A joint dark sector and nuclear physics upgrade to SpinQuest at the 120 GeV Fermilab Main Injector

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ABSTRACT

An upgrade of the SeaQuest/SpinQuest experiments at the NM4 experimental hall on the Fermilab Main Injector 120 GeV beamline represents a unique opportunity for a high impact joint nuclear and dark sector physics program. Given the historical investments in these experiments, this physics program can be realized for a modest cost and can produce world-leading physics on a near-term timescale. Accelerator-based searches for dark matter and dark sector particles are a uniquely compelling part of the worldwide search as a way to both create and detect dark matter in the laboratory. The detector upgrade concept has strong alignment with the science drivers identified through the Snowmass 2021 process for accelerator-based fixed-target dark sector experiments. The initial nuclear physics program of this new proposal would be the first of its kind and would probe the gluonic structure of the spin-1 target, investigating exotic glue contributions in the nucleus not associated with individual nucleons. This is done with a novel RF driven polarized target providing access to information from linearly polarized gluons in a tensor polarized deuteron. In this document, we discuss the scientific impact of the proposed upgrade, the alignment of the experiment with the Fermilab scientific mission, the potential to leverage Fermilab capabilities, the technical requirements, and the resource needs.

Contents

1 Introduction

Expanding the mass range and techniques by which we search for dark matter is an important part of the worldwide particle physics program and has been highlighted in the DOE-supported Basic Research Needs (BRN) Report for Dark Matter Small Projects New Initiatives[1]. Accelerator-based searches for dark matter are a uniquely compelling part of this program as a way to both create and detect dark matter in the laboratory and explore the dark sector by searching for mediators and excited dark matter particles. Recently, there has been an extensive community effort to explore dark sector physics from a model-building, phenomenological, as well as experimental perspective[1–3]. SpinQuest is a proton fixed target beam dump spectrometer experiment on the neutrino-muon beamline of the Fermilab Accelerator Complex receiving a high-intensity beam of 120 GeV protons from the Main Injector. The SpinQuest upgrade distinguishes itself from other experimental initiatives in that it has a uniquely compelling nuclear physics and dark sector program that can be achieved on a short timescale with very modest resources. It takes advantage of the long history of investment in the existing E906/E1039 SeaQuest/SpinQuest spectrometer experiments at Fermilab. The experimental schematic including proposed EMCal, target, and tracking upgrades, in red, is illustrated in Fig. 1.

The EMCal upgrade will enable a new opportunity to explore extended regions of new parameter space in visible dark sector physics scenarios. At the same time, the proposed upgrade with a new RF driver polarized target with a specialized NMR system will enhance the target tensor polarization allowing access to unique Transverse Momentum Distributions (TMDs)[4]. Unlike SpinQuest (E1039), which measures an azimuthal asymmetry on a vector polarized target, the upgrade will measure the asymmetry between a tensor polarized target pointing in the transverse direction and a target with zero tensor polarization. Such a measurement would be the first of its kind and a flagship project shedding light on a new aspect of hadron physics.

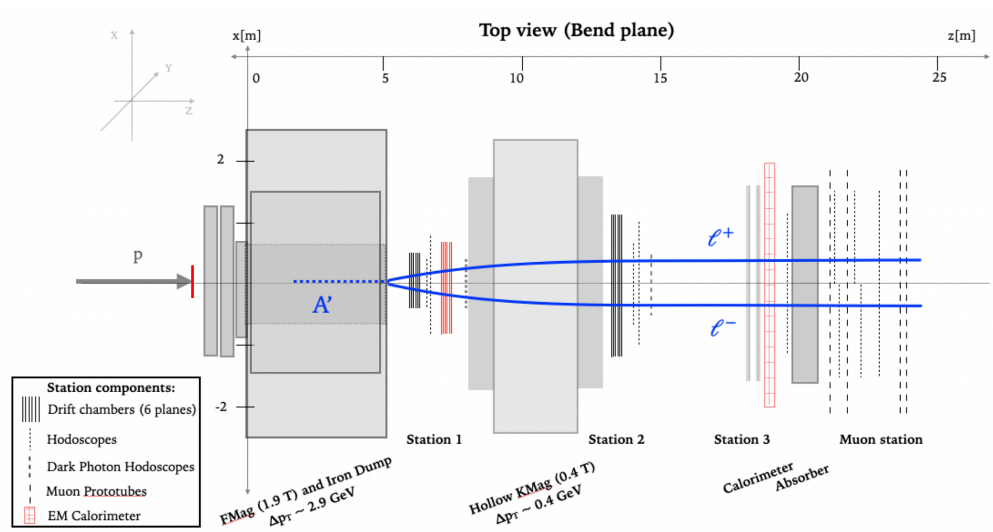

Figure 1. Top view of SpinQuest experiment including proposed EMCal, target, and tracking detector upgrades, in red; a dark sector signature is illustrated in blue.

