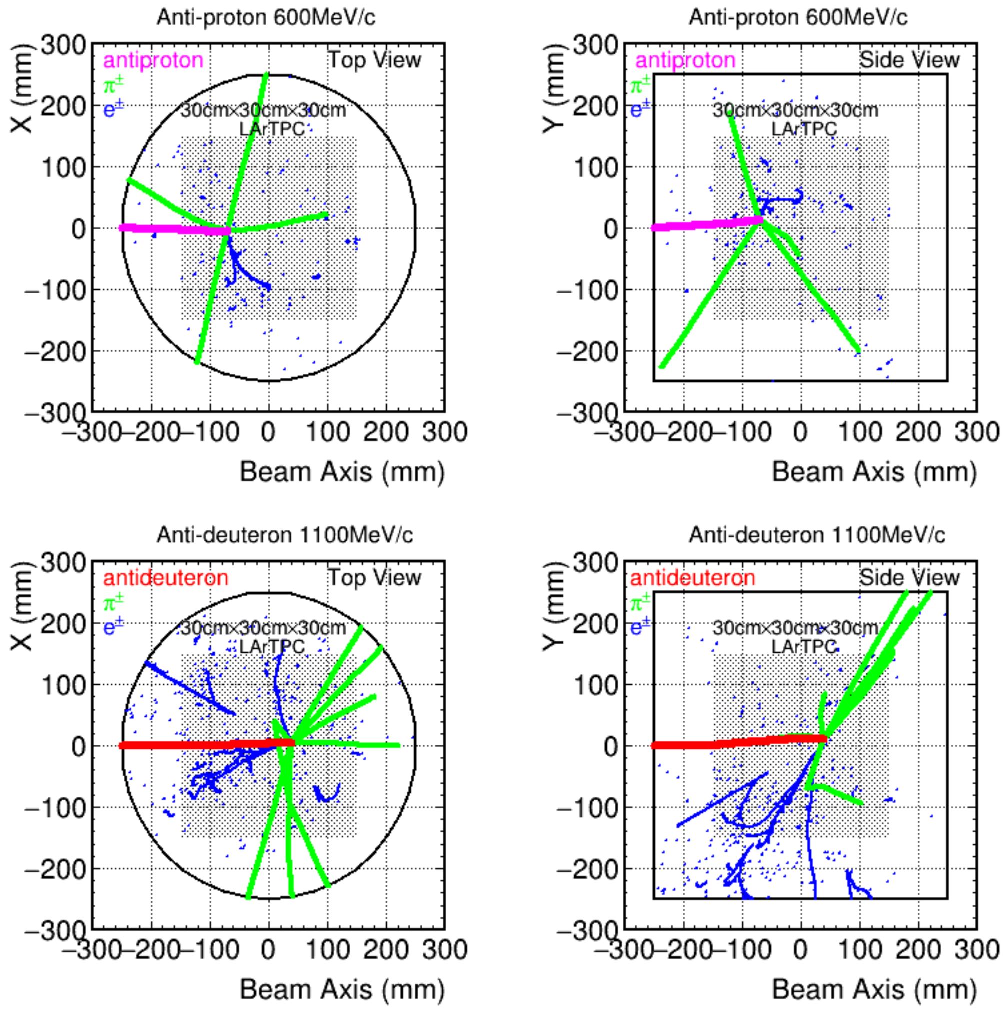

Figure 10: Event displays for the 600 MeV/c anti-proton (top) and the 1100 MeV/c anti-deuteron (bottom).

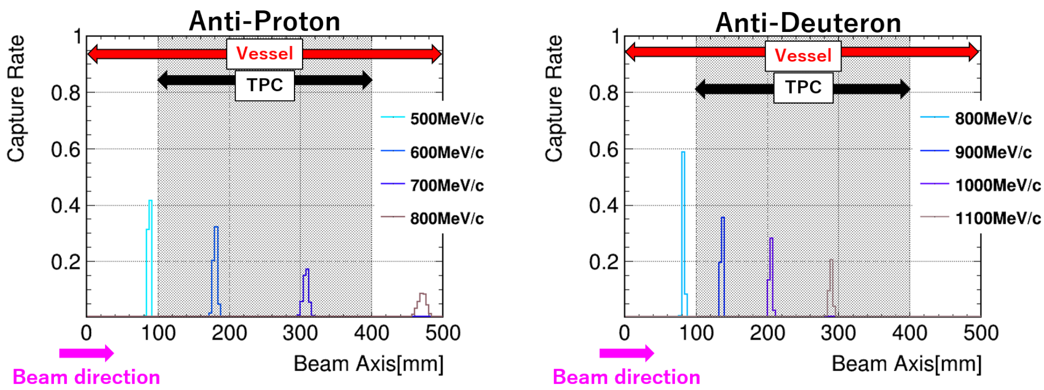

Figure 11: Distributions of the stopping points for the 500-800 MeV/c antiprotons (left) and the 800-1100 MeV/c antideuterons (right).

