Summary Report of Working Group on Equipment and Facilities: Stable Beams and Gamma Beams

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1 Open Questions

Stable and photon beam experiments address scientific questions of paramount importance for stellar evolution and nucleosynthesis: Where are the elements produced that life depends on (carbon, nitrogen, oxygen)? How do stars evolve? Where are 50% of the elements beyond iron produced? Are there nuclear signatures to probe the core of stars, e.g., CNO neutrinos for probing the solar core metallicity? Some of the poorly known nuclear reactions impacting these issues are capture reactions (e.g., ^{3}He(α, $|gamma$)^{7}Be, ^{12}C(α,γ)^{16}O, ^{14}N(p,γ)^{15}O, ^{17}O+p), heavy-ion reactions (e.g., ^{12}C+^{12}C, ^{12}C+^{16}O, ^{16}O+^{16}O), neutron sources and neutron poisons (e.g., ^{13}C(α,n)^{16}O, ^{22}Ne+α, ^{17}O+α). In addition, a relatively small number of reactions involving stable targets (e.g., ^{12}C(α,γ)^{16}O, ^{14}N(p,γ)^{15}O and ^{22}Ne+α) have a tremendous impact on stellar explosions, since these reactions determine the seed abundance distribution for core collapse, thermonuclear runaway, and the p-process. Without new dedicated and more sensitive measurements, there will be no progress on these fundamental questions in science. Future measurements of key reactions are being planned both at existing university laboratories (e.g., University of Notre Dame, University of North Carolina, Ohio University, and Duke University) and at proposed national facilities (e.g., the Dual Ion Accelerator for Nuclear Astrophysics, DIANA).

2 Advances in Reaction Rate Methodology

Since the last Nuclear Astrophysics Town Meeting in 1999 there have been three concurrent major advances in terms of deriving and employing thermonuclear reaction rates: (i) nucleosynthesis sensitivity studies are being increasingly performed, whereby the impact of a given reaction rate on an astronomical observable can be quantified; (ii) a Monte Carlo method has been developed for estimating experimentally-based reaction rates, and associated uncertainties, in a statistically meaningful manner; (iii) sophisticated reaction models (R-matrix, Asymptotic Normalization Coefficients) have been developed for analyzing reaction data, allowing for more reliable cross section extrapolations to low bombarding energy, where direct measurements become very difficult. These three computational instruments are not only important for significantly improving stellar model predictions, but are also crucial for defining the astrophysical impact of cross section measurements.

3 Experimental Methods and Techniques

Direct measurements of astrophysical crucial reaction cross sections are being planned using a variety of complementary experimental techniques at stable beam facilities: (a) in normal kinematics, i.e., protons or α-particles bombarding a heavier target. In this case, high-current ion beams in excess of 1 mA are mandatory. In addition, efforts must be invested in studying solid targets that can withstand the intense ion bombardment. Beam-induced and room background must be reduced by orders of magnitude, by a combination of ultra-pure targets, passive shielding, and coincidence detection techniques. An existing example for such a facility is the Laboratory for Experimental Nuclear Astrophysics (LENA) at the Triangle Universities Nuclear Laboratory (TUNL); (b) in inverse kinematics, i.e., heavy ions bombarding a hydrogen or helium gas jet target. In this case, the heavy reaction products are detected using sophisticated recoil mass separators with very high detection efficiency. Such a facility was completed recently at the Nuclear Science Laboratory (NSL) at the University of Notre Dame.

When direct measurements are not feasible, for example, if the signal is below current detection sensitivities, experimental methods using transfer reactions have to be employed. Some of these techniques can also be used to indirectly study reactions involving radioactive targets, provided they are close to the line of stability. These measurements, which are termed indirect since the experiments are performed at much higher bombarding energy compared to the energies of astrophysical interest, allow for measurements of the energy and quantum numbers of excited nuclear levels that correspond to astrophysical important resonances. An example is provided by indirect studies of the ^{25}Al(p,γ)^{26}Si reaction using stable beams, which include heavy-ion fusion γ-ray spectroscopy, charged-particle spectroscopy, and neutron time-of-flight spectroscopy via the (^{3}He,n) reaction at Ohio Universitys Edwards Accelerator Laboratory. In addition, the strengths of important resonant and non-resonant cross section contributions can be extracted using the Asymptotic Normalization Coefficient (ANC) method or the Trojan Horse Method (THM). In this case, the data analysis requires application of nuclear reaction models. These methods provide crucial complementary information for estimating reaction rates. However, the measurements require careful validation in order to obtain defensible reaction rate uncertainties. Such experiments are performed, for example, at the Cyclotron Institute at Texas A&M University and the John Fox Laboratory at Florida State University.