SpinQuest status At present, SpinQuest has a fully functioning polarized target and spectrometer and is eagerly awaiting the next phase of operations. The NM4 Experimental Hall is ready to take beam however there are a few more safety reviews to pass – the accelerator safety envelope (ASE) of the entire Fermilab accelerator facility must be complete before the SpinQuest accelerator readiness review (ARR) can begin. Much of the preparation for the accelerator readiness review is in place so it is expected that the review itself will only run for about a week.

2 Science goals and impact

2.1 Dark sector science goals

Dark sector science has three primary goals that can be achieved at various high-intensity accelerator-based experiments: (1) production of invisible beyond-the-standard-model states that could be responsible for the DM of the universe, (2) production of a mediator particle and detection of its visible decay products and (3) production of non-minimal rich dark sectors and detection of mixed visible and invisible decay products. These were the drivers identified during the Snowmass 2021 effort by the "dark sectors at high intensity experiments" topical group[5]. The purely-standard model (SM) signals arising from (2) are studied in the context of dark photon, Higgs portal scalars, sterile neutrinos and axion-like particle (ALP) models, while the

DM and rich dark sectors of (3) are captured by e.g. models of inelastic dark matter (iDM) and Strongly Interacting Massive Particles (SIMPs), as well as by models with flavor-specific dark sector particles. iDM and SIMP models offer the possibility of explaining the origin of dark matter in a predictive framework with concrete experimental targets; flavor-specific dark sectors can address anomalies in data as the $(g-2)_\mu$ anomaly.

In a spectrometer-based experiment such as the SpinQuest upgrade, weakly coupled dark sector states with lifetimes of order 1 m, once produced, can be detected through their displaced decays to visible SM particles. Fixed target proton beam dump experiments, in particular, offer several key advantages in probing light dark sectors. First, enormous luminosities can be attained, allowing access to tiny couplings of the dark sector with the SM. Second, light particles are typically produced with a significant boost enhancing their decay length in the laboratory frame. This ensures that the decays of these particles can occur behind a shield that filters out SM backgrounds. Third, in many scenarios, including those with dark photon mediators, high-intensity **proton** beam dumps provide the largest production rates of dark sector particles, relative to lepton beams. Secondary fluxes of hadrons, photons, and muons produced in the proton-target reactions can lead to new production mechanisms for a variety of dark - visible sector couplings. In particular, high-energy protons beams, such as the 120 GeV Fermilab Main Injector beam, offer kinematic access to heavier dark particles in the mass range of $\sim$10 GeV and below.

The SpinQuest upgrade is well-suited to probe this difficult-to-reach parameter space. The large proton beam energy and relatively short experimental baseline (or shield thickness) is well matched to study dark sector particles in previously-untested regions. The Fermilab Main Injector is ready to deliver intense proton beams to accumulate large numbers of protons on target over a relatively short time. It is also one of the most energetic proton beams (and the most energetic at a DOE-funded National lab), enabling the reach far more massive (few-GeV) dark particles. The SpinQuest upgrade also differs from previous beam dump experiments in that it can characterize potential signals, going beyond setting limits from a highly displaced energy deposition. With an EMCal upgrade combined with the spectrometer as depicted in Fig. 1, it will be able to perform vertexing, invariant mass and energy measurements below the dimuon mass down to roughly 10 MeV.

