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White Paper, Working group A5
Underground Accelerator Laboratory for Nuclear Astrophysics

Science

One of the great successes of nuclear astrophysics is the development of a detailed model for stellar evolution and energy generation. The life and death cycles of stars and the creation of heavy elements are described by networks of nuclear reactions, which characterize several distinct phases of stellar evolution. The reaction networks determine the temperature scales, lifetimes and isotopic abundances which "seed" subsequent burning phases and later generations of stars through explosive processes. The stellar life is composed of a sequence of burning phases from hydrogen burning - through the pp-chains for low mass stars ($M<1.5M_{solar}$) or the CNO cycles for massive stars ($M>1.5M_{solar}$) - to helium and carbon burning, followed by the rapid neon, oxygen, and silicon burning phases in the last years of stellar life. Despite 50 years of experimental efforts, none of the associated nuclear reactions has yet been measured at the relevant energies. A more complete quantitative understanding of the critical reactions defining the nuclear networks would improve understanding of the generation of the elements (including those necessary for life) comprising the solar system and galaxy, supernova nucleosynthesis, and the lifetime and ultimate fate of particular classes of stars. While there are a large number of reactions governing stellar burning, a number of high priority reactions to be investigated have been identified by theoretical modeling studies of stellar burning conditions.

Presently, model calculations of stellar evolution have to use nuclear reaction rates which have not been directly measured at the relatively low energies found in stars, but have been extrapolated from laboratory data taken at high energies, where reaction cross-sections are exponentially larger and thus easier to measure. The extrapolation procedure introduces substantial uncertainty to the reaction probabilities, particularly in cases where complex resonance or level interference patterns characterize the reaction cross sections. High precision measurements of nuclear reaction cross-sections at low energies (at or near the Gamow window) are necessary for reducing the present uncertainties. At stellar energies, reaction rates produced by laboratory accelerators are extremely low, in some cases requiring weeks or months of beam time to produce suitable statistical uncertainty. Precise yield measurements are contaminated by background counts from beam, target, or detector impurities, from cosmic ray produced backgrounds, and from ambient laboratory material backgrounds. To achieve the precision demanded by stellar model calculations and next generation neutrino experiments, a strong, concerted effort of new beam facilities above and underground will be necessary. These must take advantage of advanced detector and target technology, improved background shielding and higher beam intensities. A deep underground laboratory environment will suppress the cosmic ray muon and induced neutron backgrounds by several orders of magnitude (depending on the desired reaction signature), allowing cleaner detection, and will be a powerful complementary tool to existing and future above ground astrophysics facilities.

A first outline of the needs and requirements for an underground accelerator facility has been developed in the ALNA white paper
http://www.deepscience.org/TechnicalDocuments/Final/ualna_final.pdf.
The facility outlined in this report envisions two accelerator areas; a compact, high intensity, low energy accelerator for pp chain reactions; and a high intensity, heavy ion accelerator for inverse kinematic reaction and low energy fusion reactions. The energy range of both accelerators combined should ideally cover beam energies from as low as 50keV up to 1 MeV/u for ion masses up to Mg. The two accelerators should have an overlap in energy range for comparison between experiments over a common energy.

Studying the pp chain at energies below 100 keV probes the main energy balance in low-mass (sun-like) stars, and would be a main goal of the low-energy accelerator. Accurate calculations of the solar neutrino spectrum (soon to be measured at high precision by KamLand and Borexino) and solar parameters (luminosity, core metallicity) now depend on accurate cross section measurements (< 1% uncertainty) for ^{3}He(α,γ)^{7}Be and ^{7}Be(p,γ)^{8}B. The accelerator would have variable energy from < 100 keV to ~ 1 MeV and very high beam currents (> 1 mA) to ensure measurable event rates. In the CNO cycles, refined measurements will allow estimates of the lifetime of medium mass stars (> 1.5 Msolar), isotopic composition of supernova progenitors, and the fate of high mass stars (neutron star versus black hole), supernova nucleosynthesis. Recent LUNA and LENA measurements of the ^{14}N(p,γ)^{15}O reaction have demonstrated significant deviations to extrapolated cross sections for different reaction channels. Significant uncertainties are also demonstrated by R-matrix analysis of ^{15}N(p,γ)^{16}O reaction which defines the branching to the second CNO cycle. A systematic analysis of most of the CNO reactions suggests that similar uncertainties exist for most of them, affecting the branching and leakage conditions between the different cycles. This may affect the overall abundance predictions for CNO isotopes. ^{17}O(p,α)(p,γ), ^{18}O(p,α)(p,γ) are high priority reactions to define the branching points for the CNO cycles. These reactions would be studied with the low-energy accelerator, using gas targets to ensure high target purity.