5 Ongoing Efforts and Optional Upgrades

5.1 Preparation of Readout Electronics (LTARS & MicroBooNE)

As described in Section 3, the number of readout channels of GRAMS40 is currently 60 with a 1 cm readout pitch, and the LTARS 64-ch readout system was used for cosmic ray testing to verify particle(μ^-)/anti-particle(μ^+) identification capability by LArTPC. Since the diffusion of the drift electron in the LAr is a few mm, it is worth having finer segmentation for the anode readout. The number of channels for the 3 mm anode readout pitch will be 200 channels in total, and currently we are in preparation of the readout electronics upgrade with KEK and Kobe University as a joint project under KEK Open-it [18]. Enough LTARS ASIC chips (version LTARS2018_K06A) were already produced, and the prototype readout board is currently in design. Production of the first prototype board will be completed by early 2023. After testing the board and some modifications, the final version will be produced by early 2024.
Considering the current situation of shortage of semiconductors, there would be a possibility to take longer time to produce new readout boards than expected. Thus, we may consider to divert the readout electronics of the MicroBooNE experiment as a backup plan [19]. As one of the proponents who is also a GRAMS collaborator has worked on MicroBooNE and an expert on cryogenic electronics, we would flexibly adopt this backup option to realize the beam test in reasonable timely manner if necessary.

5.2 Preparation in KEK LAr Test-stand

The maximum size of LArTPC which fits inside the ϕ50 cm cryostat is 30 cm$\times$30 cm and simulation study shows that GRAMS40 can be used for the purpose of this proposal as a baseline. However, there might be still a possibility that we may want to use larger TPC to enhance detection capability that requires a larger vessel. While TPC upgrade is relatively easy, for instance, we may just construct a larger TPC or 2 sets of GRAMS40, preparing for larger vessel is not straightforward. Therefore, just in case, the new LAr test-stand is in preparation at the PF-AR South building of the KEK Tsukuba campus under the support of KEK Instrumentation Technology Development Center Platform-C [20]. Figure 12 shows pictures of the test-stand area and of the larger cryostat with the diameter of 100 cm and the height of 100 cm. The maximum size of the detector that fits inside the ϕ100 cm cryostat is 60 cm$\times$60 cm. Depending on availability of K1.8BR beam line, R&D timescale and results on further physics case study, we may consider this upgrade option in the future.

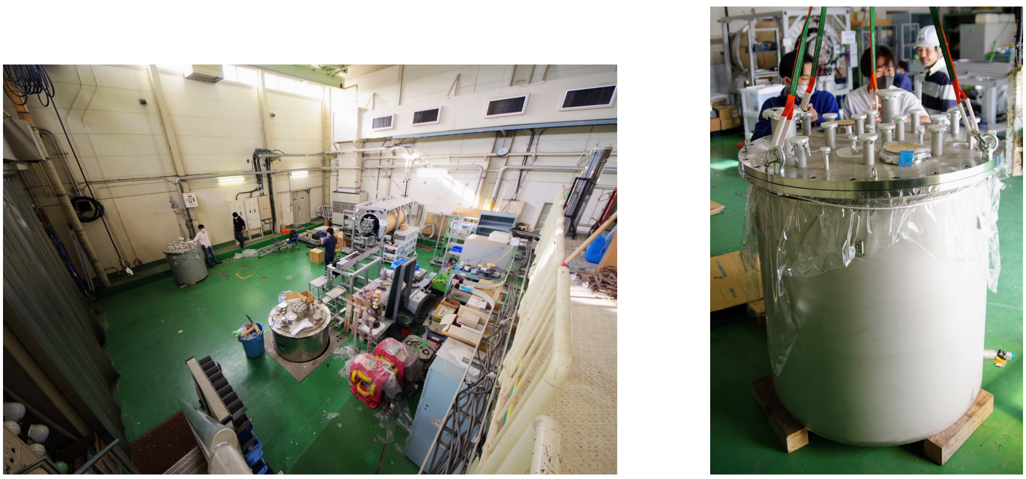

Figure 12: Pictures of the LAr test-stand at KEK PF-AR South building and the ϕ100 cm cryostat.