In Fig. 2, we present the sensitivity of a SpinQuest upgrade to dark sectors, sometimes referred to as *DarkQuest*[6]. On the left panel, we show that DarkQuest will be able to cover a sizable region of dark photon parameter space not probed by past experiments (in gray in the figure). This exploration will be possible on a much shorter time scale than other proposed experiments at CERN (FASER2) and on a comparable timescale as the proposed dump mode run of CERN NA62-dump experiment. Due to the shorter baseline of DarkQuest, the NA62-dump and DarkQuest regions are highly complementary, with DarkQuest probing regions with larger ε. On the right panel of Fig. 2, we show the DarkQuest sensivity to SIMP DM. SIMP models[7] represent an interesting framework for thermal DM annihilating through a $3 \to 2$ process. A search for displaced resonant and non-resonant leptons at DarkQuest would have unprecedented reach for such models. The two dark lines across the plot are the regions where the DM candidate has the measured relic abundance. As mentioned above, DarkQuest will be sensitive to a number of other physics scenarios such as Higgs portal scalars and axions. Of particular note, DarkQuest will be uniquely sensitive to light (sub-GeV scale) solutions to the $(g-2)_\mu$ anomaly in displaced electron and photon final states as well as prompt dimuon final states which originate from the end of the FMag beam dump[8].This is due to the large flux of secondary muons created in the beam dump from the primary proton collisions. Covering these physics scenarios are a prerequisite towards a no-lose theorem for discovering new physics related to $(g-2)_\mu$[9].

2.2 Nuclear physics science goals

Polarized Deuteron Target Novel RF-driven solid-state targets have recently been developed to manipulate composite spin systems and provide a tool for accessing and isolating particular partonic degrees of freedom. This new technology coupled with the high-intensity proton beam at Fermilab provides a unique opportunity to measure new observables not achievable at any other lab in the world. With this proposal, we intend upgrade the SpinQuest target system with an additional RF-circuit. The RF-circuit and specialized target coil are required to RF-modulate across the domain of the deuteron's Larmor frequency to manipulate the spin population densities of the target. This target modification is low cost and simple to install. The new system required to drive the RF coil has already been prototyped at the University of Virginia (UVA), where there has been a successful demonstration of spin alignment manipulation with Larmor frequency sensitivity. The RF system provides control over spin transitions in the deuterons continuous-wave NMR signal enabling novel access to enhanced tensor deuteron polarization in addition to the vector polarized target used currently in SpinQuest. This tool can be used to disentangle the internal partonic complexity in the spin-1 deuteron target allowing for investigations into how sea-quarks and gluons work together to form its transverse spin structure. Hadrons and nuclei have an increasingly intricate internal structure, likely involving quark orbital angular momentum (OAM) as well as gluonic and sea-quark contributions. The transversely polarized deuteron is the ideal starting point, containing only two nucleons whose spin configuration can be controlled directly with the UVA RF target design.

Measuring the Transverse Structure of the Deuteron The deuteron is the simplest spin-1 system and offers a distinction between particular nucleon and nuclear degrees of freedom. Initially, the deuteron target appears as a loosely bound pair of nucleons with spins aligned (spin triplet state). However, the existence of a small quadrupole moment implies that these two