A higher energy accelerator would allow the study of the helium burning phase, and also proton capture processes on higher-Z stable nuclei relevant for explosive hydrogen burning in novae. It could overcome the background limitation (from natural radioactivity from the walls of the underground cavity and beam induced background activity on target impurities) by measuring proton and alpha capture reactions in inverse kinematics. A detection scheme using a recoil separator with very high beam rejection ratio (10^{-18}–10^{-20}) would be necessary for cases with complex beam-induced backgrounds and would represent an ultimate background-rejection technique.
The reaction ^{12}C(α,γ)^{16}O has been identified as one of the most critical nucleosynthesis reactions since it determines the ratio of carbon and oxygen (critical elements for life) in the universe. A concerted, community-wide effort on this reaction could be a future flagship experiment for the underground astrophysics accelerator. He-burning reactions such as ^{12}C(α,γ)^{16}O, and ^{16}O(α,γ)^{20}Ne are important for energy generation and the fate of subsequent burning phases. Of similar significance are the ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg reactions which have been identified as the dominant stellar neutron

sources for the s-process. These reactions are critical for the production of half of the heavy elements above iron by slow neutron capture in stellar helium and possibly carbon burning. The reaction cross sections are characterized by broad, low energy resonances interfering with sub-threshold states, making reliable predictions nearly impossible without better experimental data.

The critical carbon burning reactions $^{12}C+^{12}C$ and $^{16}O+^{12}C$ determine the ignition conditions and lifetime for the carbon-burning phase of stellar evolution. The low-energy $^{12}C+^{12}C$ cross section is characterized by complex, near-threshold resonance structures which must be resolved. These reactions require a heavy-ion source capable of ~ 1 MeV/u and lower, requiring use of ion sources with intense, high-chare state beams to span the necessary energy range.

Priority for first suite of experiments

Several hydrogen-burning reactions would benefit from high-precision measurements at low energy, where the full benefit of background suppression from an underground facility would be realized. These include $^{3}He(^{4}He,\gamma)^{7}Be$, $^{15}N(p,\gamma)^{16}O$, and $^{7}Be(p,\gamma)^{8}B$, $^{17}O(p,\alpha)(p,\gamma)$, $^{18}O(p,\alpha)(p,\gamma)$, which would be studied at energies as close as possible to the Gamow window with high beam current, while extending to somewhat higher energies for $^{17}O(p,\alpha)(p,\gamma)$, $^{18}O(p,\alpha)(p,\gamma)$. These would occupy the low-energy accelerator portion of the facility, and offer some benchmarking comparisons to recent LUNA facility measurements. These experiments would use common gas target techniques, and would take advantage of common instrumentation, including a mixture of

Prioritizing reactions for the high-energy accelerator depends somewhat on the accelerator design selected: $^{12}C+^{12}C$ and $^{12}C+^{16}O$ would demand high-charge-state ECR sources combined with a DC terminal accelerator, while the He-burning reactions in the NeNa cycle would likely be more easily studied with a high-current accelerator in inverse kinematics.

Roadmap (rough order magnitude time/cost)

Low Energy Accelerator CLAIRE

A first stage accelerator CLAIRE (Center for Low Energy Astrophysics and Interdisciplinary REsearch) is presently being developed at the 88-Inch Cyclotron at LBNL and would be a power tool for the DUSEL underground laboratory. This accelerator represents the traditional LUNA approach but with significantly increased beam intensities not possible at the LUNA facility. The higher intensities would enable measuring cross sections at or closer to the Gamow window of stellar burning for the pp chains. In its first phase, this facility will consist of a high-power high-voltage platform, four solenoid lenses, and one 60^{o} analyzing magnet, providing proton and singly charged helium beams of up to 100mA with beam energies ranging from 50keV to 400keV.

