Letter of Interest for Snowmass 2021: Scientific Opportunities with the CBETA Accelerator

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The new high-intensity, multi-pass Energy Recovery Linac (ERL) at Cornell University, called CBETA, offers unprecedented capabilities to look for new physics at low energies. Here we describe the accelerator and outline experiments to search for new interactions and to determine the reaction rate of the important radiative capture reaction $^{16}\mathrm{O}(e, e'\alpha)^{12}\mathrm{C}$ in the astrophysically interesting region.

I. THE CBETA ACCELERATOR

The Cornell-BNL Test Accelerator (CBETA) has been developed at Cornell University with funding provided by the New York State Research and Development Authority, the National Science Foundation, and industrial partners. It employs superconducting RF cavities and Fixed Field Alternating Gradient (FFAG) permanent magnets to accelerate electrons injected from a photoinjector in four passes. In December 2019, full energy recovery and acceleration was demonstrated at CBETA. Starting with an electron beam of 6 MeV, the CBETA accelerator brought beams to 42, 78, 114 and 150 MeV in four passes through the energy recovery linac (ERL). CBETA is the first multi-turn ERL to recover energy using SRF. It is the first accelerator to use a single beamline with fixed magnets to transport seven different accelerating and decelerating electron beams.

II. SEARCHING FOR NEW INTERACTIONS

On the cosmic scale, we see evidence of significant mass that does not interact electromagnetically – hence dark matter. The prevailing assumption is that dark matter will take the form of additional stable particles to be added to the standard model. The focus over several decades has been to look for a particular type of new particle, a Weakly Interacting Massive Particle (WIMP), via a rare scattering from an atom in a large detector, typically located deep underground to minimize the rate of background events. Thus far, no conclusive evidence for WIMPs has been found. Searches will continue for at least another decade, but will reach a fundamental floor in this approach due to the inability to distinguish between a neutrino-atom interaction and a WIMP-atom interaction.

A complementary approach is to search for evidence of the mediator of an interaction between the known elements of the standard model and those unknown particles that make up dark matter. These extensions to the SM invoke new or existing interactions to couple the new particles to the known elements of the standard model. These interactions can be sought in a laboratory setting.

Recently, we see a suite of anomalies in the behavior of particle [1], nuclear [2, 3], and atomic [4] experiments which could be resolved by adding a new, MeV-scale interaction to the standard model. Generalized models to explain these anomalies lead to a large parameter space of couplings which require a broad search effort to fully explore these 'lamp post' regions.

A leading candidate is a so-called protophobic fifth force [5], which has separate coupling strengths to different quark and lepton flavors, allowing it to reproduce anomalies while evading the limits of existing searches that rely on production via pion decay. Dramatic increases to integrated luminosity would be needed to extend the pion-decay approach enough to conclusively rule out such a force. Experiments that probe via a suite of hadronic productions, or via leptonic production, are already being mounted [6, 7]. Lower-energy machines allow searches to be performed more agilely as anomalies arise, and may have easier access to MeV-scale masses.

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Beyond these anomalies, the persistent question of dark matter motivates a broad spectrum of experiments seeking evidence of dark matter and its interactions with the SM. In accelerator settings, the signature of such a particle can take the form of missing energy (if the mediator is stable or decays to non-interacting final state), excess of SM final states with a characteristic invariant mass (if the mediator decays to SM final states) or modifications of expected spectra (if the mediator is too massive to be produced on-shell).

The current generation of anomalies manifest through leptonic interactions or final states, motivating direct searches for leptonic couplings to new physics. A lepton machine such as CBETA is a natural choice for such searches, with $O(100\text{ MeV})$ beam energies aiding in the search for rare, MeV-scale particles by reducing the complexity of final states and widening decay opening angles that may be inseparable at higher energies.