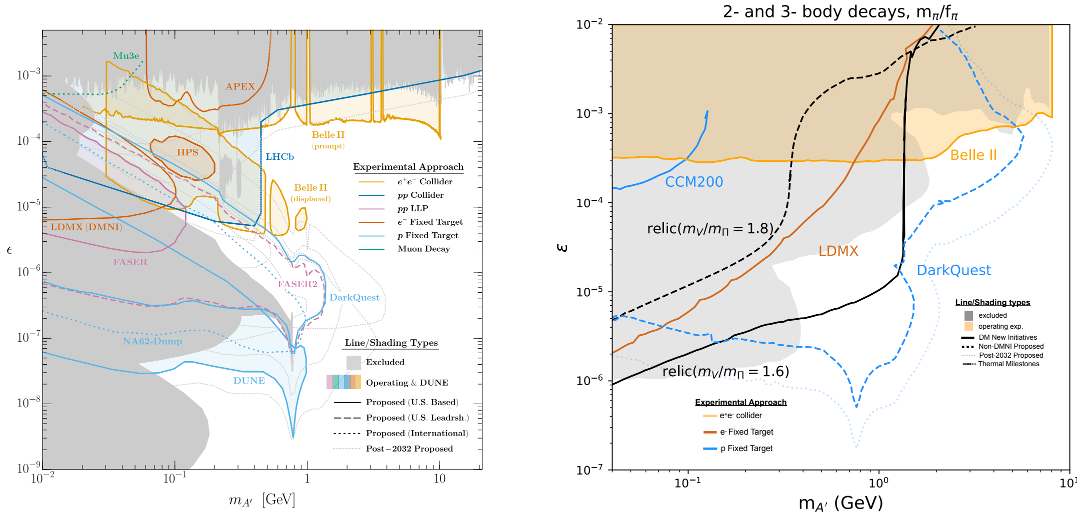

Figure 2. Comparison of the DarkQuest reach and the reach of other running or proposed experiments. Left: visible dark photon model[10]. Right: SIMP dark matter model[11]. The black line represents the region of parameter space that predicts the measured DM relic abundance. In gray we show the bounds from past experiments.

nucleons are not in a pure S-state of relative orbital angular momentum and that the force between them is not central. The spin configuration and alignment of the deuteron provide a way to separate and study the sea quark and gluon contributions directly. Only recently has technology been developed to manipulate solid-state DNP (Dynamic Nuclear Polarization) ensembles that allow for highly controlled alignment in high-density targets. These tools make it possible to expand our physics sensitivity to the correlations between geometric properties and partonic transverse dynamics. The use of the Transverse Momentum Distribution functions (TMDs) of polarizable nuclei offers the necessary connective interpretation, allowing for the exploration of how geometry emerges from quark and gluon properties.

We propose to measure the deuteron sea-quark and gluon transversity TMDs as well as the neutron and deuteron transversity TMDs. The quark transversity distributions of the nucleon are decoupled from the deuteron-gluon transversity in the Q^2 evolution due to the chiral-odd property in the transversely-polarized target. The gluon transversity TMD only exists for targets of spin greater or equal to 1 which implies that there are additional targets to explore. his experiment would be the first of its kind and would probe the gluonic structure of the deuteron, investigating exotic glue contributions in the nucleus not associated with individual nucleons. The TMDs contains detailed information on non-perturbative phenomena and are critical to the interpretation of spin-dependent hadron-hadron collisions, providing the advantage of a multi-dimensional exploration of the structure of nucleons and nuclei. Through this avenue, spin physics studies of the strong force in its non-perturbative domain and beyond can provide insight into color confinement as well as the origin of dynamic mass and charge density. The culmination of spin physics has yet to come, but novel experiments like this will ultimately reveal exactly how partonic interactions manifest into hadronic and nuclear degrees of freedom.

3 Alignment with and augmentation of Fermilab capabilities

Alignment with Fermilab scientific mission With the evolution of the SeaQuest experiment to the SpinQuest experiment and our proposed upgrade, there have been a number of highly impactful spin physics results[12] and will continue to deliver a compelling spin physics program.

Meanwhile, the search for dark matter and dark sectors is one of the key science drivers for HEP of this generation. Recently, there has been a growing interest in looking for sub-GeV dark sectors in intensity frontier accelerator-based experiments. This is highly aligned with other Fermilab scientific efforts. As an example, one of the early results in this subfield was the MiniBooNE dark matter result[13] at Fermilab. More recently, the millicharged particle search at ArgoNeuT[14] is also an exciting new result which sets new bounds on millicharged particles which are a potential dark matter candidate. These are not isolated examples as there is a rich literature of dark sector physics searches at short-baseline neutrino experiments[15] such as SBND[16] and NOνA[17] which complement the SpinQuest (upgrade) dark sector physics program. Looking forward, a large part of the DUNE beyond the SM physics program involves putative dark sector physics scenarios[18,19]. See the upper left panel of Fig. 2 for the complementarity between the DUNE reach and the reach of the SpinQuest upgrade on the dark photon parameter space. Furthermore, searches for dark sectors at the SpinQuest upgrade can uncover potential solutions the the g-2 anomaly[20].

Leveraging Fermilab capabilities The SpinQuest upgrade is a very fitting proposal for leveraging Fermilab's current capabilities to deliver impactful, near-term physics. It leverages core capabilities from the accelerator complex, experimental infrastructure, existing detectors and detector technology, and personnel. The key unique features of the SpinQuest upgrade to deliver world-leading physics is the high-energy, high-intensity proton beam that is available at the Fermilab accelerator complex coupled with the short baseline detector downstream of the beam dump. Then, because of the existing support for the NM4 experimental hall and spectrometer and magnets from SeaQuest, the resources needed to get physics from the SpinQuest upgrade are quite modest.