In addition, a high charge state, high intensity ECR ion source can be added that would extend the energy range of the accelerator for helium to 800 keV, for nitrogen to 2MeV and for carbon up to 1.6MeV at beam intensities of up to several hundred pμA. This higher energy option will provide an energy overlap to the high energy accelerator. The low energy accelerator is a small and compact device that will fit on a $10x6m^{2}$ footprint, which includes the gas target and the detector. Accelerator R&D has been conducted at

LBNL for the design of the device and a preliminary cost estimate has been made, making it a good candidate for early implementation at the DUSEL facility.

High Energy Heavy Ion Accelerator

A high energy, heavy ion accelerator would substantially extent the physics reach of the facility. Presently two options for the accelerator are being discussed, a DC accelerator (a Tandem, Tandetron, Dynamitron or Pelletron accelerator) or a 1MeV/u RFQ/LINAC. Both systems have distinct advantages and disadvantages, which will have to be studied in more detail before a design decision can be made. Design parameters including current requirement, final energy and maximum energy spread need to be defined to begin a design study. Such a study would occupy 3-4 people for 6-12 months.

The main advantages of DC accelerators are the low energy spread and the good beam quality. A commercial Tandetron or Pelletron tandem would provide superior beam quality but has limitations in beam intensity. For lower energy machines, very high currents can be achieved (tens of mA have been demonstrated for up to 3MeV), but it would be impossible to extend these machines to 1MeV/u for heavy ions at these intensities. Further disadvantages are the tight space and limited power available at the high voltage terminal, which reduces the flexibility of the system. In addition, the maximum voltage available at the terminal will limit the maximum energy. If this approach is chosen, R&D should be conducted to design a high current ESQ accelerator for the lower energy range and to build compact, permanent magnet medium charge state ECR ion sources to extend the energy range of commercial pelletron systems at higher intensities.

On the other hand, a linac design provides maximum flexibility in terms of final energy range and injector options. However, since it is a bunched beam system the energy spread will inherently be higher than in the case of the DC accelerator systems. An RFQ/LINAC accelerator would consist of an ion beam injector that accelerates the ion beam to the injection energy of the Radio Frequency Quadrupole (RFQ) accelerator, an external bunching section, the RFQ and single cavities that accelerate the beam to the desired end energy. However the minimum energy of the system would be defined by the fixed output energy of the RFQ. For example at ISAC in TRIUMF, the energy variability ranges from 150keV/u (output energy of the RFQ) to 1.3MeV/u. The end energy would be modular and easily upgradeable by adding more cavities. There are several design choices that will have to be made for the design of such an accelerator, in particular the maximum current required and the input charge state of the injected ion beam. To overcome the limitation in energy resolution, a possible design solution would be to guide the beam through a spectrometer. This would provide a low energy spread beam for experiments that require tight energy resolution ($< 0.1\%$), but that can tolerate lower intensities. The CLAIRE injector would be ideally suited as a first stage for such a heavy ion linac.

Background

Background sources include the beam transport system, reactions on target impurities, elastic and inelastic beam scattering, environmental radiation (detector activity and room background) and cosmic-rays. The important He-burning reactions, a major motivation for the facility, can result in beam-induced neutron backgrounds which may conflict with deep underground neutrino detector experiments. Inverse kinematics, using dense helium gas targets can reduce and control these backgrounds.

Experimental Areas, Detectors and equipment

Careful attention must be given to detector materials and to shielding against ambient (room, cavity wall) backgrounds in the experiment hall cavity.

- windowless re-circulating gas target (gas jet and gas cell)
- a Ge-NaI detector array to offer Q-value gating
- Si strip detector systems for final state particle detection and beam measurements
- Segmented Ge or Ge strip detectors offer rejection of beam-induced and room environmental backgrounds via event geometry reconstruction.
- Heavy ion recoil separator for high-Z reactions, integrated with target interaction region detectors

Depth

A depth of 4000 m.w.e. (corresponding to about 1500 m of rock) would be sufficient for the operation of such a facility. This would place the accelerator laboratory into the main campus level at 4850 ft. A different operating level may be desirable so that low level neutrino detection facilities may be shielded against (low level) beam-induced neutron or neutrino backgrounds generated in the long term experiments.

Space

Experimental cavities of $50x20x15m^3$ are currently envisioned for this level.