5.3 Preparation of Secondary Particle Counter

Many of the secondary particles (mainly pions) produced by the antiproton/antideuteron capture are expected to pass through (out) the LArTPC. Although detecting outgoing hadrons is not necessary for the purpose of this proposal, since GRAMS plans to do this procedure to strengthen event reconstruction quality in the LDB flight, it should be worth discussing to realize this system even with a partial coverage. We are thus in preparation of scintillation counters surrounding the cryostat (horizontal direction only) to detect these secondary particles. It will be very useful information to understand the properties of the argon exotic atoms.

6 Beam Time Request and Schedule

As already described, to achieve our physics goal, more than 10^5 antiproton capture events should be collected and analyzed. Maximum (full) drift time is about 400 μs even at lower electric field of 200 V/cm and thus $\sim$1 KHz data-taking is in principle possible at maximum without pileups, however event rate will be limited by the detector DAQ rate ($\sim$100 Hz). Since the beam intensity at K1.8BR is high enough, avoiding pileup events will be rather important by adjusting the slit to control the beam rate down to less than 1 KHz including backgrounds.

On the other hand, for antideuteron beam, dedicated study for beam tuning will be needed before the exposure to the LArTPC. It would be highly desired to obtain such data, even a few capture events, to verify signal efficiency and background rejection power at the same rigidity as antiprotons. Given this situation, we would like to ask to study antideuteron beam tuning before (anytime prior to) the LArTPC beam exposure, by using present beam counters.

Antideuteron Beam Study Request

Beam Particle:	Antideuteron 1100 MeV/c
Detectors:	Present beam counters at K1.8BR beam line (+ ToF counters if necessary)
Beam Time:	8-hour (anytime prior to the LArTPC Beam Request)
Beam Rate:	TBC (*e.g.* 1 antideuteron per spill [1])

Considering the detector DAQ rate ($>$ 100 Hz), capture rate ($>$ 30 %) and duty factor ($\sim$ 50 %), we expect 0.5×10^5 events can be collected per an hour. In order to ensure at least 10^5 antiproton capture events for each momentum point with a contingency factor of 2, and at least a few events of antideuteron, beam time is requested as follows:

Summary of Beam Request (LArTPC beam exposure)

Beam Particle:	**Antiproton 600 MeV/c and 700 MeV/c** **Antideuteron 1100 MeV/c (in case of successful beam study)**
Detectors:	One LArTPC and scintillation counters
Beam Time:	6-hour each (2-hour beam tuning + 4-hour data taking with commissioning)
Beam Rate:	Less than 1 KHz (including background particles)

Since our primal success is to understand antiproton background with high statistics, while collecting antideuteron signal data is "maximum" success in this proposal. Therefore, depending on the results of antideuteron beam study, there might be a possibility to carry out this measurement without antideuterons.

Figure 13 shows the time schedule of the beam exposure. Based on previous experience and current configurations, preparation time without beam at the K1.8BR experimental area will be 3 days, including installation, assembling, pre-cooling, LAr-filling and operation test. After setting the system up in place, all the system will be ready in queue for stating of beam exposure. We will be flexible for the beam starting time, and even parasitically operate with other experiments. Actual requested beam exposure time would be 1 day for antiprotons and antideuterons, and additional 1 day will be needed for withdrawal and cleanup. More concrete plan will be flexibly prepared in consultation with J-PARC facility experts.

As explained in previous sections the detector setup with GRAMS40 is already established and operating at the Waseda LAr test-stand, ready for the beam exposure at J-PARC even now. Further development to improve the readout segmentation will be ready by early 2023. Additionally, as a optional upgrade, development for the larger TPC at the KEK LAr test-stand will be also completed by early 2024 if necessary. Therefore we would like to carry out data taking within two-year timescale by the end of 2024 at the latest.