A note on collaboration For the past 2 years, there has been significant work to bring the the dark sector and the nuclear physics communities in SpinQuest together and understand the complementarity of the two physics programs and scientific goals. This has resulted in researchers from the HEP community joining the SpinQuest collaboration. Due to the support of Fermilab in hosting the spin physics program, this has enabled students, postdocs, scientists, and professors from both of the communities to interact and bring together a compelling and synergistic SpinQuest upgrade proposal.

4 Technical Requirements & Resource Needs

4.1 Upgrade technical requirements

The following physics and performance drivers are the motivation for the proposed SpinQuest detector upgrades.

- **Dark sector searches below 2m$_\mu$** requires a calorimeter that can reconstruct electromagnetic and hadronic signatures at the beam rate of 53 MHz
- **Measurements of tbe transverse structure of the deuteron** requires a new ss-RF modulating NMR coil around the target cell currently used at SpinQuest
- **Improved (displaced) tracking acceptance and performance** can be achieved by additional an additional tracking layer just before the KMAG.

The proposed schedule for studying, designing, installing, and commissioning this system is shown in Fig.3. Further details of each upgrade is described below.

4.2 Resources and schedule

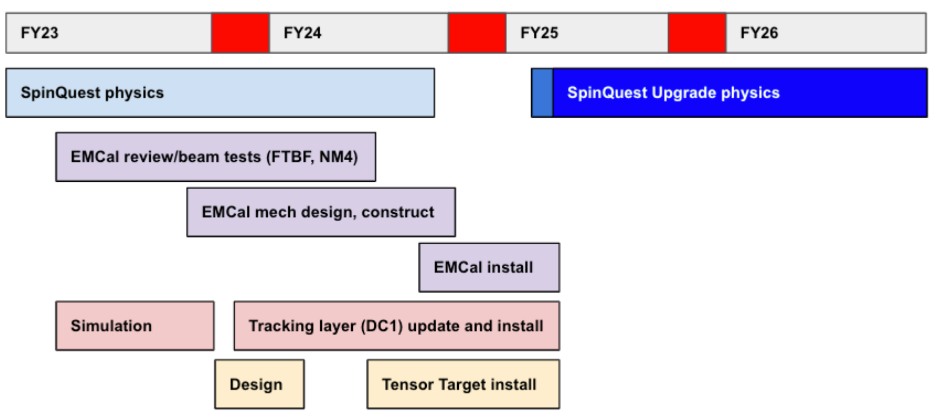

Figure 3. Proposed schedule for SpinQuest and upgrades discussed in this proposal

4.2.1 Electromagnetic Calorimeter Readout

The EMCal detector[21] comes from the non-operational PHENIX experiment at Brookhaven National Laboratory, eliminating the cost of designing and building a new calorimeter. While the EMCal detector itself is reusable, the photomultiplier tubes (PMTs) used to detect the scintillation light must be replaced. The most cost effective solution is to replace the PMTs with silicon photomultipliers (SiPMs). Each EMCal "module" consists of four independent readout channels, and the entire 2m x 4m EMCal sector consists of 648 modules (2592 total readout channels). The light for each channel is concentrated into a 6mm diameter bundle of optical fibers, which is well-matched for a single 6mm x 6mm SiPM. The SiPMs produce an analog signal that must be processed at the beamline frequency of 53 MHz to trigger the full read out and digitization of the EMCal data for events of interest. The front end electronics boards that house the SiPMs and send the analog signal off of the detector have been prototyped at Boston University with the help of the BU Electronics Design Facility. In 2023 we will finalize the design, fabricate, and test the front-end boards in the BU High Energy Physics Lab. The analog signal will be processed using the FERS-5200 front-end readout system developed by CAEN™ Electronic Instrumentation. This system is designed to be a low cost solution for the readout of large detector arrays, and particularly those using SiPMs. The CAEN A5202 ASIC board is the heart of the system, which is based on the WeeRoc™ Citiroc ASIC. The A5202 collects 64 channels and forms a trigger signal if any of the channels is above a programmable threshold. This trigger signal can be shared across the full system (41 A5202 boards), and the subsequent digitization and acquisition of the energy measurement for each channel is also performed. The energy calibration will be carefully monitored using a medium power nanosecond pulsed laser. Finally, new computing hardware will required to store the raw EMCal data and perform the event reconstruction and data analysis.