Apart from direct and indirect measurements using hadron beams, photon beams become increasingly important for nuclear astrophysics. The worlds premier laboratory in terms of photon beam intensity and resolution is the High-Intensity γ-ray Source (HIγS) at the Triangle Universities Nuclear Laboratory. Measurements can be performed by directing a quasi-monoenergetic γ-ray beam on a suitable sample. The cross section for a reaction of interest can be obtained by measuring the reverse reaction and by applying the reciprocity theorem. A particularly important example is the ongoing measurement of the ^{16}O(γ,α)^{12}C reaction in order to estimate the ^{12}C(α,γ)^{16}O rate, which is crucial for the evolution of stars, at low energies. Astrophysically important levels can also be studied via nuclear resonance fluorescence, i.e., (γ,γ'), in order to measure precise compound level energies and quantum numbers.

4 Opportunities and Experimental Needs

The past decade featured the construction and commissioning of dedicated stable and photon beam facilities for nuclear astrophysics in the U.S. All of these facilities are university-operated accelerator laboratories: Duke University (mono-energetic photon beam), Ohio University (neutron time-of-flight), Texas A&M University (indirect transfer studies), University of North Carolina (normal kinematics), and University of Notre Dame (normal kinematics and inverse kinematics with recoil separator). The unique and diverse training of graduate students at university facilities cannot be overemphasized: by the time of graduation, the students have become experts in radiation detectors, high-voltage and vacuum systems, electronics, computer programming, nuclear and astrophysics. Consequently, they are highly attractive for academic, federal and corporate employers in an increasingly competitive job market.

Certainly, some important stable-beam and γ-ray-induced reactions will be measured at these facilities over the next decade. To take advantage of the full capabilities of these laboratories, future equipment upgrades are mandatory for measuring astrophysical key reactions, e.g., ^{12}C(α,γ)^{16}O, ^{14}N(p,γ)^{15}O, and ^{22}Ne+α, at lower energies. Future equipment needs include: (a) development of higher ion beam intensities and implementation of pulsed low-energy beams; (b) next-generation γ-ray detector arrays with an increased detection efficiency; (c) construction of ultra-pure low-background neutron detectors, based on the extensive expertise of the neutrino and dark matter community; (d) increase of photon-beam intensity at HIγS.

We expect that these experiments will approach the astrophysical important energy region and, thereby, significantly improve knowledge of crucial thermonuclear reaction rates. However, stable-beam measurements at stellar energies ultimately require a dedicated underground laboratory, where the cosmic-ray muon background is reduced by orders of magnitude. The only underground accelerator facility at the moment is the Laboratory for Underground Nuclear Astrophysics (LUNA), operated for the past 20 years by a European collaboration in the Laboratori Nazionali del Gran Sasso, Italy. A particular highlight among LUNA achievements is the first measurement of a reaction, ^{3}He(^{3}He,2p)^{4}He, at energies occurring in the Sun, which greatly improved our interpretation of the ^{8}B solar neutrino flux. Nevertheless, LUNA has limitations in terms of beam intensity, ion beam type, and detection versatility for measuring the key reactions discussed above. In response to the urgent scientific need, a next-generation underground accelerator facility in the U.S., the Dual Ion Accelerator for Nuclear Astrophysics (DIANA), has been proposed by a conglomerate of groups (University of Notre Dame, University of North Carolina, Western Michigan University, and Lawrence Berkeley National Laboratory). DIANA will be located 1.4 km below ground and will represent a unique combination of background reduction achieved by several orders of magnitude, ion beam intensities up to 100 mA at low energies, and available ion beams ranging from protons to oxygen.

We emphasize the utmost importance of upgrading the university-based laboratories for: (a) pursuing complementary experiments at higher energies in order to reduce uncertainties in existing data; (b) developing new experimental techniques and radiation detectors; and (c) attracting and training the future workforce in cutting-edge nuclear technology.