A baseline experimental design would employ adjustable spectrometers positioned to maximize acceptance for a desired mass window. Such designs readily reach mass resolutions better than $\sim$250 keV, and can in principle take advantage of very high luminosities. With a 100 mA beam and thin gas target of areal target density $10^{18}/\text{cm}^2$, instantaneous luminosities on the order of $10^{36}/\text{cm}^2/\text{s}$ would be achieved. The needed target density has been demonstrated for the MAGIX gas jet target[8], and higher operational densities are expected. In such a configuration, energy loss and rescattering of final state particles in the target is negligible, opening up the possibility to further control backgrounds by selecting final state kinematics where the recoiling target proton can be detected by, eg, a silicon detector in the target chamber. This, in turn, permits searches for invisible final states which are not possible in comparable thick-target experiments.

III. DETERMINING THE REACTION RATE OF ^{12}C$(\alpha,\gamma)^{16}$O IN THE ASTROPHYSICAL REGION

The helium burning stage in massive stars is dominated by two reactions: radiative triple-α capture and radiative α capture on ^{12}C. Their rates directly affect the ^{12}C/^{16}O abundance at the end of burning stage and highly influence the modeling of subsequent nucleosynthesis [9]. At stellar energies, the triple-α capture rate is known with an uncertainty of $\sim$10%, but the situation for the ^{12}C$(\alpha,\gamma)^{16}$O rate is much worse [10]. Hence, the elusive goal over decades is to improve the precision of the ^{12}C$(\alpha,\gamma)^{16}$O rate at stellar energies [11].

The direct measurement of the extremely small cross section ($\sim 10^{-5}$ pb) at Gamow energy $E_g \sim 300$ keV is impracticable. Therefore, the strategy is to measure the cross section at larger energies and extrapolate that result to stellar energies. Several methods have been employed through the years: direct reaction measurements [12–25], elastic scattering ^{12}C$(\alpha,\alpha)^{12}$C [26, 27], $\beta-$delayed α-decay of ^{16}N [28–30]: see the recent review in [10].

In photodisintegration, the ^{16}O nucleus is disintegrated by a real photon beam $q = \omega$, but this process can also be induced by a virtual photon $q > \omega$ coming from electron scattering [31]. A huge advantage of using the reaction involving exchange of a virtual photon compared to that with the real photon is that in the astrophysical region determined by ω one can independently control the magnitude of transferred 3-momentum q to the final state α-particles, either by selecting the angle of the scattered electron θ_e or the beam energy E_e. Further, it is necessary that the produced α-particle has enough kinetic energy to exit the jet target to reach the detector. For the real photon process close to threshold, all nuclei are 0^+ so only the E1 (electric dipole) and E2 (electric quadrupole) multipole contribute to the cross section [12]. By measuring the angular distribution of the produced α-particles, it is possible to separate the contributions of each multipole. In an exclusive electrodisintegration experiment, the final state of the scattered electron is measured in coincidence with the final state of the α-particle and by using the conservation of energy and momenta the final state of the unobserved ^{12}C can be determined and any excited state can be separated.

We have published a detailed paper [32] where we developed the formalism and a simple model which relates the radiative capture reactions and the electrodisintegration reactions. We took an experimental input in terms of S-factor data below $E_{cm} < 1.7$ MeV, assumed optimal detectors (magnetic spectrometer for the electrons, and ion detectors for the α-particles), 100 days of data taking using the electron beam energy and current capabilities of the CBETA, performed Monte Carlo calculations and projected statistical uncertainties of the S_{E1} and S_{E2} factors [12]. The calculated statistical uncertainties are a significant improvement over those in existing experimental data.

The full set of Monte-Carlo simulations for beam energies $E_e = 74$, 114 and 150 MeV, electron scattering angles $\theta_e = 15^\circ$, 25° and 35°, and other modeling parameters can be found in [32]. The overall conclusion is that when comparing the results from [32] with the most accurate measurements from [20] and [23], the uncertainties in the determination of S_{E1} and S_{E2} at a given energy above threshold are improved by at least ×5.6 and ×23.9, respectively.

The optimal experimental layout is to place the α-detectors around the direction of a virtual photon where the α-particles have the largest kinetic energy at a given Q^2. The operation of α-detectors in close proximity of the Megawatt electron beam will be very challenging, but it has already been demonstrated that such high power ERL beams can be achieved with minimal halo [33].

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