A test stand has been constructed with a single EMCal module, the custom SiPM board, and a single A5202 ASIC board to demonstrate the concept using cosmic rays. In order to study the integration of the EMCal detector into the existing spectrometer, the test stand will be relocated to Fermilab in 2023 for characterization in the Fermilab Test Beam Facility and for background rate studies in NM4. We have assembled a budget based on direct quotes for the necessary instrumentation (approximately $500k) and seed funding is available to continue development. The installation of the full EMCal sector will require technical support from Fermilab. The detector must be relocated from Brookhaven to Fermilab and transferred into the NM4 cavern. A mechanical support structure will be required to raise the detector to the beam axis. Tracking station 3 will need to be moved upstream to create sufficient space to install and access the EMCal sector. After the detector is installed and the tracking detectors repositioned, an updated survey of the spectrometer may be required. This will require modest resources from Fermilab in the form of technician, mechanical engineering, geodesist, and metrologist effort.

4.2.2 Polarized Target

This proposal requires the same SpinQuest polarized target system recently installed in the NM4 experimental hall at Fermilab. The target system consists of a 5T superconducting split pair magnet, a ^{4}He evaporation refrigerator, a 140 GHz microwave source, and a large 17,000 m^3/hr pumping system. The target is polarized using Dynamic Nuclear Polarization (DNP)[22,23]. The maximum polarization achieved with the deuteron target is around 50% vector polarization with a packing fraction of about 60%. The technology that we will use in the proposed experiment to separate sea quark and gluon observables is a selective semi-saturating (ss) RF system developed by UVA[24,25] combined with our continuous wave NMR so that the composite spin system can be manipulated and measured simultaneously. This ensures that the target remains continuously optimized even as it endures radiation damage from the beam.

The selective ss-RF excitation requires an additional coil around the target cup. The ss-RF is modulated over the frequency domain of interest at the appropriate RF power to semi-saturate the NMR line resulting in a manipulated bulk magnetization. The ss-RF can then be used to tune the target polarization to either a tensor or vector-enhanced state during beam target interaction time. The figure-of-merit of the experiment is improved by alternating a tensor enhanced with zero tensor and vector enhanced polarization every beam spill. The FNAL beam cycle is perfect for this sequence allowing just enough time to prepare the target spin configuration before the next spill. UVA has already prototyped and tested this system. What remains is the final production system which is estimated to cost about $65k. UVA will seek funding for the construction of this instrumentation. Installation of the entire system into the NM4 experimental Hall would take approximately 2 working days.

4.2.3 Additional Tracking Layer

The SpinQuest spectrometer depicted in Fig. 1 shows two tracking layers between FMag and KMag, collectively referred to as Station 1. However, the second of those high-precision tracking stations is currently not operating due to difficulties in operation. Reviving additional tracking layers between the FMag and KMag would provide substantial improvement in the physics performance of the experiment. Additional pattern recognition before KMag, where detector occupancy is the greatest would improve pattern recognition capability, rejecting background particles more efficiently, and improve vertexing resolution. Furthermore, the additional tracking layer would extend the acceptance of the detector to charged displaced particles to roughly 8 m (the position is configurable, to a degree). This would then increase the overall sensitivity of the experiment to dark sector particles.

Existing proportional chambers from the HyperCP experiment[26] stored at the Fermilab site would be a good candidate detector for this proposed additional tracking layer. These two chambers each have an aperture of $1.212 \times 0.405\, m^2$ with a wire pitch of 1.5 mm. Their installation would provide additional points for tracks upstream of the analysis magnet, KMag. We plan for the readout through the SeaQuest/SpinQuest ASDQ, Level-shifter board. The TDC electronics require 176 ASDQ cards and 22 Level shifter boards and 44 TDCs – which are available.

We plan for simulation studies in the near future to quantify the impact of this additional tracking layer before the KMag. While this aspect of the upgrade is not critical, we anticipate that it will bring important additional capabilities to DarkQuest. Once the studies are completed, we will identify the resources needed for this upgrade. However, since it relies solely on existing detectors and readout, we expect the resource needs to be modest.

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