Low energy accelerator: CLAIRE: $10x8x5m^3$

High Energy Accelerator: $30x20x5m^3$, space for SF6 (if needed)

Experimental hall: 20x15x5 m^3 with additional space of 5x10x5 m^3 for housing the necessary power supply units for magnetic and electric beam optics systems.

Control area, Counting area: 8x8x5 m^3

Power supplies: $5x10x5m^3$

SF6 storage, Cooling water, Cryogenic equipment/cryogenics 10x10x5 m^3.

Above ground areas

Machine shop area

Above ground office space and counting areas

Laboratory space for general use such as experiment preparation, detector testing and target preparation; a space of 10x10x5 m3 would be sufficient.

Infrastructure for Accelerator and Experimental halls

- Overhead crane systems for transporting and positioning heavy equipment
- De-ionized cooling water
- Air conditioning
- Electrical power requirements 200kW (CLAIRE)
- LINAC ?
- Tandem Pelletron ?

Auxiliary Equipment

Sufficient experience in the design and operation of such equipment is available within the working group. There is also close overlap with the design requirements for similar equipment for nuclear astrophysics experiments at RIA.

- windowless re-circulating gas target (gas jet and gas cell)
- evaporator and target laboratory (a serious shortcoming at LUNA)
- a Ge-NaI or Ge-BGO detector array
- Segmented Ge or Ge strip detectors,
- a number of Si strip detector systems
- heavy ion recoil separator.

How to arrive at realistic cost estimates

Accelerator facility CDR: 4-5 FTE, 12 months
Low energy accelerator

- CLAIRE: Accelerator R&D has been started; a detail project and cost estimate exists, PreCDR has been conducted, a preliminary cost estimate exist

1 MeV/u heavy ion accelerator: Pre CDR 4 FTE

- Pre CDR: Design study must be conducted before the accelerator option can be decided.
    - High intensity LINAC
    - DC Accelerator
- A CDR for the high energy accelerator option would require and would take about 12 months
- Accelerator specifications and requirements must be developed by the community (workshops)
- Estimate cost of assembly in a mine – engineering or construction constraints associated with access (i.e. maximum part size to go down lifts/shafts)

Experimental equipment R&D: 2-3 FTE 12 months

- Experiment concepts, design the layout, detector, high purity target (feasibility study) need to be developed and costed
- Consolidate existing cost estimates to a coherent overall experimental equipment plans for the facility
- Beam diagnostic instrumentation cost estimates
- Identify R&D for detector arrays and background suppression
- Cost of Ge-BGO or Ge-NaI array for Q-value gating (crystal volume, PMT cost, Ge size)
- Input from design of Notre Dame recoil separator to inform cost estimates for replication and underground construction
- Evaluate utility of "exotic detectors": LXe TPCs

E&O

Nuclear astrophysics involves popular questions which market well to the lay public (How do stars burn? Where did the earth's elements come from? How common might extraterrestrial life be?). An accelerator facility would provide a unique opportunity in the region for students to learn accelerator-based nuclear physics. Local students may serve as operators (after training). Long experiment run times will require a number of experimenters to monitor the experimental data taking, another obvious area for student participation.

Several aspects of the astrophysics experiments, such as target preparation, involve chemistry expertise and technical assistance which could serve as bridges to other academic specialties. Synergies exist with low level counting facilities for activation measurements.

There is interest from South Dakota colleges to participate (based on meeting with SD faculty at LBNL). Presently, this effort is more actively pursued by the high-energy physics collaborations, but low energy nuclear astrophysics offers attractive participation opportunities and should see greater effort in education opportunities. The relatively short time scale in which those experiments can be built and used for physics experiments at DUSEL makes them an excellent candidate to involve local universities. In addition, the Colorado School of Mines has faculty with low energy nuclear astrophysics expertise.

For graduate and post doc level education and outreach opportunities, accelerator based astrophysics offers complex, high precision experiments not common to most research departments, which would diversify the research areas available to local physics graduate programs.

JINA has developed a strong outreach program over the last five years and will be a natural partner in developing material for the undergraduate level as well as at the K-12 level. In terms of international outreach, JINA has joined the LUNA group and participates in experiments there. The opportunity exists to build this relationship into an international collaboration in education and outreach in nuclear astrophysics