As for the safety management, based on the experience that we have performed similar beam exposure of the LArTPC in October 2010 at the J-PARC hadron facility K1.1BR (J-PARC T32) [21,22], we will follow the safety criteria of the J-PARC hadron facility (handling of cryogenic liquefied gas, oxygen deficiency, radiation etc). In addition, we plan to promote safety education and training for students and relevant researchers.

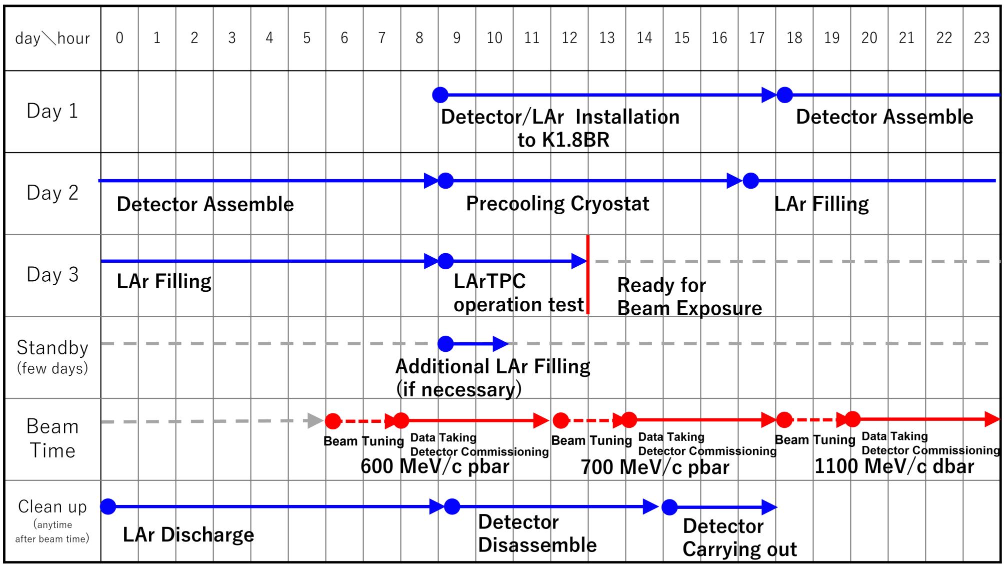

Figure 13: Work schedule of the beam experiment.

7 Resource and Cost

We have developed the LArTPC detector for more than 10 years and thus all the equipment including vacuum chamber, purification system, TPC, monitoring, slow-control, DAQ system and data storage e.t.c have been already constructed and operational. Typically several 1-week duration test-runs have been safely carried out every year. At least two shift crews monitor the whole system and take data on a round-the-clock basis during the run, for which one shift is organized by 8 or 12 hours, depending on the situation. Maximum duration of continuous operation so far is one month without any incidents. This has been established by ~10 trained graduate students and 3 to 4 faculty members from Waseda University and the University of Tokyo who can be expected as main contributors to this antiparticle beam measurements.

Regarding costs, since the all systems with necessary infrastructure are already in place at Waseda, remaining items would be transporting those to J-PARC (~$10K) in addition to DAQ upgrade (less than $20K) for finer charge segmentation and liquid argon purchase ($1K per 144L ELF tank). We may consider additional cost for strengthening safety measures, especially in the hadron hall, this is to be further addressed with the facility safety committee at J-PARC. Including contingency costs, we are quite sure that all the costs can be fully covered by JSPS KAKEN-HI Kiban-A (22H00133) and Kiban-B (22H01252) already funded during the years of 2022-2024 and constant university budget will be also secured for supporting the travel expense and accommodation at J-PARC. There is no showstopper in terms of resource and cost for realizing this proposed experiment.

8 Summary

Antimatter survey is one the most attractive approach for cosmic DM search and the next generation project, GRAMS has grown up world-wide aiming simultaneously for both astrophysical observations with MeV gamma rays and an indirect dark matter search . One of the most important milestone is to verify Ar-exotic atom production and decay and K1.8BR beam line at J-PARC provides antiparticles with the optimal momenta, accelerating the GRAMS antimatter survey project forward. In this proposal document, we request 1 day beam time for antiproton and hopefully antideuteron if beam study is successfully established before the beam time.

The K1.8BR is the unique facility for this study and we would like to perform this measurement within two-year timescale by the end of 2024 at the latest, limited by secured budget condition and to avoid resource conflict toward prototype balloon flights being proposed to NASA.

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